DOE/CS/32522-T1

MASTER

Solar Photovoltaic Applications Seminar: Design, Installation and Operation of Small, Stand-Alone Photovoltaic Power Systems

MASTER

July 1980

Prepared for:
U.S. Department of Energy
Assistant Secretary for Conservation and Solar Energy
Office of Solar Applications for Buildings

Under Contract No. AC01-77CS32522

Available from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price: Printed copy: $19.00
Microfiche: $ 4.00

DOE/CS/32522-T1
Dist. Category UC-63

Solar Photovoltaic Applications Seminar: Design, Installation and Operation of Small, Stand-Alone Photovoltaic Power Systems

July 1980

Prepared for:
U.S. Department of Energy
Assistant Secretary for Conservation and Solar Energy
Office of Solar Applications for Buildings
Washington, D.C. 20585

Prepared by:
PRC Energy Analysis Company
McLean, Virginia 22102
Under Contract No. AC01-77CS32522

B A C K G R O U N D

The Department of Energy (DOE) Act of 1978-Civilian Applications (Public Law 95-238, Section 208) authorized $12,000,000 in FY 1978 to acquire life-cycle cost-effective photovoltaic systems for Federal facilities. That program was greatly augmented by the establishment of the Federal Photovoltaic Utilization Program (FPUP) under Title V, Part 4, of the National Energy Conservation Policy Act (Public Law 95-619) which authorized the appropriation of an additional $98,000,000 for FY 1981.

As indicated in P.L. 95-619, the key objectives of FPUP are:

(1) To accelerate the growth of a commercially viable and cooperative industry to make photovoltaic solar electric systems available to the general public as an option in order to reduce national consumption of fossil fuel.

(2) To reduce fossil fuel costs to the Federal government.

(3) Stimulate the general use within the Federal government of methods for the minimization of life-cycle costs.

(4) To develop performance data on the program.

To achieve the objectives established by Congress, the FPUP must stimulate industry and market development. It must support the applications that have been identified as having significant market potential in the private domestic arena and in foreign countries as well as in the Federal agencies.

The FPUP is being conducted in five cycles, depending upon funds availability, as summarized in Table 1.

Table 1. FPUP Application Cycles

Fiscal Year	Cycle	Major Applications	Cost Effective
1978	I	Small Remote	Now
1979	II III	Small Remote Intermediate Remote	Early 1980's
1980	IV	Intermediate Remote	Mid 1980's on
1981	V	Residential Selected Intermediate Grid Connected	

To date, FPUP has funded more than 3,000 photovoltaic applications in thirteen Federal departments (listed below) at a cost of $23,000,000. Every state is represented by applications, except North Dakota. There are also applications in the West Indies, the Pacific Islands and Europe.

The Advisory Committee established in P.L. 95-619 has been chartered and members named. A rule for the monitoring and assessment of systems installed under the program was published in final form on November 7, 1979.

The program will be closely coordinated with the activities and experiments underway under the Solar Photovoltaic Energy Research Development and Demonstration Act of 1978 (Public Law 95-590). Technical support will be provided to the agencies that will draw on the technical expertise gained both by industry and DOE field centers in prior applications. This seminar material is part of that technical support.

Participaing Federal Agencies

Department of Agriculture
Department of Commerce
Department of Defense
Department of Energy
Department of Interior
Department of State
Department of Transportation
Department of Treasury
Environmental Protection Agency
General Services Administration
Health and Human Services Administration
National Aeronautics and Space Administration
Tennessee Valley Authority

PREFACE

This seminar material was developed primarily to provide solar photovoltaic (PV) applied engineering technology to the Federal community. An introduction to photoconductivity, semiconductors, and solar photovoltaic cells is included along with a demonstration of specific applications and application identification.

The seminar details general systems design and incorporates most known information from industry, academia, and Government concerning small solar cell power system design engineering, presented in a practical and applied manner. Solar PV power system applications involve classical direct electrical energy conversion and electric power system analysis and synthesis. Presentations and examples involve a variety of disciplines including structural analysis, electric power and load analysis, reliability, sizing and optimization; and, installation, operation and maintenance.

Four specific system designs are demonstrated: water pumping, domestic uses, navigational and aircraft aids, and telecommunications. All of the applications discussed are for small power requirement (under 2 kilowatts), stand-alone systems to be used in remote locations. Also presented are practical lessons gained from currently installed and operating systems, problems at sites and their resolution, a logical progression through each major phase of system acquisition, as well as thorough design reviews for each application.

All PV system applications discussed are solar powered. The radioisotope powered photovoltaic system is not considered, except as a secondary possibility for supplemental energy. A distinguishing characteristic of these small PV power systems is that they can be stand-alone systems. The utility grid-connected application is a secondary possibility for required supplemental energy.

TABLE OF CONTENTS

TABLE OF CONTENTS
Continued

TABLE OF CONTENTS
Continued

TABLE OF CONTENTS
Continued

TABLE OF CONTENTS
Continued

TABLE OF CONTENTS

Continued

SECTION I
INTRODUCTION

The subject matter of this seminar is solar photovoltaic (PV) power systems, which are stand-alone systems. This section will enable the seminar participant to: describe the PV process and the equivalent circuit; plot a typical current-voltage (I-V) curve under various insolations and temperatures (to determine the electric power profile); list the array-to-cell component nomenclature; sketch block diagrams; and, show load/array interactions on an I-V plot. The radioisotope powered PV system is not considered.

1.1 SOLAR (PV) CELLS

Solar radiation, as it impinges upon the earth, has the properties of both energy waves and particles. The wave property is associated with both the light spectrum detectable with glass prisms, heat, and electromagnetic radiation. The wave and particle properties are associated with the production of electricity by PV cells (semiconductors). In brief, the energy particles (photons) penetrate the two-layered PV device (solar cell). The top (n layer) contains many free electrons. The bottom (p layer) contains many highly mobile positive charges called holes. Photons of high enough energy pass through the thin n layer and are absorbed by atoms in the p layer. Electrons are energized and hole-electron pairs are created. The electrons wander around in the p layer until recaptured by holes. If the electrons enter the junction between the n and p layers, they get caught in the crystal electric field charge differential near the p-n junction and are drawn into the n layer. Hence, electrons gather in the upper layer and the region becomes negatively charged. Because the electrons have migrated from the p region, the p region becomes positively charged. Therefore, a voltage develops across the junction as though it were a capacitor. If wires are connected to the top and bottom of the cell, a current will flow through the wire (see exhibit 1.1). As a result of the photon bombardment, the solar cell (semiconductor) acts as an electron source. This entire process is termed photoconductivity. The photon is defined as a quantum of electromagnetic energy having both particle and wave behavior. It has no charge or mass but possesses momentum and carries the energy of light. The frequencies of the photon radiation equal the speed of light divided by the photon wavelengths. The energy of the radiation equals the frequency times a constant.

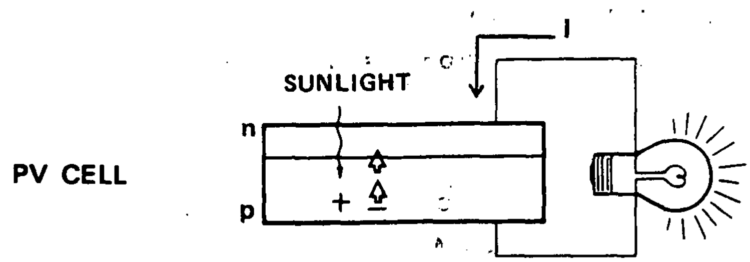


Exhibit 1.1 Solar Photoconductivity of the p-n Junction Semiconductor

Exhibit 1.2 shows an equivalent circuit for one cell. Due to photoconductivity, a current source is contained within the circuit. The current source is "shorted" (paralleled) by a diode (which represents the p-n junction) with a current that opposes the photon-induced current. This semiconductor junction dark current is a function of the semiconductor reverse saturation current and p-n junction voltage. The dark current is always present, even for an un-illuminated cell, which is typical of semiconductors. In addition, there is a series resistance resulting from the bulk electrical resistance of the cell material, as well as the series resistance of the electrical leads and the joint between the leads and the cell material. A shunt (parallel) resistance also is present, simulating the recombination of electrons and holes that occurs within the material before the electrons can leave the cell for load current. The unilluminated current is also referred to as the dark current. $I = I_L + I_D$ where I_L = illuminated current and I_D = unilluminated current, and I = cell output current.

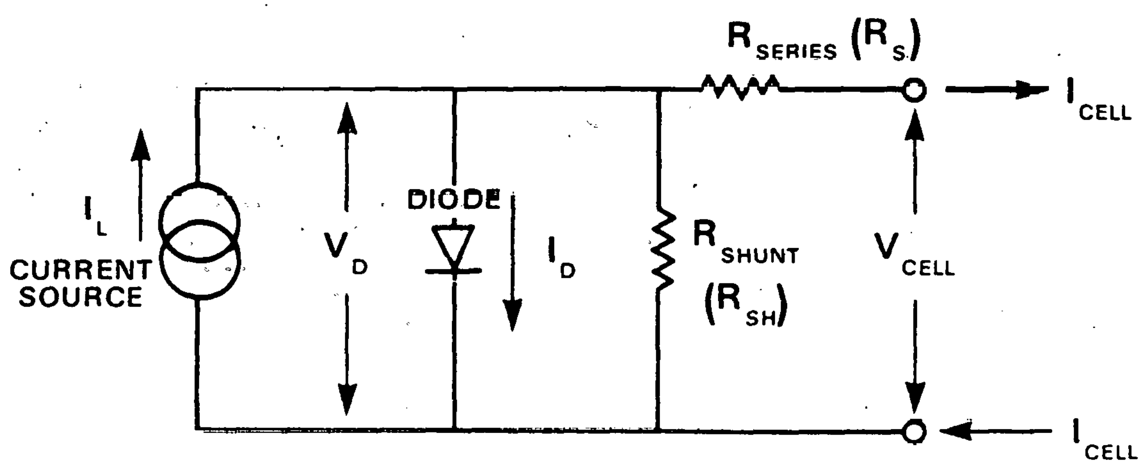


Exhibit 1.2 Equivalent Circuit for Solar Cells.

Exhibit 1.3 illustrates the voltage-current relationship for a single cell. The cell output is shown in the upper left. The power output of the cell is equal to the product of the current and voltage; the maximum-power point is indicated as P_M in the exhibit. The upper right curve shows the variation of output current and voltage with insolation (solar flux). An insolation intensity of 100 mW/cm^2 corresponds to a clear day at sea level. The curve shows that the short-circuit current is proportional to the insolation, but that the open-circuit voltage is insensitive to insolation. The effects of temperature are illustrated on the curve on the lower left. The maximum output power decreases approximately 0.5 percent per degree (C) temperature increase. This effect is illustrated on the lower right. Unlike conventional generators, the PV cell current decreases for increases in cell voltage.

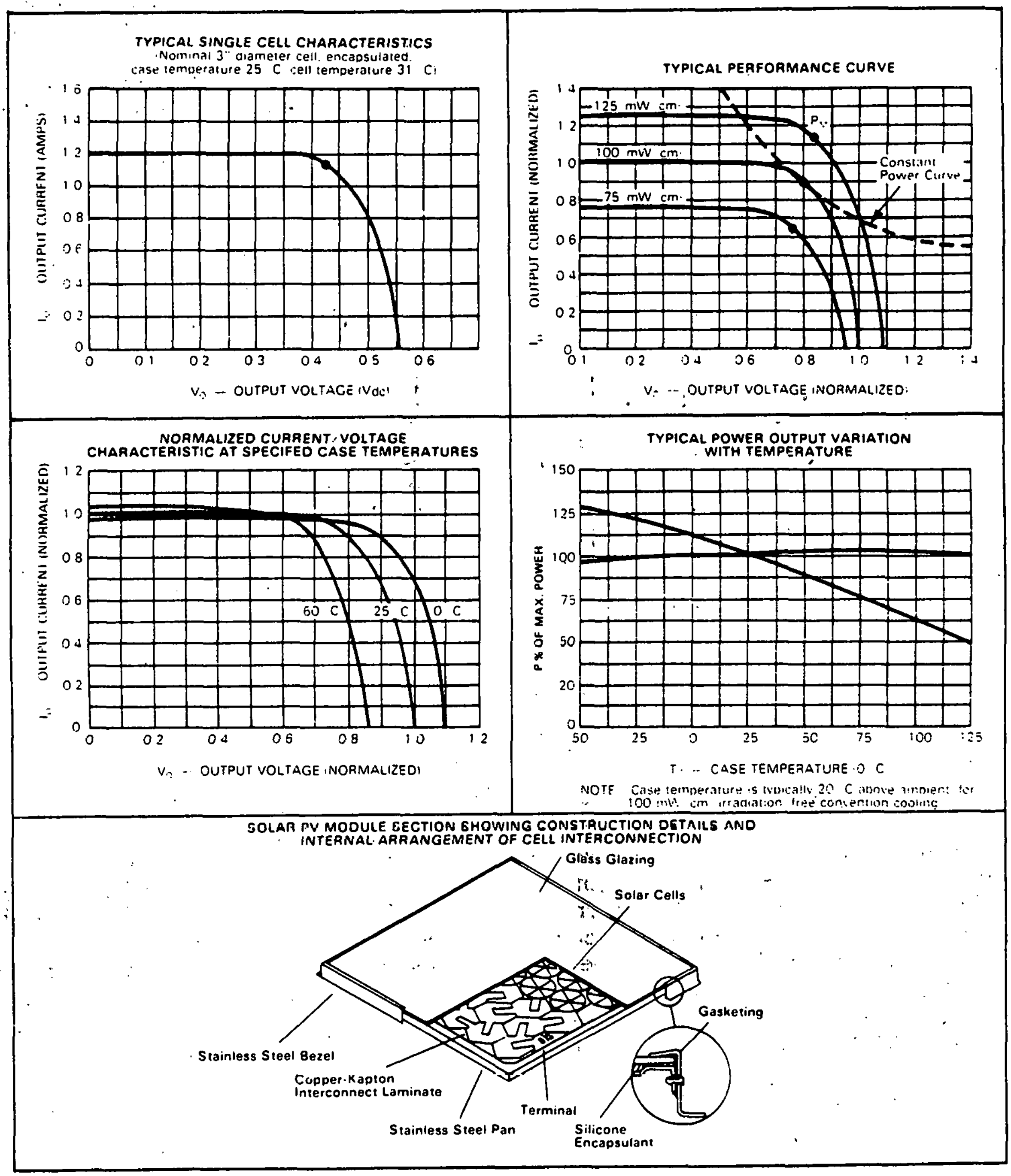


Exhibit 1.3 The Relationship Between Current and Voltage for Typical PV Cells.

1.2 COMPONENTS OF THE PV SYSTEM

A PV array is composed of many subarrays, panels, modules, and cells in various series, parallel, star, and delta combinations. Environmental effects are usually mitigated by designing solar cell packages that "control" the near-term effect of the environment. Present-day construction encases the solar cells behind tempered, low-iron-content glass, backed up by high temperature silicone rubber compounds and a back supporting member such as a fiberglass sheet as illustrated in exhibit 1.4. The solar PV power system is a stand-alone system but can incorporate back-up power. One-axis and two-axis tracking collectors are not considered in this seminar, and usually involve the mounting of PV modules at the foci of concentrators. These collectors are being studied in the solar heating/cooling, solar thermal power system, and solar total energy system programs.

Exhibit 1.5 shows a PV array and component parts. Individual cells are wired together and mounted to produce a module. The individual cells within the module are wired together to produce the required output voltage and current. These cells are usually placed in a compound of silicone rubber because it has good thermal expansion and weathering capabilities. Currently, these modules are covered with glass, plastic, or a silicon-rubber compound to provide further protection to the cells. They are then wired together to form a panel of adequate electrical and structural size. Panels are usually installed side-by-side. The structure is tied together and electrically and structurally integrated to form subarrays. Subarrays are then arranged, usually one behind the other (although a side-by-side arrangement is possible), to form arrays. Exhibit 1.6 shows network connections for balanced loads and generators. The summation of current at any node equals zero, and the summation of voltage in any loop equals zero, according to the Kirchhoff circuit laws of the conservation of energy/charge. Voltage equals energy per unit charge, and current equals charge per unit time. The final array configuration is heavily dependent on the cell I-V characteristics.

Based on application and load requirements, the terminals of the array are connected to various "power conditioning" equipment. This power conditioning equipment is designed to convert the direct current (DC) produced by the array to a more suitable type (alternating current (AC), if AC voltage is required) and various duty cycles of power. Exhibit 1.7 shows the basic components of the PV system. The power conditioning equipment also integrates battery storage and supplemental energy sources (if required) with the PV array and load. The system is regulated to maintain system voltage, adequate battery storage, and frequency for AC loads, continuously.

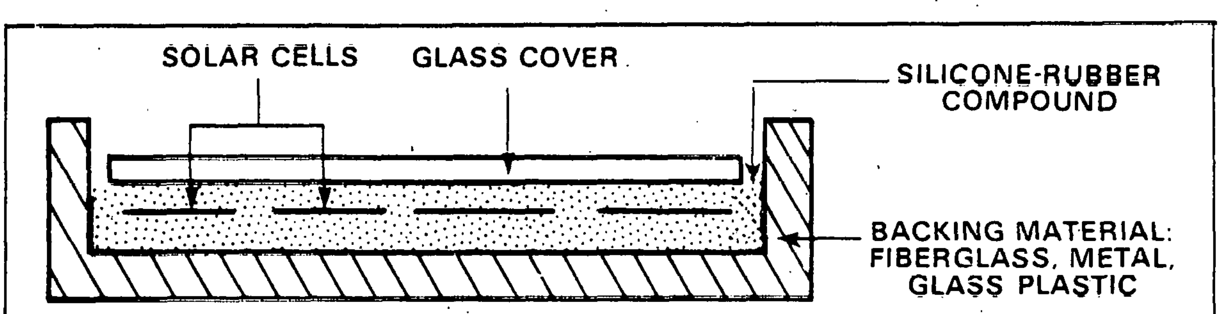
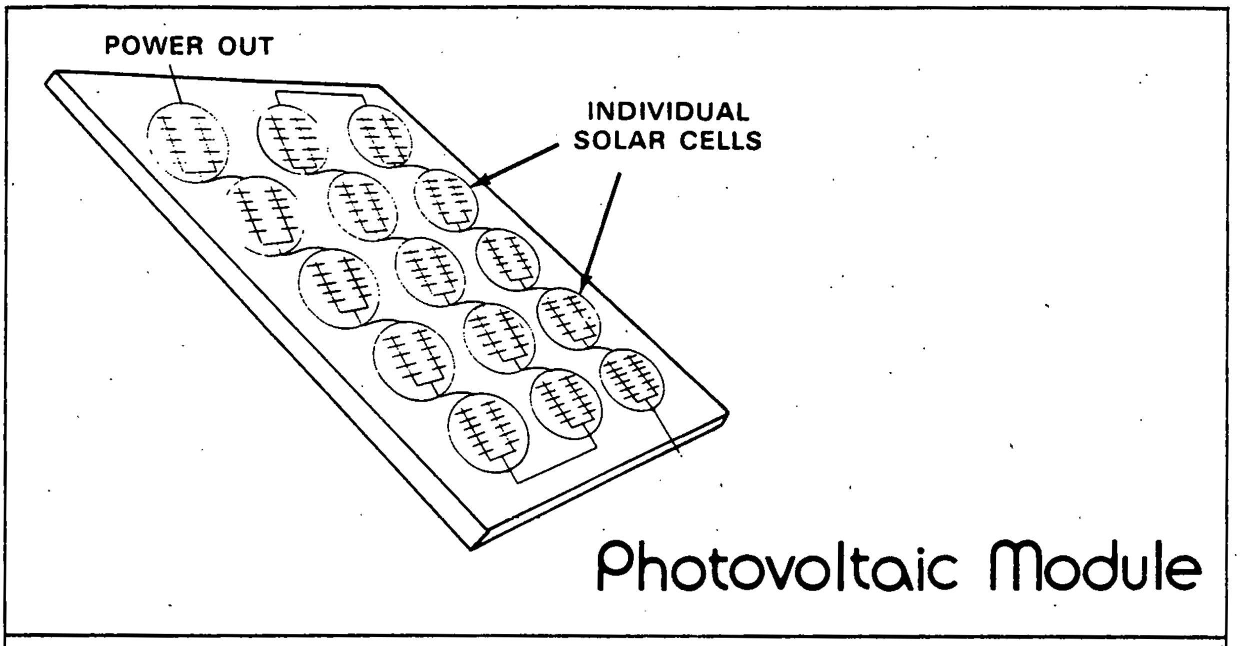
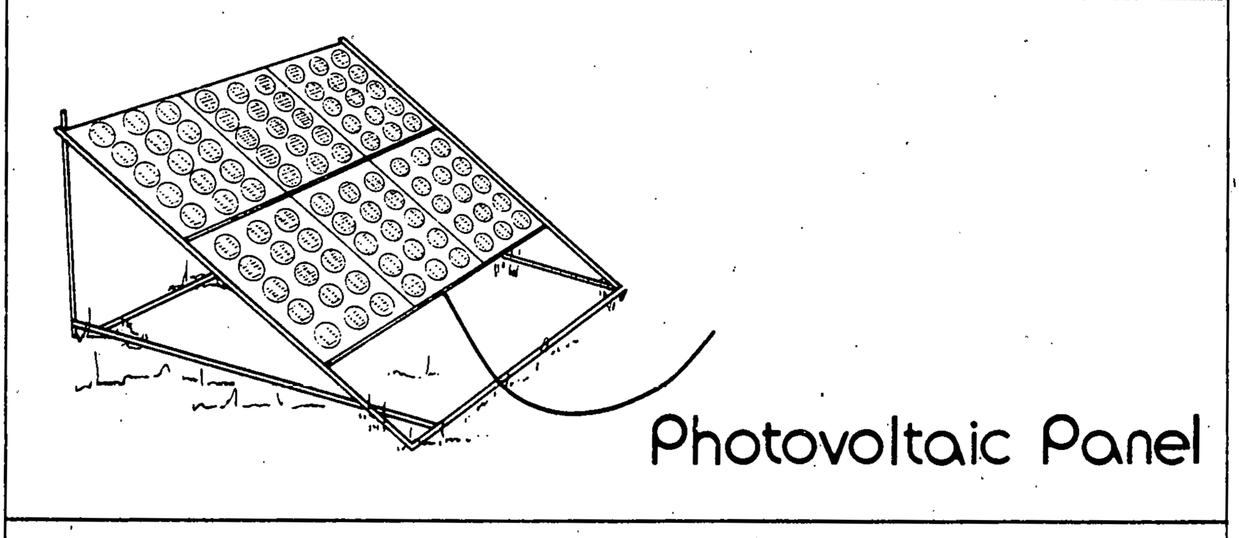


Exhibit 1.4 Cross-Section of a Photovoltaic Module.





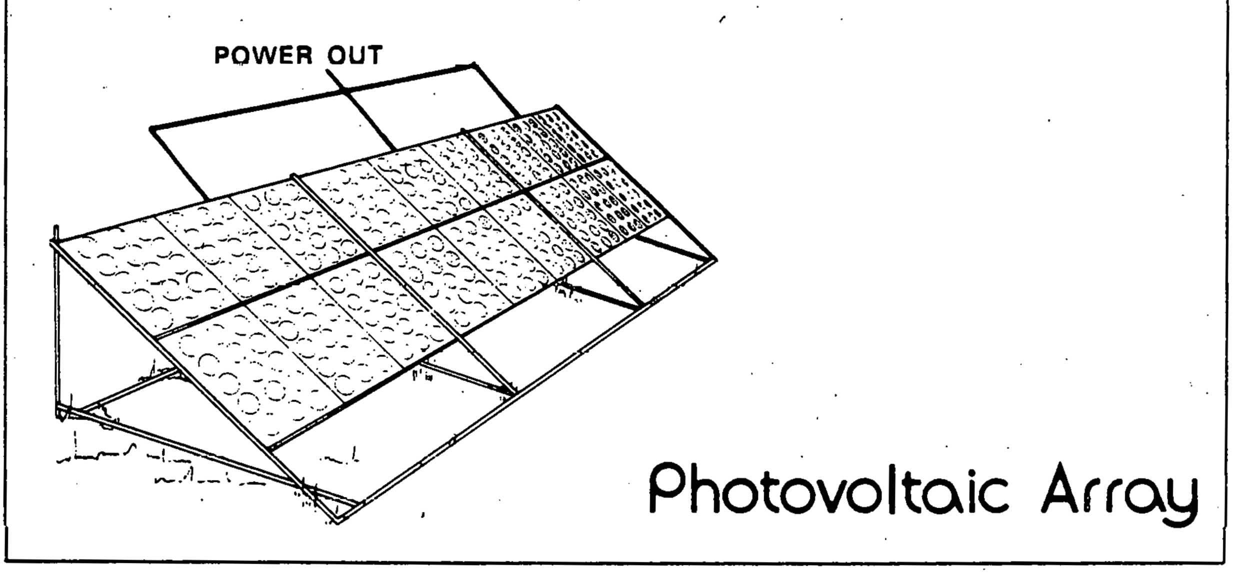
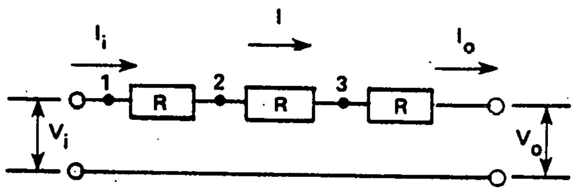


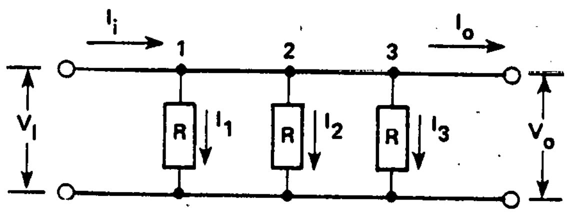
Exhibit 1.5 Solar Cell Array Components.

R = Resistance, I = Current, V = Voltage, P = Power, i = in, o = out



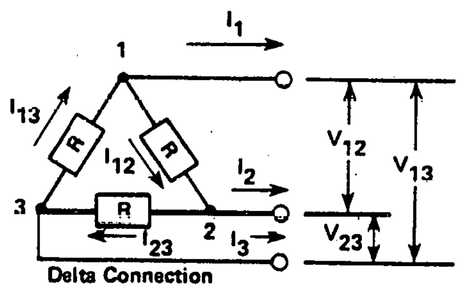
Series Loads (R)

$I_i = I_o = I$, $V_o = V_i - 3IR$



Parallel Loads (R)

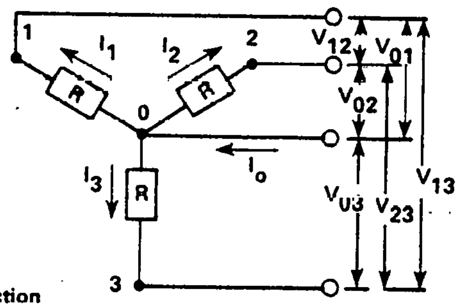
$I_1 = I_2 = I_3$, $V_I = V_o = V$, $I_o = I_i - 3V/R$



Delta Connection

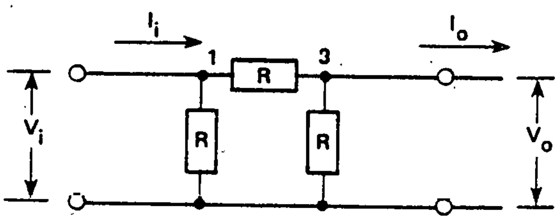
$I_{12} = I_{13} = I_{23}$ $I_1 = I_2 = I_3$

$V_{12} = V_{13} = V_{23}$ $V_{12} = I_{12}R$



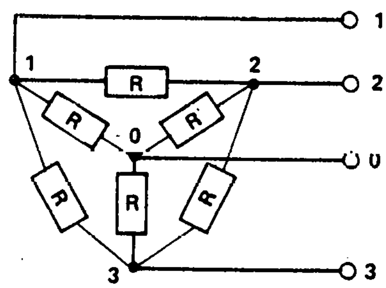
Star Connection

$I_1 = I_2 = I_3$, $V_{12} = V_{13} = V_{23}$, $V_{01} = V_{02} = V_{03}$

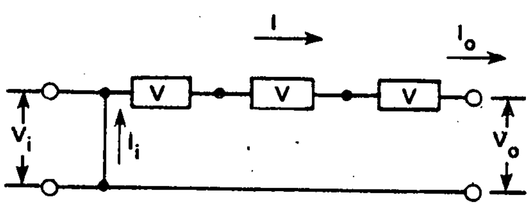


Series Parallel

$V_o = R(I_i/2 - I_o)$, $I_i = 2V_i/R$

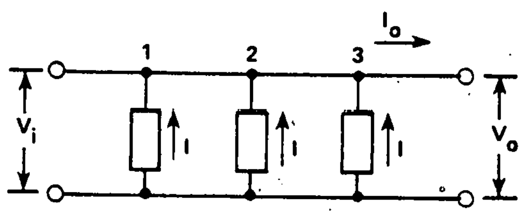


Star-Delta



Equal Generators in Series

$I_i = I_o = I$, $V_o = 3V$



Equal Generators in Parallel

$V_I = V_o$, $I_o = 3I$

$V = IR$: Ohms Law, $R_t = R_1 + R_2 + R_3$: Series Load Law

$1/R_t = 1/R_1 + 1/R_2 + 1/R_3$: Parallel Load Law.

Exhibit 1.6 Balanced Network Connections

A power inverter is an element of the power conditioner and is an electrical device that bidirectionally switches the polarity of the array output direct current at a desired frequency (usually 60 cycle) for AC applications (see exhibit 1.8). The operation of the electronic switching on-off devices produces an alternating current "square wave" effect that is highly undesirable, so a filter is employed to smooth out the square edges. This sinusoidal conditioned power can then be used in place of utility power for conventional AC electricity or in conjunction with utility power for grid connected applications. The amplitude of the voltage wave is adjusted to match the effective voltage required. For a 60 cycle per second frequency (60 Hertz) sine wave, 170 volts peak AC produces the equivalent of 120 volts DC. The DC equivalent is the r.m.s. value (root-mean-square), the effective value.

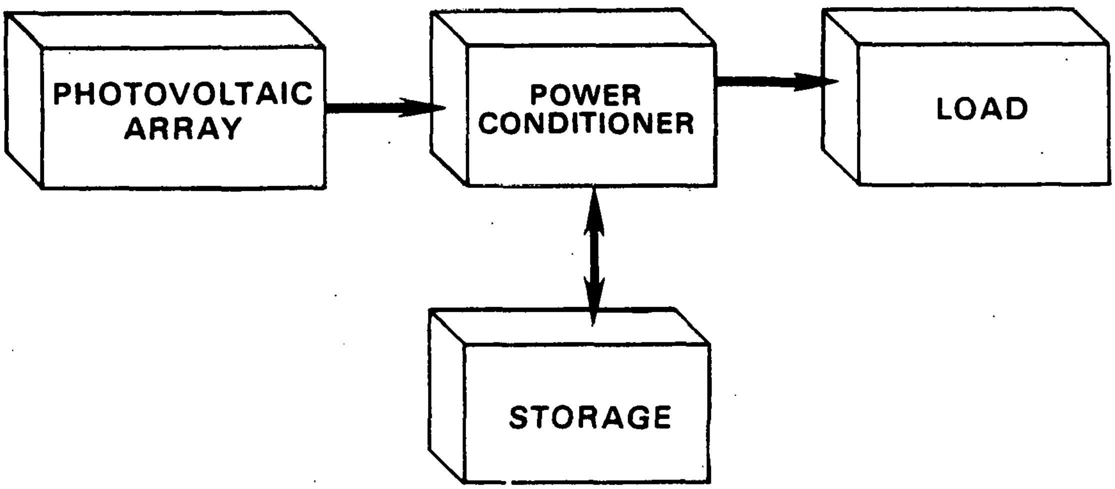


Exhibit 1.7 Basic Components of the Photovoltaic System.

Energy storage is necessary for solar-produced power during sunset, night, sunrise, inclement weather, or a series of cloudy days. The best-suited and most common storage device is the electrical storage battery. Batteries are inherently DC devices and, for some applications, the array and a battery storage system can be employed to provide power directly to a load without a power inverter (exhibit 1.9). Applications of such systems include DC motors for irrigation of farm land, providing power to DC-operated radio equipment, and applications where DC transmission and/or distribution are required or feasible.

Systems designed for AC loads can use storage batteries in various ways. Exhibit 1.10 illustrates the addition of a DC/AC power inverter to the system shown in exhibit 1.9.

Exhibit 1.11 is a different design for using storage batteries for AC loads. The system in exhibit 1.10 can be improved by adding a converter, and a smaller power inverter (exhibit 1.11). This retrofit would be made if the load requirements are reduced drastically when stored energy is used (e.g., nighttime minimal load). A low voltage array can supply a high voltage load while charging batteries at an intermediate voltage.

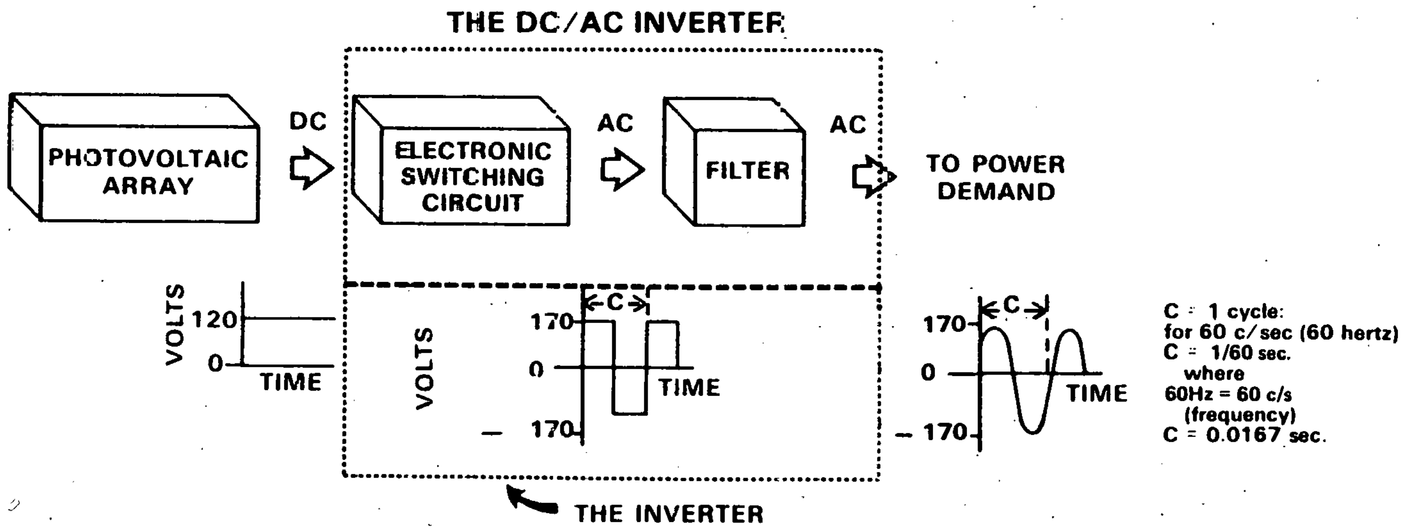


Exhibit 1-8 Operation of the Basic Power Inverter (DC/AC)

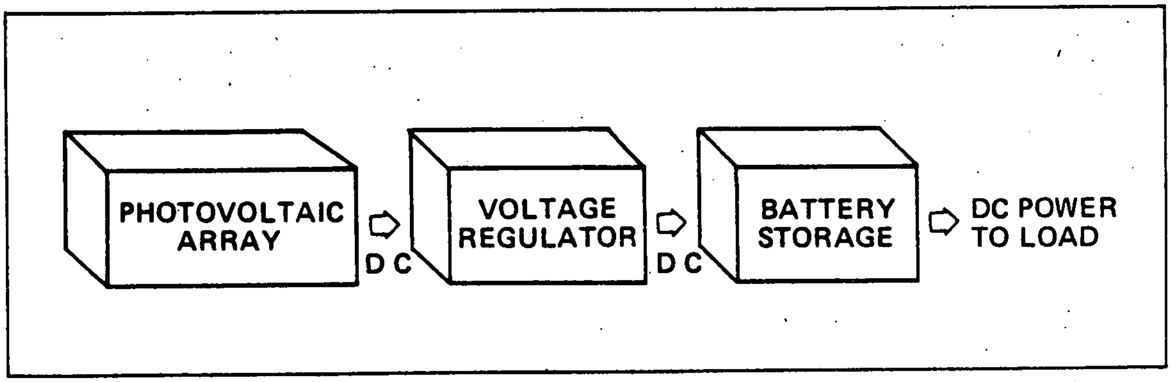


Exhibit 1.9 Supplying DC with Battery Storage.

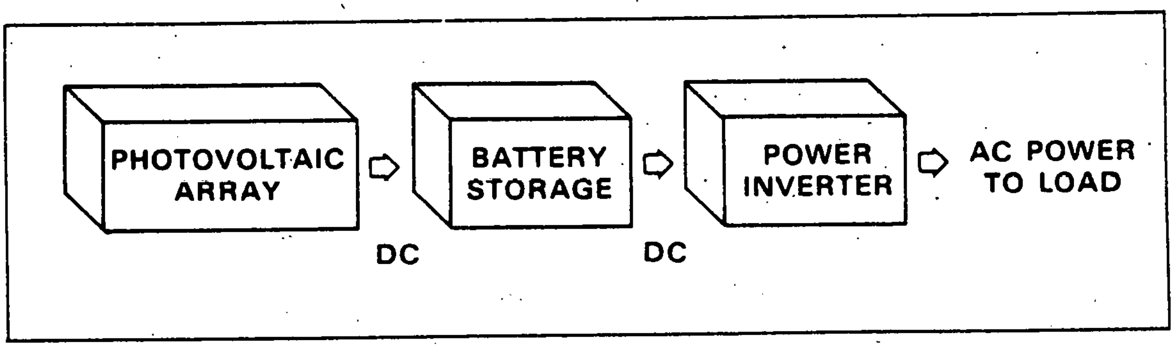
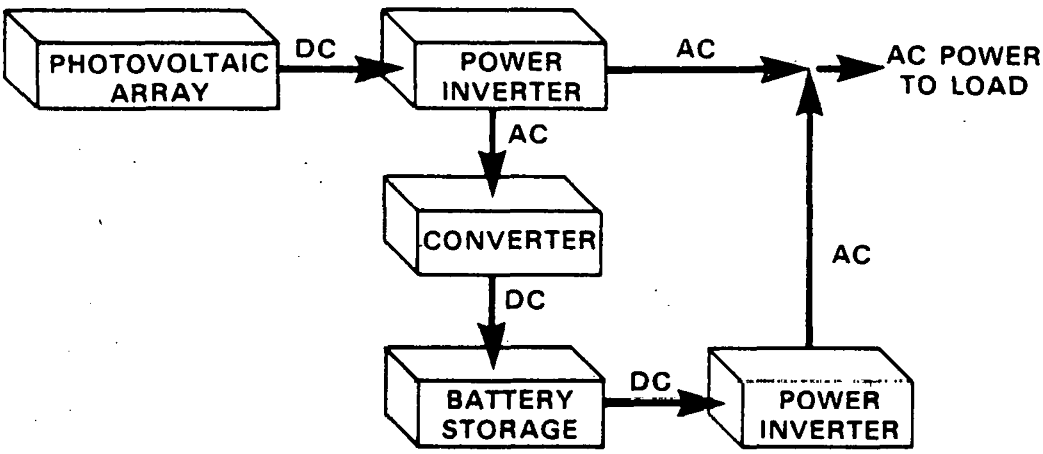


Exhibit 1.10 Supplying AC with Battery Storage.



IF INVERTER #1 IS 20% EFFICIENT AT NIGHT LOAD, USE OF ONLY ONE INVERTER GIVES 1.9% TO 2.7% EFFICIENCY AT NIGHT.

Exhibit 1.11 Supplying AC with Battery Storage for Low Night Demands.

DIRECT	STORED
9.0%	5.3%
13.2%	10.3%

EFFICIENCIES

1.3 SUPPLY/LOAD INTERACTION

Exhibit 1.12 illustrates the current-voltage relationship of cells under various illuminations. With decreasing (or increasing) amounts of illumination, the solar cell maximum power point "moves" for a constant load. The cell power ouput (P = V x I) is maximized, where P = power, V = voltage, I = current, Isc = short circuit current, and Voc = open circuit voltage. The rectangular area of the I-V plot is the cell electric power for a given operating point. The I intercept is Isc and the V intercept is Voc for V = O and I = O, respectively, for the curves.

The design load locus is a line (y = mx + b) where y = current, m = a constant (1/R), x = voltage, and b = o. Isc is a linear function of intensity (insolation) and Voc is a logarithmic function of intensity. Varying the load to produce optimal conditions results in maximum power being transferred from the array to the load. While the actual load may not change in value, the system can compensate for a shift in the load by either adding or decreasing the power going into storage. A distinguishing characteristic of PV cells is that current decreases for increases in cell voltage. Resistance (R) equals voltage/current, where one ohm equals one volt per ampere.

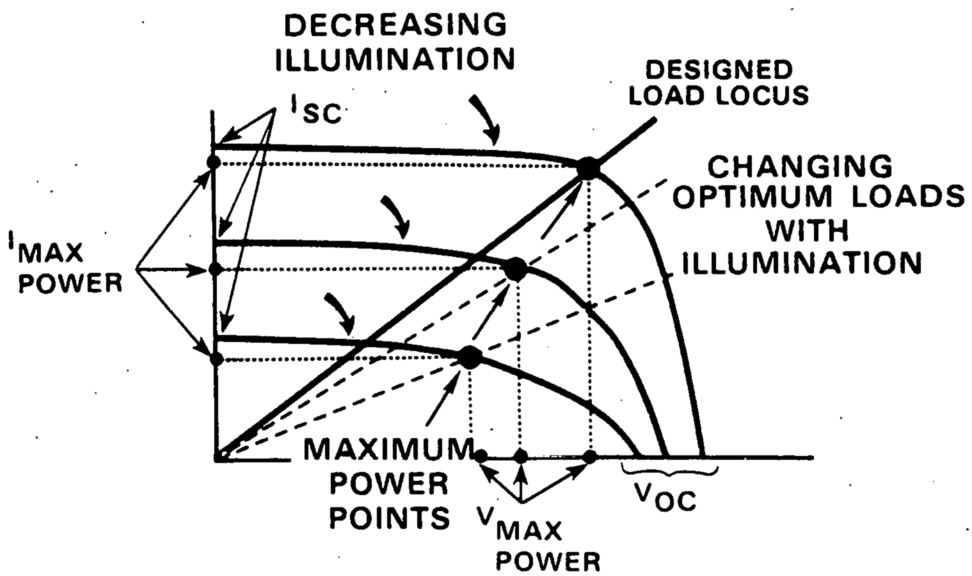


Exhibit 1.12 I-V Relationship of PV Cells with Decreasing Illumination.

Exhibit 1.13 shows the system illustration in Exhibit 1.11 with the addition of a maximum power tracker and a reference solar cell. The maximum power tracker adjusts the effective load on the photovoltaic array, using the signal from the reference solar cell. This compensates for a change in power due to a change in illumination.

The system shown in Exhibit 1.13 is considered to be an effective system for supplying power to a varying load under varying solar (insolation) conditions. Also shown in the figure is a backup system which can be utilized as a supplement or to supply power when prolonged periods of lack of sunlight completely deplete the storage capability of the photovoltaic system. Energy storage and backup power are regulated to cause an optimal effective load condition.

Pl = Pa + Ps + Pb where Pl equals effective load power, Pa equals array power, Ps equals storage power, and Pb equals backup power. Ps becomes negative when the battery subsystem is being charged.

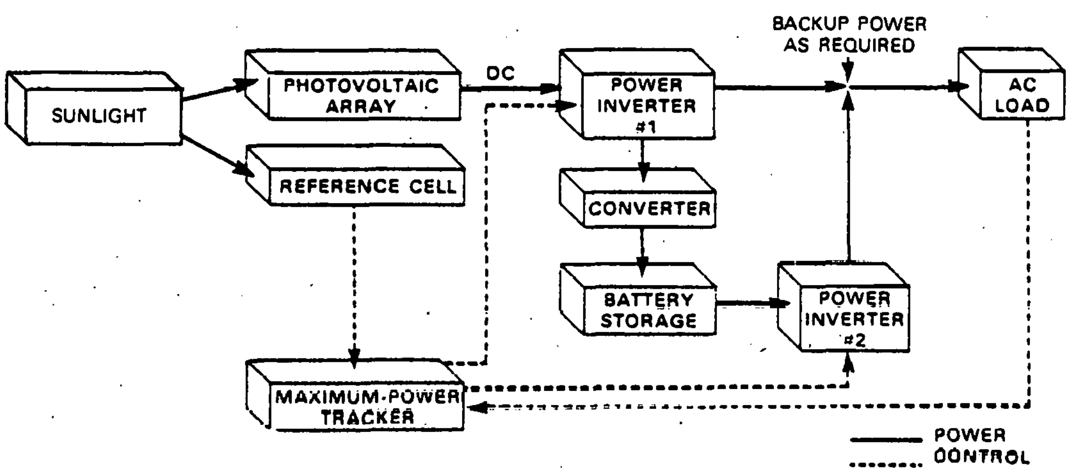


Exhibit 1.13 Maximum Power Tracking

SECTION 2
PHOTOVOLTAIC ARRAYS

2.1 BACKGROUND

Solar cells are the basic unit of a photovoltaic power system and convert sunlight directly into DC electricity. The incident photons are absorbed in the solar cells and produce a flow of electricity when an electrical load is connected to the solar cell. Solar cells are a form of solid state diode and can be made from various semiconductor materials. However, the preponderance of experience is with silicon. Photoconductivity of semiconductors is the fundamental principle of solar cell electricity, where conductivity is the reciprocal of resistivity. Resistance equals resistivity x length/cross-sectional area.

The use of silicon solar cells in outer space dates back to 1958 with the launch of Vanguard I. Hundreds of silicon-solar-cell-powered spacecraft have a few thousand years of cumulative operational experience in space. No space flight has ended because of solar cell failure. In addition to space applications, many remote terrestrial power applications, such as communication repeater stations, have been operated by private and governmental organizations for up to 10 years at power levels from 1 to several hundred watts. Historically, silicon solar cells have been in general use on Earth since 1955 when the Bell Telephone Laboratories successfully powered telephone amplifiers in field tests. RCA was involved also.

2.2 SOLAR CELL CHARACTERISTICS

Solar cells are fabricated from high purity single-crystal, silicon wafers which are doped with the necessary trace elements to form a semiconductor material. Doping increases the number of charge carriers. An n-p diode junction is formed by diffusing a second element, such as phosphorous or arsenic, into boron containing silicon wafers to form a 0.001 in. layer of doped material on the illuminated surface of the cell. The designation n-p refers to negative and positive charge carriers. The contact of the doped and undoped layers (the n-p junction) produces an electrical field within the silicon. When the solar cell is exposed to sunlight, the photons (light energy from the sun) are absorbed by the silicon and energize electrons within the crystal. The built-in electrical field separates the electrons from the parent material and gives rise to an electrical potential of approximately 0.5 volts. To access this voltage, electrical contacts are added to the front and rear surfaces of the cell as shown in Exhibit 2.1. The contact on the front (illuminated) surface is characteristically a finger-like grid pattern designed to maximize current gathering while minimizing shadowing of the surface. An anti-reflective coating is also sometimes added to the surface of the cell to minimize surface reflections and increase the energy absorbed.

Typical solar cells have efficiencies of 10 to 15 percent and, therefore, generate approximately 12.5 W per square foot (ft^2) of area under peak, midday solar illumination (maximum insolation equals 100 W per square foot of air). The cell voltage is a function of the cell materials only and is independent of cell size. The current from a cell is a function of the incident radiation and is directly proportional to the illuminated surface area. For space applications, power per unit area is very important, so cells are cut into squares or rectangles to achieve high packing factors. When crystals are "grown," the manufacturing process results in a silicon ingot, cylindrical in shape. For terrestrial applications where cost is most important, solar cells are generally circular so maximum use can be made of the silicon crystal's cylindrical shape.

Exhibit 2.2 shows how the I-V output of a typical cell varies with insolation. The current density is used for the current axis and is designated J. The open circuit voltage, as determined by the cell junction, varies only slightly with illumination level, but decreases at a rate of approximately 2 mV/°C with increasing temperature. The maximum power output from the cell occurs at the knee of "maximum power point" of the I-V curve. The maximum power is typically about 0.7 times the product of open-circuit voltage and short-circuit current. (The factor 0.7 is called the "fill factor.") The short-circuit current is nearly independent of temperature and is directly proportional to the solar illumination level (insolation). The basic relationships used are Ohm's law: V = IR, where R is resistance; J is the current density, J = I/A, where A is the area, and P = V x I, where P is the power. Also, voltage equals energy per unit charge and current equals charge per unit time. A solar cell is a current generator and its output is proportional to the exposed area and the sunlight intensity on the area. The current density (current per unit area) for a given insolation level is a good indicator of solar cell capability.

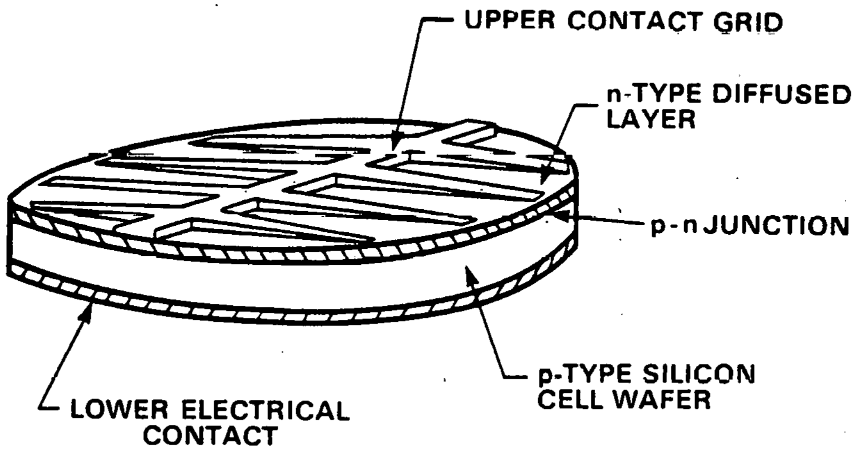


Exhibit 2.1 Typical Terrestrial Solar Cell Structure.

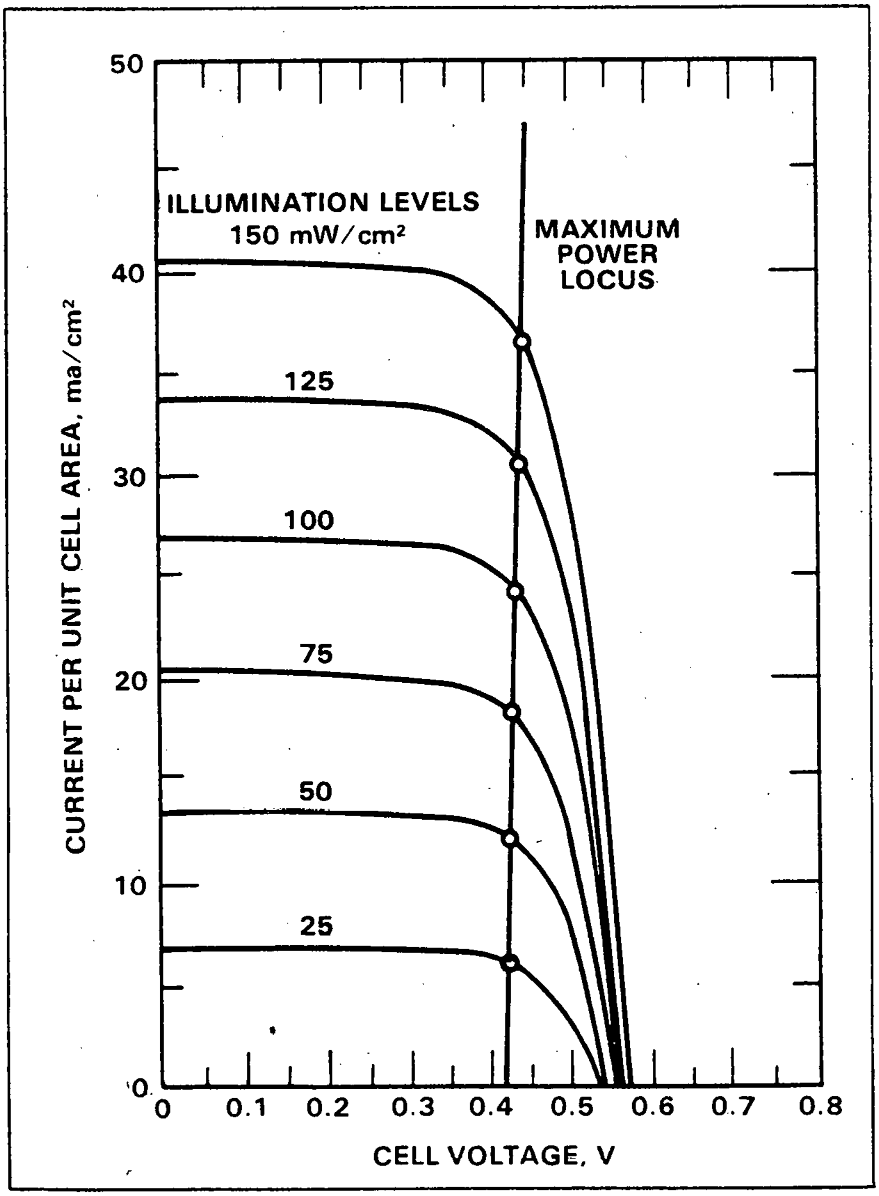


Exhibit 2.2 Current Density vs. Voltage for Different Levels of Cell Illumination

J = I/area, ImA = 0.001 Amp

2.3 ARRAY PERFORMANCE CHARACTERISTICS

To achieve higher voltage and power levels, individual solar cells are combined in series and parallel like storage battery cells. The smallest grouping of cells, a solar cell module, consists of a string of series-connected solar cells as well as the encapsulating material needed to support the cells and provide protection from the environment. Typical solar cell modules provide about 5 peak W/ft^2 of module area and weigh from 0.1 to 1.0 lb/W. To achieve larger power levels, modules are grouped into "solar panels" or "subarrays" with sizes close to 4 ft^2. Panel efficiencies range from 10 to 12 percent.

To achieve the needed voltage and power levels, solar arrays are constructed by combining solar panels. The term solar array is generally reserved for the complete array of cells, modules, and panels, independent of the size of the total installation. For an installation with a single module, the module would be referred to as the solar array. The same would be true if the array consisted of 1 solar panel or 1 subarray.

One of the primary advantages of solar cell power is the reliability and design flexibility resulting from the extreme modularity of solar arrays. The modularity allows designs to be easily scaled up and down without requiring requalification of the basic power generation unit. Units also can be added or subtracted to match changing power requirements. In the event of a module failure, the series/parallel redundancy of the system will allow the system to remain operable with only a minor loss of power. The extreme modularity combined with the nearly infinite shelf life of spare modules also greatly simplifies parts inventory and maintenance operations.

Electrical circuit principles state that voltages in series add and in parallel are equivalent to the value of the lowest voltage. Likewise, currents in parallel add, while in series are equivalent to the lowest current produced (refer to exhibit 2.3). Current sources in parallel are summed at a constant system voltage to determine the total system current, and voltage sources in series are summed at a constant system current to determine the total system voltage. Generally, current sources in series are equivalent and voltage sources in parallel are equivalent.

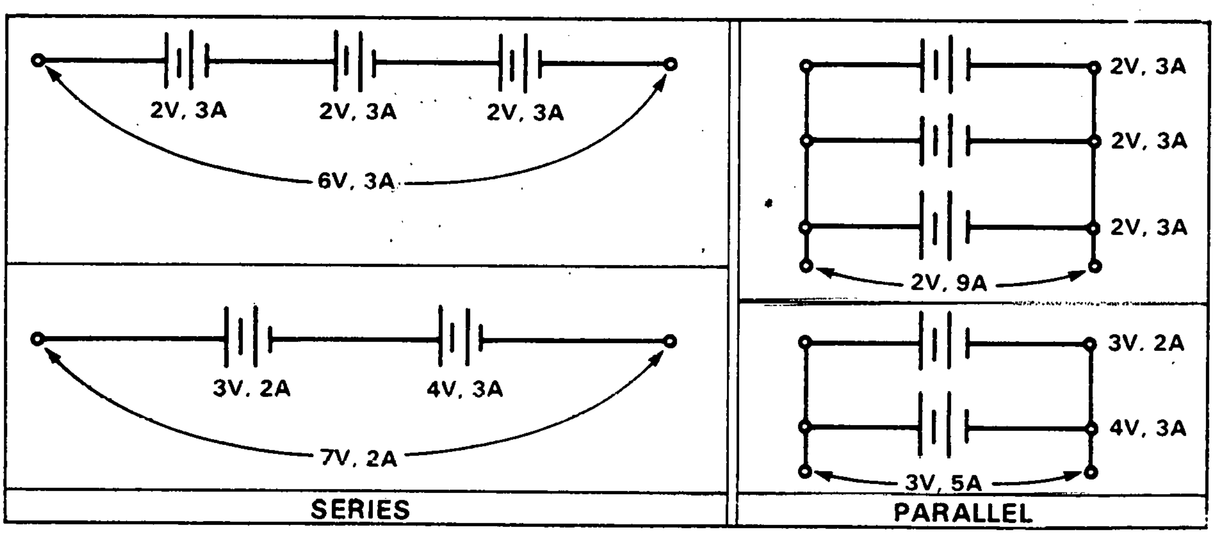


Exhibit 2.3 Basic Series—Parallel Relationships.

To compute the I-V characteristics of a solar array one must, therefore, sum the currents of all the cells (or modules) at each voltage (for a parallel connection of cells) minus the losses of the interconnects. Exhibit 2.4 shows such a computation. No interconnect losses are assumed. It should be noted that only for identical cells is the maximum power available from the array equal to the sum of the maximum power available from the three individual cells. For cells in series, the sum of all individual cell (or module) voltages minus the voltage drop across the interconnects must be computed at each current level to produce the array IV curve. It should be noted that these curves must be computed at a given insolation level and at a given temperature.

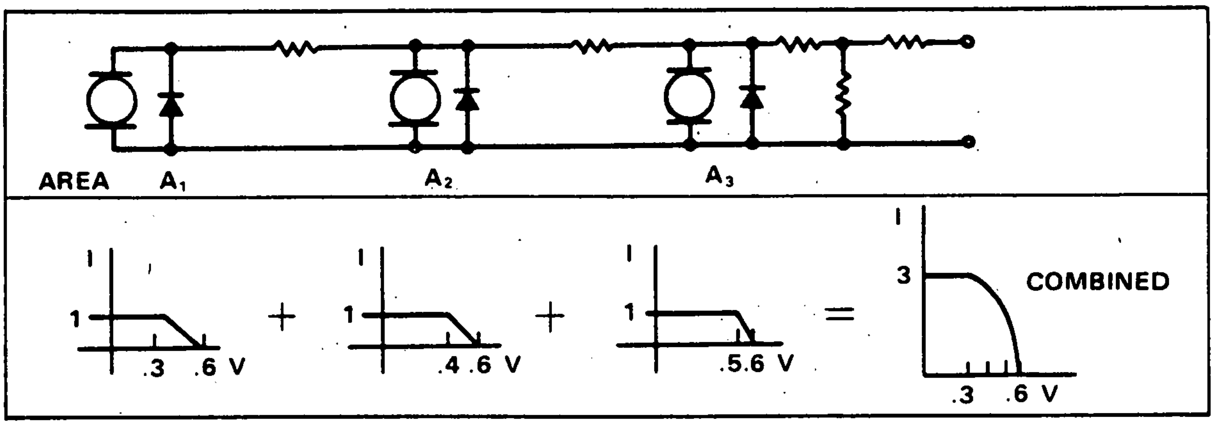


Exhibit 2.4 I-V Characteristics of Unmatched Cells in Parallel.

The effect due to shading (or damaging) a portion of an array depends on whether the cells in that array are in series or parallel. If the cells are connected in series (see exhibit 2.5), the output current of the array will be limited by the current of the single shaded cell, which causes a dramatic decrease in output power. The parallel combination, however, suffers a decrease in current equal to the current of a single cell (see exhibit 2-6). For example, there are two panels of ten cells each, one cell is connected in series, the other 9 in parallel. Each cell is operating at about 0.45 volts and 1 amp, therefore, the power output of each panel is 4.5 watts (10 x 0.45 x 1). If a single cell is completely shaded in both panels, the power output of the series panel connected array will drop to almost zero while the parallel connected panel array will output 4.05 watts (if each parallel string is protected by a diode from back biasing), by the computation 4.50 watts – 0.45 watts = 4.05 watts. Corrosion and cell breakage manifest themselves as increased series resistance, possibly approaching infinity (open circuit). A series network of solar cells would be rendered inoperable due to this type of failure compared to a partial decrease in power in a parallel network.

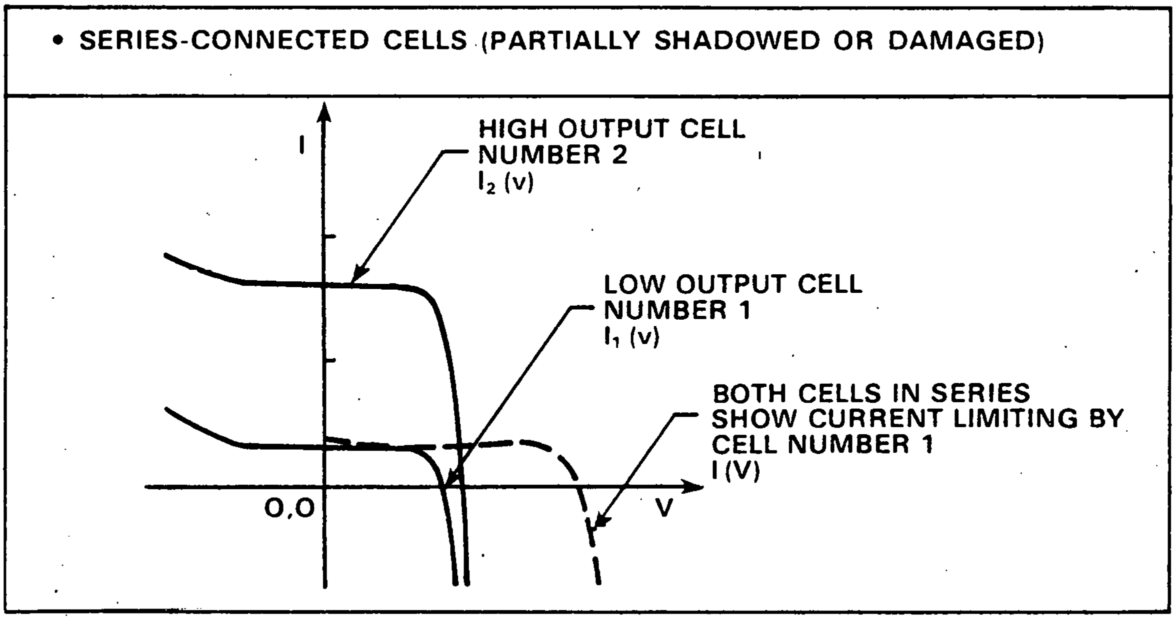


Exhibit 2.5 Shadowed Solar Cells.

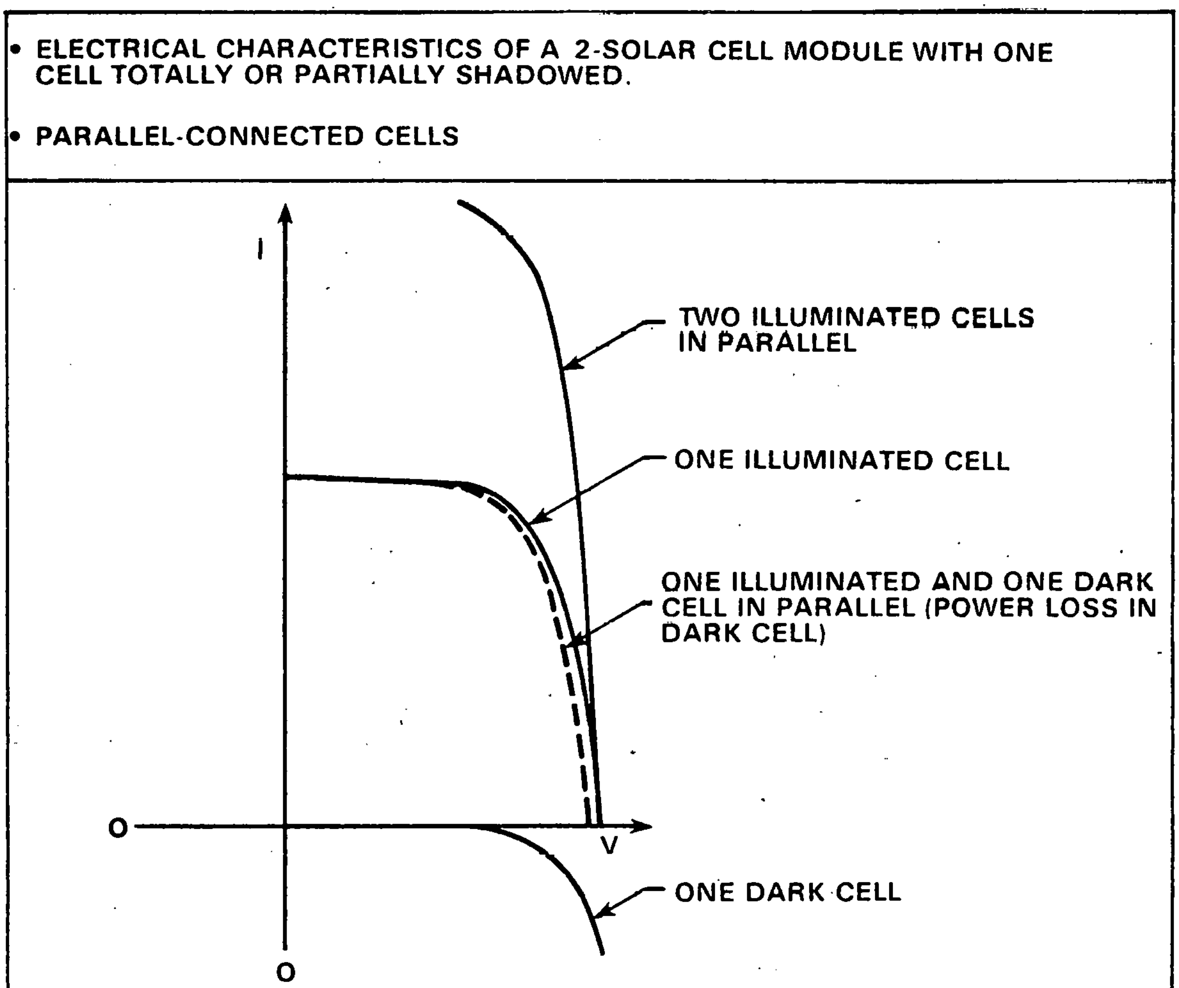


Exhibit 2.6 Shadowed Solar Cells.

Were it not for the cost of carrying high currents and of inverting DC voltages to AC voltage, designers would always arrange the cells in parallel. Cells are usually placed in series to meet a minimum adequate system voltage, and then multiple strings of cells are paralleled to attain the required system current. Keeping the system voltage low reduces the possibility of injury due to electrical shock. The alternative to large strings of series connected cells, when high system voltages are required, would be to utilize a DC-AC inverter to transform the voltage up to desired levels by use of electromagnetic induction from AC voltage in a transformer. The tradeoff would be the added inefficiency of the DC-AC inverter as compared to the higher reliability of the paralleled cells (assuming the probability of inverter failure is smaller than the probability of a failure of a cell in the series string). DC amplifiers can also be used. For an increase in voltage there is a corresponding decrease in current due to the law of the conservation of energy and since power equals voltage x current.

Environmental effects are usually mitigated by designing solar cell packages which "control" the near-term effect of the environment. Present-day construction encases the solar cells behind tempered, low-iron-content glass; backed up by high temperature silicone rubber compounds, and a back supporting member such as a fiberglass sheet (refer to Exhibit 2.7)

2.4 CELL DEGRADATION

Solar photovoltaic cells, particularly silicon cells, exhibit an extremely stable element that has been only slightly (1 in 10^8 atoms) doped to produce the desired photovoltaic effect. The contacts, which are placed on both sides of the solar cell to collect the produced current, will also exhibit a life time of greater than 20 years if protected from the environment. When this protection or isolation from the environment breaks down, degradation will take place, causing poorer system performance and ultimately a shorter life time for the system.

Solar cell degradation, therefore, is due primarily to the effects of temperature and humidity and to the corrosion effects of the surrounding environment. As shown in exhibit 2.7, local humidity and oxygen will tend to oxidize (corrode) the contacts and interconnects of the cell. This corrosion manifests itself in the form of increased series resistance to the flow of available current, resulting in power losses and finally, when advanced corrosion is present, to an open circuit. Many cell manufacturers now use redundant interconnects to help mitigate this problem.

The glass transmits the incident solar energy (low-iron-content glass absorbs less than 1% of the usable incoming radiation) to the cell while protecting the cell from major shocks (i.e., hail) and from the environment. The silicone rubber serves to cushion the cell from any minor shock, as well as providing a transfer medium for heat dissipation. The thermo/mechanical characteristics of this material are usually matched as closely as possible to that of the cell to minimize stress caused by thermal cycling. The backing material supports the package for structural strength and rigidity, and provides moisture-permeation protection (with the addition of Tedlar® or a similar material) from the environment.

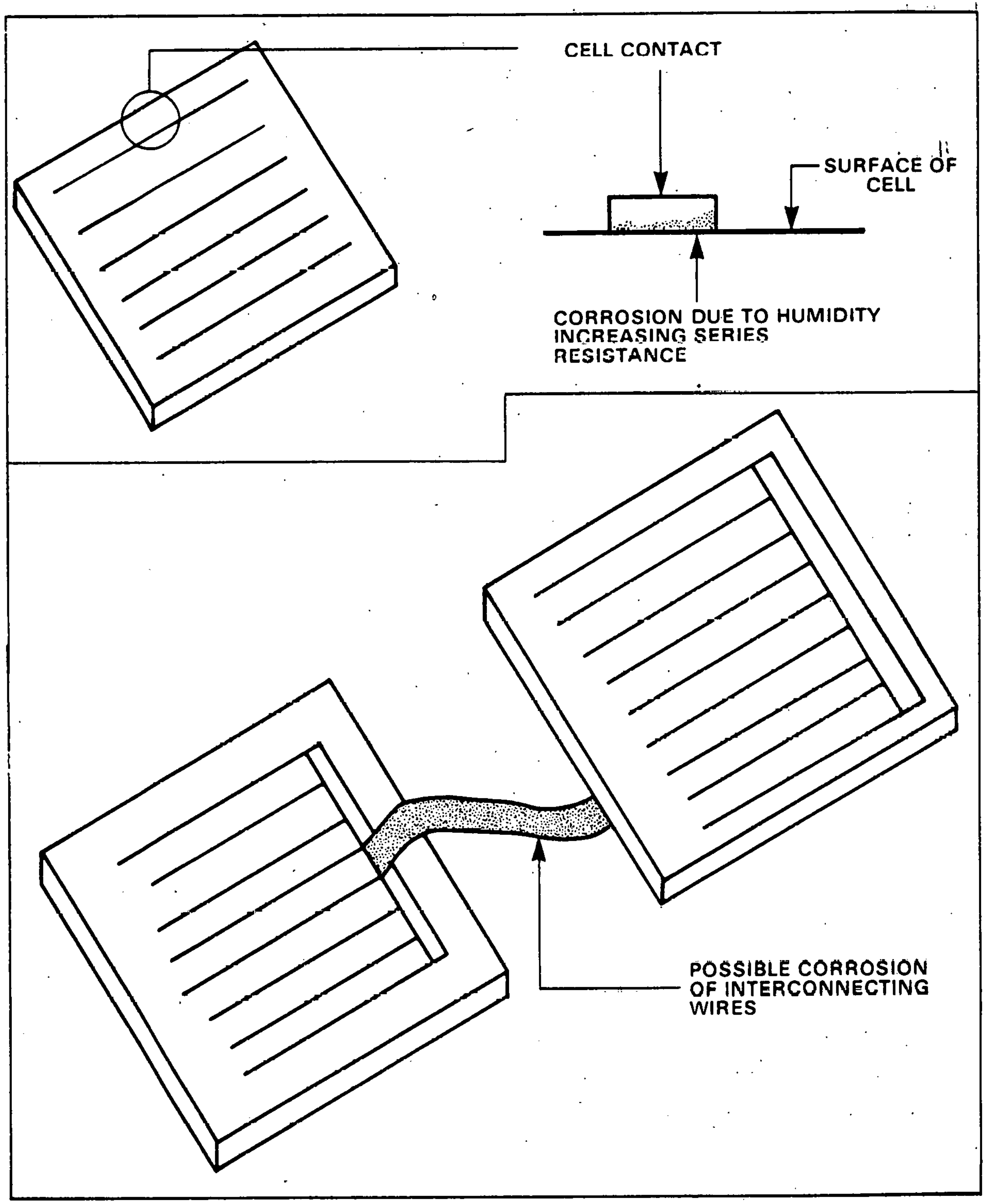


Exhibit 2.7 Corrosion Effects on Solar Cells.

The front encasing material employed also has an effect on the output-power degradation over the system's life. Field data collected on the effects of soiling on array performance show that one can expect at least 2-8% ouput-power degradation due to soiling if glass is used as an encapsulant, at least 6-20% if a semi-flexible silicone conformal coating is used, and a minimum of 8-20% if room temperature vulcanizing (TRV) rubber is used. The silicon-based compounds will also suffer transmission degradation due to the effects of ultraviolet light. Transmission losses due to these effects can grow to 10%, over several years, before stabilizing.

Temperature effects exhibited by the environment contribute to the cells' degradation in two major ways. First, thermal cycling causes expansion and contraction of the cell at rates different than the host material that the cell may be encased in. The resulting physical stress may cause hair-line cracks to develop which can result in total loss of cell output. The second aspect of temperature degradation centers around the fact that power output from the cell will decrease approximately 0.4% per ^{o}C of increasing temperature.

Modes of failure and degradation are summarized in Exhibit 2.8A and Exhibit 2.8B (compiled by JPL).

2.5 OPERATIONAL CONSIDERATIONS

The solar array as a power source must be compatible with the load. Such factors as grounding, safety and maintenance, electro-magnetic interference, and lightning protection must be considered during the system design, as well as power processing for primary and parasitic loads and power conditioning.

Center-tap grouping of the solar array electrical current via a resistor is recommended. A short in the array can then be detected via a sensing circuit of two resistors and an ammeter (see exhibit 2.9). If a short occurs anywhere on the array, current will flow through the ammeter causing a deflection of the meter's indicator needle. The current flow through the meter can also be utilized to energize switches and remove the defective array from the system.

KEY	ENVIRONMENT	Probable Importance	Investigative Status	Effect/Problem Observed in Field	REMARKS
	ELECTROMAGNETIC				
S	Solar and γ Rays	□	⊗		Few at earth's surface
	Ultraviolet (UV)	■	◑	△	
	Visible	◨	◑		
	Thermal infrared	◨	◑		
T	Terrestrial thermal infrared	□	◑		
	ATMOSPHERIC AIR TEMPERATURE	■	◑	△	Inc. diurnal and seasonal variations
	ATMOSPHERIC WATER VAPOR				
	Cloud cover	◨	◑		
HU	**HUMIDITY**, inc. Fog and condensation on surface	■	T,◑	△	
P	Precipitation				
	Drizzle	◨	◑		
	Rain	◨	T,◑		
	Sleet	◨	◑		
Ha	Hail	■	T,●		
Si	Snow	◨	◑		
	Ice (rime)	◨	◑		
ATM	Atmospheric Pressure	□	○		
	THUNDERSTORM				
	Thunder	□	○		
L	Lightning	■	◑		
W	**WIND**	■	T,◑	△	Inc. Wind gusting
E	**WIND BLOWN SAND AND DUST**	■	◑		
	Airborne contaminants				Strongly location dependent
Cp	Particulate (inc. dust)	■	◑	▲	
Cv	Volatile condensible material	◨	○		
CC	Corrosive/oxidative (ozone) agents	□	T,◑		
C_f	Microbiological (inc. fungus)	□	○		
C_s	Salt Fog/spray	■	T,◑		
	Flora (inc. seeds, pollen leaves)	◨	○		
•	Fauna (inc. droppings)	◨	○		
Sh	Solar occlusion (shadowing by tall buildings/trees)	◨	○		
F	Flames (flammability)	■			

LEGEND:

■◨□ Probable degradation: significant effect, some effect, minimal effect

●◑○⊗ Investigative status: completed, in progress, needed, not needed.

△▲ Field effect observed: possible, confirmed.

T Test requirement exists

AR Hoffman, June, 1978

Exhibit 2.8A Degradation and Failure Mechanisms from Environment.

KEY	ENVIRONMENT	Probable Importance	Investigative Status	Effect/Problem Observed in Field	REMARKS
	INDUCED ON MODULE				
	Handling (inc. shock and vibration)	■	○		
Vs	Shipping (inc. shock and vibration)	■	◑		
	Storage	□	○		
In	Installation	◨	T. ◑		Warped mounting surface test
Cl	Cleaning				
	Chemical	◨	◑		
	Physical	◨	◑		
	Acoustic Noise	□	○		Primarily truck traffic and jet airplanes
	EMC conducted/radiated susceptibility	□	○		
Et	Load electrical transients	■	○		
V	Applied voltage	■	○		
I	Current				
	INDUCED BY MODULE/ARRAY				
	Variable power output (daily, seasonal)	□	○		
	EMC conducted/radiated emissions overvoltage applications	■	○		
	Array transients	■	○		
	NATURAL DISASTER				
	Earthquake	□	○		
	Flood	□	○		
	Fire	□	○		
	Hurricane	□	○		
	Tornado	□	○		
	MANMADE DISASTER				
	Vehicular Accident				
Ho	Hostile activities				
	Individuals	■	○		
	Organized groups	◨	○		
	Warfare	□	○		
	Ignitable Fluid Release (i.e., explosive atmosphere)	□	○		

LEGEND:
- ■◨□ Probable degradation: significant effect, some effect, minimal effect
- ●◑○⊗ Investigative status: completed, in progress, needed, not needed.
- △▲ Field effect ovserved: possible, confirmed.
- T Test requirement exists

Exhibit 2.8B Degradation and Failure Mechanisms from Handling and/Operations.

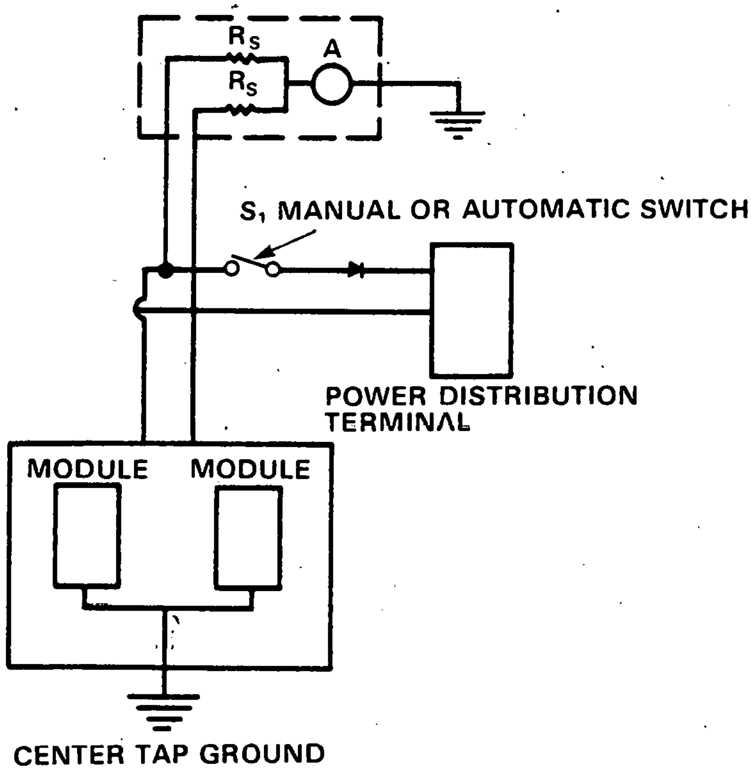


Exhibit 2.9 Terrestrial Solar Array Grounding and Safety Protection.

Because the array is an active power source when illuminated, care must be taken during servicing and maintenance. In the interest of safety, the array voltage should be no higher than 50-60 volts (as recommended by the National Electrical Code). If a higher voltage is required, switches should be installed between the cell modules at 50-60 volt intervals. These switches can then be disengaged, during maintenance, to limit the voltage anywhere on the array.

The electrical circuitry of the PV array, when acting as a power source, will radiate an electromagnetic (E-M) field. This internally generated interference can be limited by arranging the array wiring to cancel the generated E-M field. Electronic switching voltage regulators or inverters, if included in the PV systems, can cause a voltage ripple to be fed back into the array circuitry. The E-M interference generated, and any problems that it might create, should be estimated. Electric fields are primarily of three types: Capacitance Effect, Faraday Effect, and the Hall Effect. The resultant electric field is the summation of components present. The magnetic field of conductors carrying current is estimated by Ampere's Law.

Photovoltaic arrays are exposed to the environment and are, therefore, vulnerable to lightning strikes. The benefits of providing lightning protection in the form of lightning rods and arresters will depend on the location of the system and should be investigated.

2.6 LOADING CONSIDERATIONS

The photovoltaic array in reality is neither a constant current nor a constant voltage source; therefore, specific analyses must be conducted to optimize its use as a power source. The combination of cells in series and parallel arrangements results in a specific maximum power output (voltage and current) under design operating conditions (i.e., insolation, temperature, loads, etc.). Unlike a battery, which will provide extremely large amounts of current at a relatively constant voltage (as required by the load), a photovoltaic array cannot provide more power than induced by the insolation. The result of overloading an array is essentially to cause a demand current greater than that of the maximum power point (refer to exhibit 2.10) and thereby to reduce the power output from the array. For this reason, photovoltaic systems not incorporating battery storage cannot be used effectively to

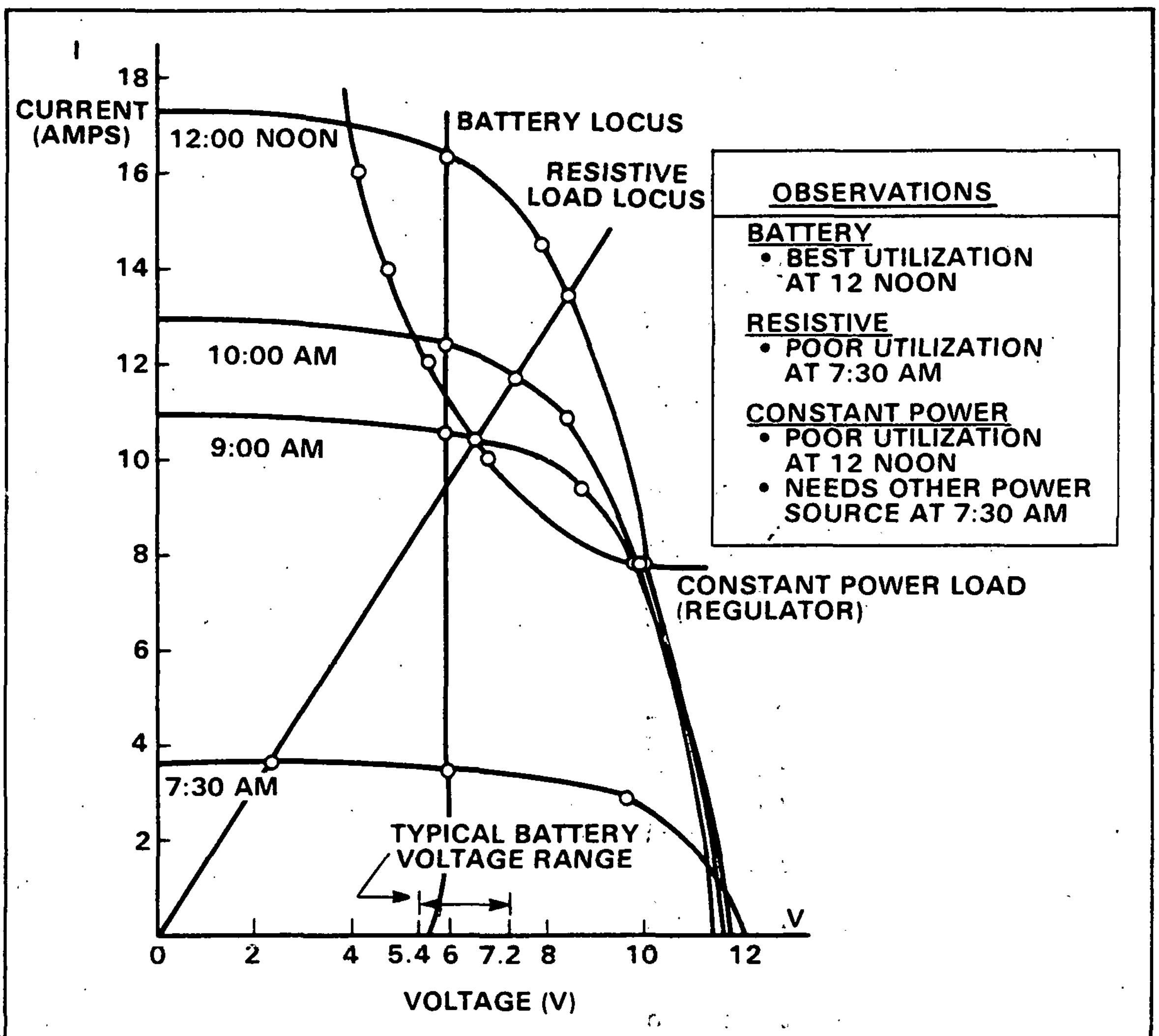


Exhibit 2.10 Power Utilization Considerations-One-Day Operation in Terrestrial Operations.

supply power for short high peak demands. Adding loads in parallel decreases system resistance and increases system current even though individual load current may not decrease. If enough loads are added in parallel, then individual load current may decrease and resistive losses throughout the system will increase. The net effect is voltage and power loss due to high current resistance loss, where power loss = $I^2 \times R$ and voltage loss = I x R. I is current, and R is resistance. The power of the load equals V^2/R load where V is the system voltage. A decrease in system voltage magnifies the power decrease by the square of voltage.

2.7 CELL TYPE TRADE-OFFS

Photovoltaic cells, like transistors and diodes, can be fabricated from various materials which exhibit the proper electrical characteristics under controlled doping. Currently, the semi-conductor industry relies on silicon and germanium as host materials in transistors, diodes, and integrated circuits. The PV industry presently utilizes silicon as the primary host material. Two manufacturers are producing cells made from cadmium sulfide. Due to the thinfilm nature of cadmium sulfide cells, much less material is needed for their construction than is needed for a typical silicon cell. This inherent advantage promises lower costs per watt, once efficiency and manufacturing problems are overcome.

Every manufacturer of solar cells has what he believes to be a "proprietary" technique or encasement design which make his cells and arrays superior. For example, some manufacturers now market solar arrays which feature stainless steel or thick glass frames, instead of aluminum frames, to reduce corrosion effects in marine environments. The technique used to apply the current collector grids on the solar cells varies from manufacturer to manufacturer. Some silk-screen the grids on, while others use vapor deposition techniques which they feel will aid in reducing both series resistance and delamination effects. Before selecting an array for a given application, trade-offs, in both quality and cost, must be evaluated.

2.8 ARRAY TRADE-OFFS

Presently available on the market as off-the-shelf products are solar photovoltaic modules of various physical sizes, producing various outputs, made of various materials (casings). Trade-offs associated with the selection of an array (sub-array, panel, module, and cell) lie with the specific application of the system and the resulting environment in which the system is to operate, including the availability of back-up systems or the possibility of an electrical grid-connected application. The distance from a distribution or transmission line could be a factor.

For example, a photovoltaic array which is to provide power to a small direct-current refrigerator on top of a mountain requires that the array be lightweight, small in physical size, and transportable. Under these conditions (assuming there is enough insolation for the application), an array may be chosen which folds on a central axis, uses a silicon rubber compound to reduce weight, and which contains "high density" cells, which are higher efficiency photovoltaic cells designed to cover more of the available area of the encasement (refer to exhibit 2.11).

The array shown in exhibit 2.11 was optimized for a specific application at a specific location. The same array shown could not provide 20-year lifetime and power if placed on an ocean bouy. In the marine environment, consideration must be given to salt-water corrosion, wind, and currents which prohibit physical stabilization and corrosive effects of bird droppings. A more suitable array might be as shown in Exhibit 2.12.

In contrast to the array shown in exhibit 2.11, the array shown in exhibit 2.12 is designed to be rugged, highly efficient under all conditions of motion, and resistant to a marine environment. The module would more than likely be covered with tempered glass and sealed at the edges of the panel, and the casing would be steel instead of lighter weight aluminum. The cells can be either round or high-density hex-sided, depending on the available area on the buoy and the power requirements. Costs also play a role as the high density modules are more expansive than the standard round cell designs.

In conclusion, selection of any one solar array is mainly dependent on the power requirements, operational environment, and cost associated with the system.

2.9 ENVIRONMENTAL EFFECTS

As discussed earlier, the environment in which the photovoltaic system is to operate plays a major role in the overall performance, lifetime, and initial cost of the system.

The combination of site remoteness and the environment must be examined, if the system is to last for many years, since remote sites will suffer from infrequent maintenance.

Environmental effects, such as temperature cycling, freezing, high humidity, fog, snow, wind, etc., result in specific system performance (or lack of performance) and, therefore, should be included in the calculation and resulting selection of a specific system. A chart summarizing the operating characteristics and capabilities of available PV modules is contained in Section 9.

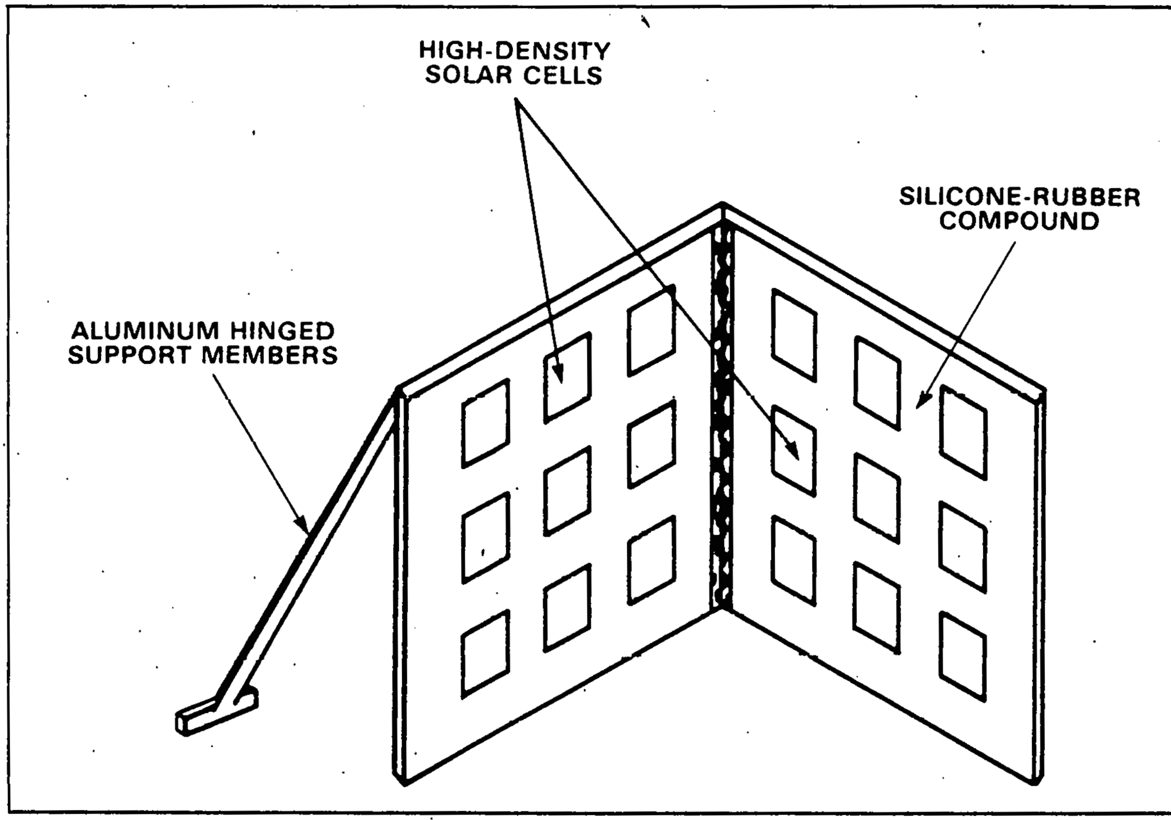


Exhibit 2.11 A Simple Array Design Incorporating Lightweight Design, Portability, and High Density Solar Cells.

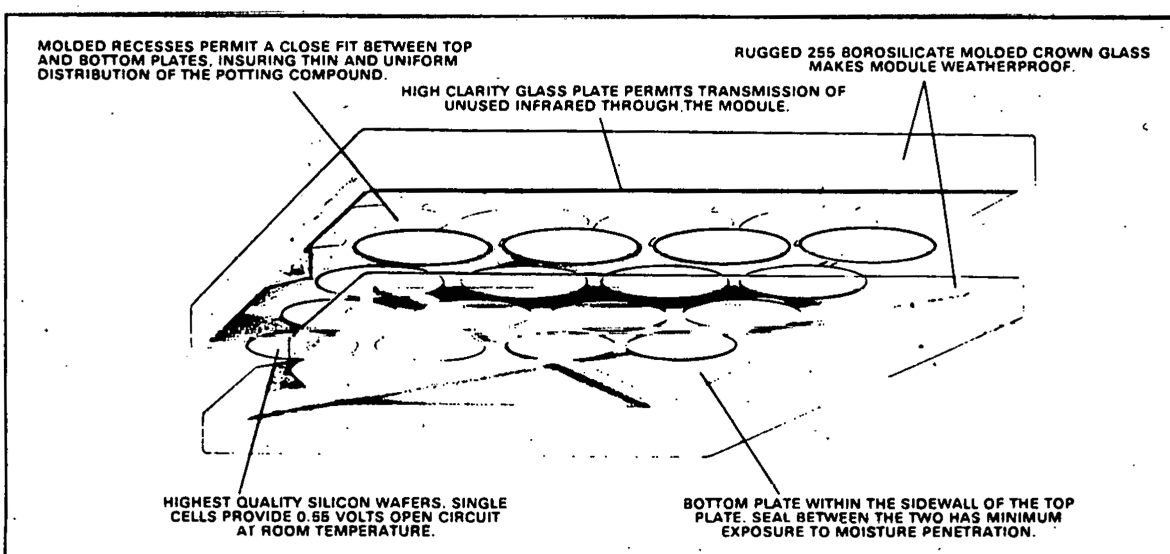


Exhibit 2.12 PV Array Used to Power Buoy Lights.

SECTION 3
STRUCTURAL ANALYSIS

3.1 INTRODUCTION

What has been dealt with up until now is the PV electrical system and its design. The PV system's structure represents approximately 3 percent of the total cost of present systems. In future systems, when the cell costs drop to 50 cents/peak W, the structure will represent approximately 20 percent of the total system cost. In both cases, the structure must be provided and will influence the usefulness of the application. In this section, an introduction is provided to the various building codes applicable to commercial structures. One code will be discussed in detail, so the reader will be able to calculate, at least for preliminary evaluation, the size and complexity of the supporting framework. The structural analysis involves the civil engineering of the solar power system; and thus is comprehensive, rigorous, extensive, and involves environmental engineering, engineering law, engineering administration, and civil works codes.

3.2 STRUCTURAL LOADS

Structural loads are tabulated in exhibit 3.1. They consist of dead loads:--the weight of the panel, and the structure--as well as various live loads: maintenance crews, wind, snow, hail, ice, settlement, seismic loads, and deflection-induced loads. Typical values of the various loads are also shown. Wind and snow are both of the same order of magnitude and, for solar cells, represent a much greater load than the weight of the panel. The other loads are usually less significant; many are not even considered in some of the commonly used building codes.

3.3 BUILDING CODES

Exhibit 3.2 shows the common building codes applicable to solar cell systems. The Building Officials and Code Administrator International, Inc. (BOCA), the Uniform Building Code (UBC), and Standard Building Codes are applied extensively in building design. They are called model codes because they include all the elements important to a code, but do not include some of the local idiosyncracies. Each locality has its own building code and many simply adopt one of the model codes. BOCA has been adopted by many of the Atlantic communities and the UBC is common in the West. The Standard Building Code is so common in the South that it is frequently called the "southern building code." The American National Standards Institute (ANSI) also has a building code (ANSI A58.1), similar to the previous three, but it treats the wind loads more extensively than the others.

Dead Load	5 lb/ft²
Live Loads	Approximate Pressure
Maintenance	12 lb/ft²
Snow	20 lb/ft²
Wind	25 lb/ft²
Seismic	0.3* Wt
Hail	Glass limit
Ice	Wire limit
Settlement	2"/50'
Deflection	1% of span

Exhibit 3.1 Structural Loads (Pressure is given as pounds per square foot)

Building Officials and Code Administrator International, Inc.: **BOCA Code**—Adopted mostly in Eastern U.S. and by the International Conference of Building Officials
Uniform Building Code: **UBC**—Adopted mostly in Western U. S.
Southern Building Code Congress Standard Building Code: **SBC**—Adopted mostly in Southern U. S.
American National Standards Institute **ANSI**—ANSI A58.1
National Bureau of Standards **NBS**—NBS IR 76-1187: Interim Performance Criteria for Solar Heating and Cooling Systems in Commercial Buildings
HUD Minimum Property Standards (Department of Housing and Urban Development) 4900.1: One and Two family dwellings 4910.1: Multifamily dwellings 4920.1: Care-type housing 4930.1: Solar Heating and Domestic Hot Water

Exhibit 3.2 Building Codes.

The National Bureau of Standards (NBS), at the request of ERDA (now DOE), examined the various codes as they might be applied to solar power systems. The result was NBSIR 76-1187. This code is not widely accepted. Seismic, hail, ice, settlement and deflection specifications, ignored in many of the other codes, are included in the NBS code. At ERDA's request, the Housing and Urban Development (HUD) Minimum Property Standards were modified for solar energy systems. The NBS standard, the most complete code, frequently references the HUD and UBC codes and must be used in conjunction with these codes.

A comparison of the structural requirements as defined by the various codes for one particular location (Albany, New York) is presented in exhibits 3.3 and 3.4. The first section defines the minimum roof load for roofs at various angles. The code assumes the structures will be occupied. Some code administrators consider these minima to pertain to snow only. Others presume they apply to all categories of loads and are, therefore, applicable to the slant area, not the horizontally projected area.

The snow loads should be applied to the horizontally projected area, as specified in the Southern code. Factors should then be applied to allow for the fact that the snow will not accumulate on a steeply slanted surface. Allowance must also be made for drifting. When dealing with unoccupied structures, the UBC avoids these complexities by calling only for the use of the minimum roof load. The variation in the snow load requirement is substantial among the codes.

The wind load is also not computed in the same manner for all codes. The Southern and ANSI codes call for an allowance for suction on the leeward side, and allow some load reduction for tilted surfaces. The other codes treat the array the same as vertical signs. The codes are ambiguous as to the surface to which the load must be applied, not specifying whether it should be the vertical projection or the slant area, which are possibilities. If the horizontal thrust—the major effect of the wind—is being computed, there is no difference. However, the codes do not include the evaluation of the vertical force. To be safe, the wind load should be on the panel (slant) area.

Design Load for 12' Solar Panels In Albany, N.Y.

Slope = 57.5°
Spacing = 30'

ITEM \ CODE	Southern	UBC	BOCA	ANSI	NBS	HUD
Minimum Roof Load (due to people, snow, etc.)						
18°	20lb/ft²	20 lb/ft²	20 lb/ft²	20 lb/ft²		
45°	16 lb/ft²	16 lb/ft²	16 lb/ft²	16 lb/ft²		
45°	12 lb/ft²	12 lb/ft²	12 lb/ft²	12 lb/ft²		
Snow Load	•					Use ANSI
Basis	Horizontal Proj.	—	—			
Horizontal	30 lb/ft²	—	25 lb/ft²	25 lb/ft²		
Sloped (a–30°)/50°						
or Static	× 0.55	—	× 0.55	× 0.55		
or Drifting	× 2	—	× 2	× 2		
Avg. Depth	× 0.68	—	× 0.68	× 0.68		
Design Load	34.0 lb/ft²	12 lb/ft²	34.0 lb/ft²	34.0 lb/ft²		
Wind Load Basis	No Shielding		Can be Shielded	25 yr No Shielding	•	Use ANSI
Front Load Speed	85 MPH			70 MPH		
Pressure	14 lb/ft²	20 lb/ft²	15 lb/ft²	19 lb/ft²		
Tilt/Suction	× 1.25	—	—	× 2		
Design Load	17.5 lb/ft²	20 lb/ft²	15 lb/ft²	38 lb/ft²		
Rear Load Pressure	—	20	—	19		
Tilt/Suction	—	× 1.25	—	× 2		
Design Load	—	25 lb/ft²	—	38 lb/ft²		
Seismic Lateral Load, V = ZIC_PSWt	Use ANSI	C_P* Z* Wt $Z \leq 1$ $IC_P S \leq 1$	Not Severe	C_P* Z* Wt $Z \leq 1$	• in Doubt, use $C_P = 1.0$	Use UBC with $C_P \times 0.30$
Hail					Map, Table	Same as NBS
Ice On Wires					Map, Table	
Deflection						
Thermal					—	
Moisture					—	
Settlement					2" in 50'	
Ground Uplift					0.9 × Wt.	
Under Load**					$\delta < \frac{1.25}{180}(1.5 + 0.2D/L)$	

* Calls for use of HUD, model code, or local code

**S = Span, D= Dead Load, L = Live Load, δ = Deflection in Incline

Pressure is given in pounds per square foot.

Wind speed is given in miles per hour.

Exhibit 3.3 Comparison of Codes.

3.4 USE OF THE BOCA CODE

The purpose of this section on structural analysis is to provide at least one method for estimating the loads on the structural members and structural system required to support the solar-cell array. It is not a complete course in the application of the codes. In fact, such a course would include local variations in the code and, therefore, would be far more extensive than the few codes listed in exhibit 3.2. The BOCA code is considered because it is the most easily applied. However, some of the variations used by other codes will be indicated.

3.4.1 WIND LOADS

Signs must be designed to withstand wind loads; occupied buildings are not. For signs that are ground mounted, top within 50 feet of the ground, the wind exerts a 15 pound per square foot (lb/ft^2) force on the sign under maximum conditions. If the sign top is more than 50 feet high from the ground, the load is 20 lb/ft^2. If the sign is roof mounted, the load is 30 lb/ft^2. Wind loading from front and back is to be treated the same. Most signs are vertical, so the code does not include tilt effects. Therefore, it seems necessary to design for the loads just mentioned as applied to the slant (array) area and not its projection for vertical mounting.

An example using projections is given in exhibit 3.4. A 60-foot wide, 100-foot long collector is mounted at a 30° tilt to the horizontal, so its highest point is 30 feet from the ground. Since this is less than 50 feet, the design wind load is 15 lb/ft^2. The lateral force is 15 lb/ft^2 multiplied by the array area of (60 x 100) ft^2 and multiplied by the vertical component projection factor (sine of 30°): the horizontal force is 45,000 lb. The vertical force is computed similarly, except the vertical force is computed as multiplied by the cosine of 30°, so the vertical load is 77,940 pounds, using the horizontal projection factor. Pressure equals weight per unit area and force equals pressure x area.

While other codes make a distinction as to the region of the country in which the sign, or collector, is mounted, the BOCA code does not. Exhibit 3.5 shows the wind loads on buildings as specified in the ANSI code. The loads are for vertical surfaces placed 30 feet above ground level. The regional variation is seen to be significant. For heights other than 30 feet, the table in exhibit 3.6 is used.

The effects of tilt (as defined in the Southern Code) further alter the wind loads (see exhibit 3.7). If the southern code were applied in Albany, New York, the force on a vertical sign would be 15 lb/ft^2, in agreement with BOCA, except this load would be multiplied by 1.5 to account for suction on the leeward side. In Norfolk, Virginia, the load would be 24 lb/ft^2, multiplied by 1.5 to account for suction on the rear surface, for a total of 36 lb/ft^2.

None of the codes allows for the effect of rows of collectors. Some data were obtained on saw-tooth roofs and are presented at the bottom of exhibit 3.7. For the 45° isosceles roof, the force on the first slope is only 0.3 times the map values, and only a suction is felt on the other slopes (negative factors). On more tilted surfaces, a higher force is felt on the first slope, but higher suction is felt on the others. No code allows for this type of wind loading. An isosceles triangle has two equal angles.

Wind Loads—As required for signs	
Front	Ground Mounted: Under 50' High: 15 lb/ft² Over 50' High: 20 lb/ft² Roof Mounted: 30 lb/ft²
Rear	Not included separately—Use same as "Front"

Example:

An array 60' wide and 100' long is tilted at 30° and is ground mounted:

SIN 30° = 0.500	H = 60' sin 30° = 30' (<50')	D = 60' COS 30° = 51.96'
COS 30° = 0.866 p = Pressure H = Height to ground L = Length S = Width	F_o = pHL = 15 × 30 × 100 F_o = 45,000 lb	F_d = pDL = 15 × 51.96 × 100 F_d = 77,940 lb

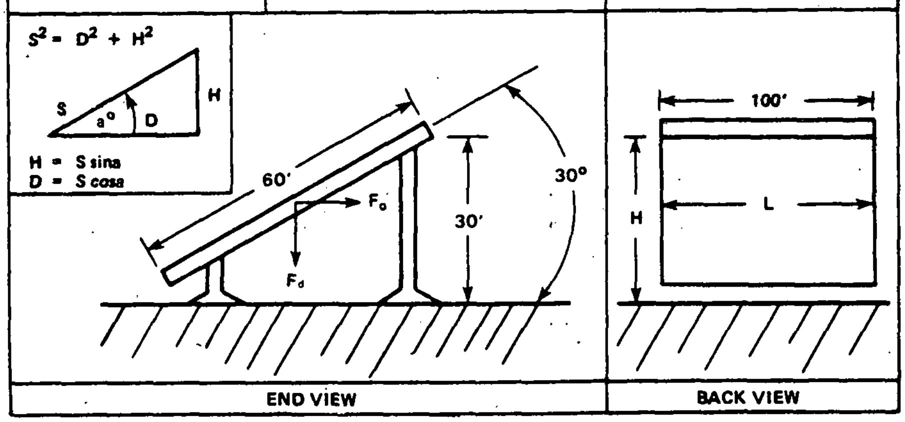
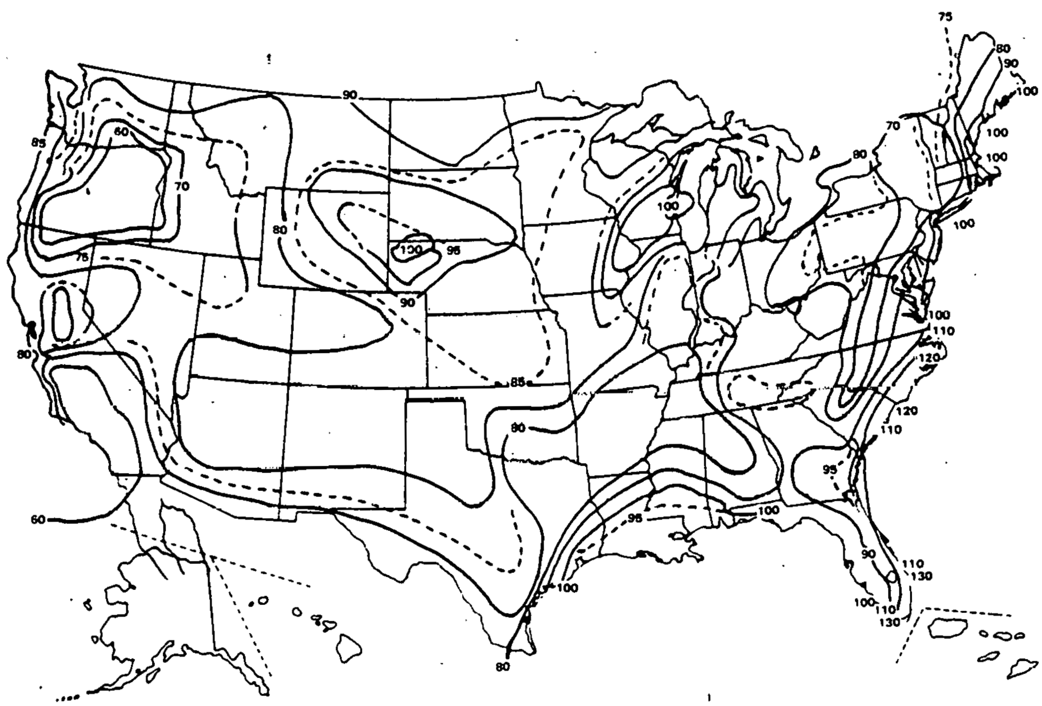


Exhibit 3.4 BOCA - A Typical Model Code (Pressure: pounds per square foot)

Only the UBC and ANSI codes distinguish between winds from the front and winds from the rear. The wind loads, as specified by various codes, are seen to vary by a factor of greater than 2:1. HUD calls for use of ANSI, the largest load; NBS calls for the use of HUD.

The seismic loads are all in agreement with the ANSI code, although BOCA states that seismic loads are not as severe as wind or snow loads and need not be considered under normal circumstances. Hail, ice, and deflection-induced loads are included only in the NBS and HUD codes. The ice loads pertain only to the icing of wires. The deflection limit is not a stress limit, but an aesthetic limit.



Note: Wind force at 100 mph is 25 lb/ft²

Exhibit 3.5 Wind Loads—Some Complications Due to Region.

Fastest mile wind velocity at 30 ft above ground,
50-yr mean recurrence

HEIGHT	PRESSURE FORCE/MAP PRESSURE
30′	1.0
50′	1.3
100′	1.8
150′	2.1

Exhibit 3.6 Wind Loads—Some Complications Due to Height.

3.4.2 SNOW LOADS

The BOCA requirements for snow loads are shown in exhibit 3.8. The loads are taken on the horizontal projection of the surface with an additional correction for tilted surfaces, because not as much snow sticks to these as to horizontal surfaces. (Rime ice, a frozen mist, can form on surfaces in some parts of the country, especially in mountainous areas. Rime ice will stick to vertical surfaces in thicknesses up to several feet. If rime ice is important at the location of interest, special design procedures must be used, in conformance with local codes). The correction for tilt is shown in exhibit 3.9. The factor of 0.8 is applied even for a horizontal surface, which is the basis for the map.

The code makes additional allowances for drifting near vertical surfaces. There is no mention made of drifting near titled surfaces. The authors' suggestion is to use the vertical projection of the solar collector and the drift angle of 27° as deduced from the tables in the code. Exhibit 3.10 shows the geometry of the drift. The map is based on 10 lb/ft^3 for the density of the snow, so this density can be used to estimate the force on the collector due to drifting. The average depth of the snow on the collector is given by the equation on the figure. The load, in lb/ft^2, is the product of the average depth in feet and the snow density. Despite the snow loads just computed, the design load should not be less than the minimum loads as shown in exhibit 3.11, where pressure equals weight per unit area and density equals weight per unit volume. Density x depth equals pressure.

3.4.3 SEISMIC LOADS

According to the BOCA code, the seismic loads are not as severe as wind and snow on signs, so seismic loads need not be considered (see exhibit 3.12). ANSI calls for lateral loads due to seismic effects that are equal to the dead load multiplied by two factors, Z and C_p. The value of Z depends on the region of the United States (0.25 for the middle Atlantic states and 1.0 for the most severe conditions in California). The same map of Z is given in the UBC and Southern codes. A reasonable value for C_p is 0.3 (see exhibit 3.13).

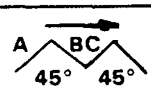
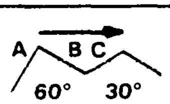
TILT	NORMAL PRESSURE (SOUTHERN CODE)		NORMAL PRESSURE PER TYPICAL DATA
	FRONT	REAR	TOTAL
70 - 90°	0.80	+ 0.70	
60 - 70°	0.65	+ 0.70	
50 - 60°	0.55	+ 0.70	
40 - 50°	0.25	+ 0.70	
30 - 40°	- 0.25	+ 0.70	
20 - 30°	- 0.75	+ 0.70	1.3
10 - 20°	- 0.93	+ 0.70	1.2
	a: b: c:		0.3 - 0.6 - 0.6
	a: b: c:		0.6 - 0.7 - 0.7

Exhibit 3.7 Wind Loads—Some Complications Due to Tilt.

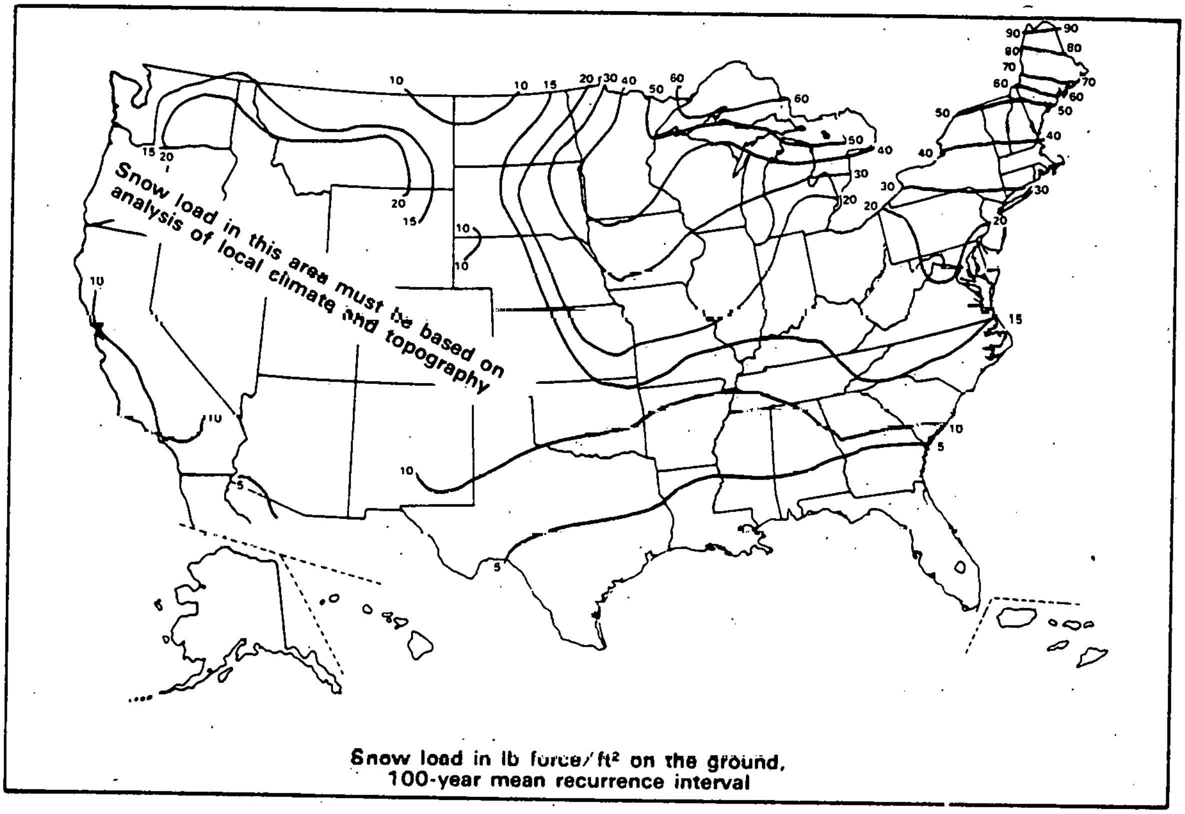


Exhibit 3.8 BOCA—Snow Loads.

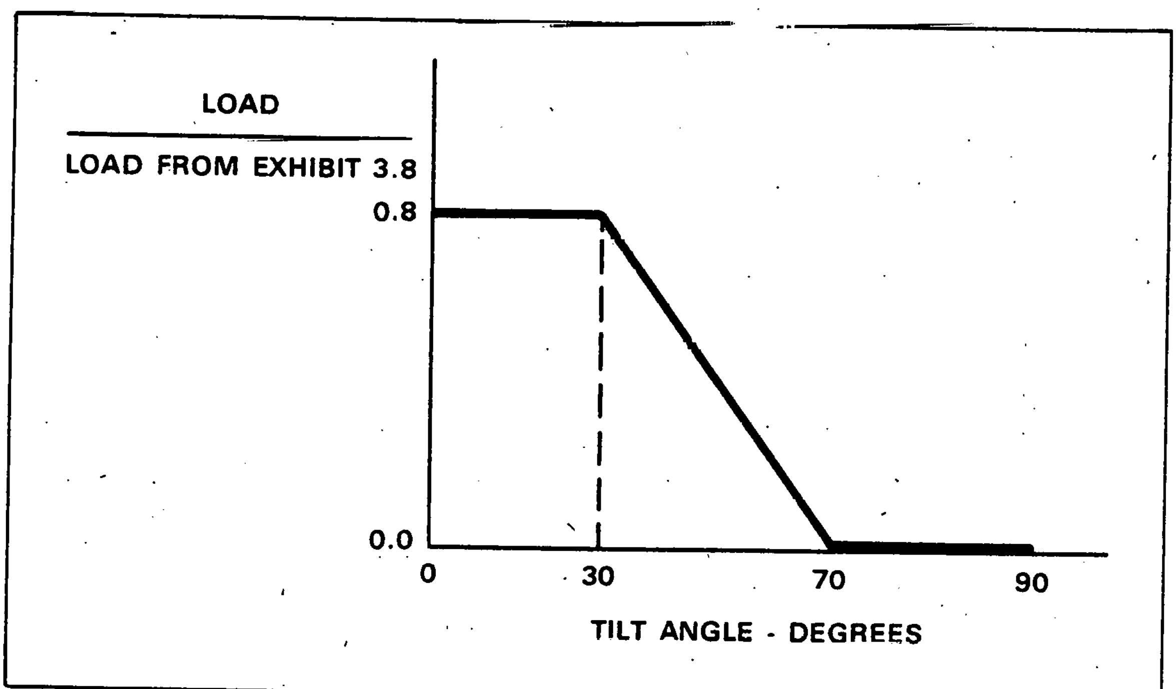


Exhibit 3.9 Snow Loads—Tilt Effect.

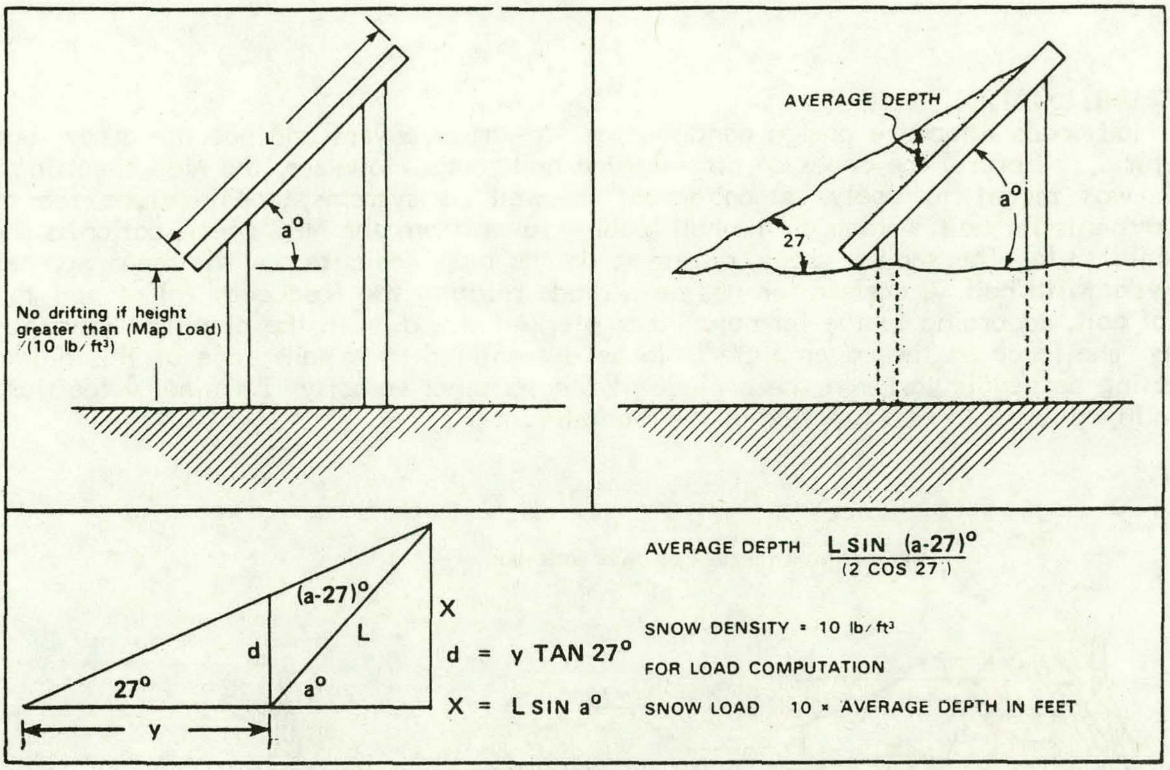


Exhibit 3.10 Snow Loads—Drift Effect.

Despite Previous Computations

TILT	MINIMUM LOAD
0° to 8°	20 lb/ft²
18° to 45°	16 lb/ft²
45° to 90°	12 lb/ft²

Exhibit 3.11 BOCA—Minimum Loads.

Assumed less stringent than wind or snow, since structure unoccupied.

Exhibit 3.12 BOCA—Seismic Loads.

ANSI calls for lateral load on signs = 0.3 *Z* Wt

ZONE	Z
1	0.25
2	0.50
3	1.00

Exhibit 3.13 Seismic Load—Some Complications.

3.4.4 HAIL LOADS

Hail loads impose a design condition on the array covers and not the array support structure. Therefore, the codes do not mention hail loads. However, the NBS specification, which was meant to apply to collectors as well as systems, does include the HUD requirements for hail. A map of the hail loading taken from the NBS specification is shown in exhibit 3.14. The shaded areas, displayed on the map, indicate d – the mean number of days/year with hail. A correlation has been made relating the frequency (d) of hail to the size of hail, according to the formula: diameter = 0.3 x d, with the diameter measured in inches. The force on the cover plate is to be determined by a hail stone of this diameter impacting perpendicularly on the surface at the terminal velocity. Terminal velocities are shown in exhibit 3.15 as a function of the diameter.

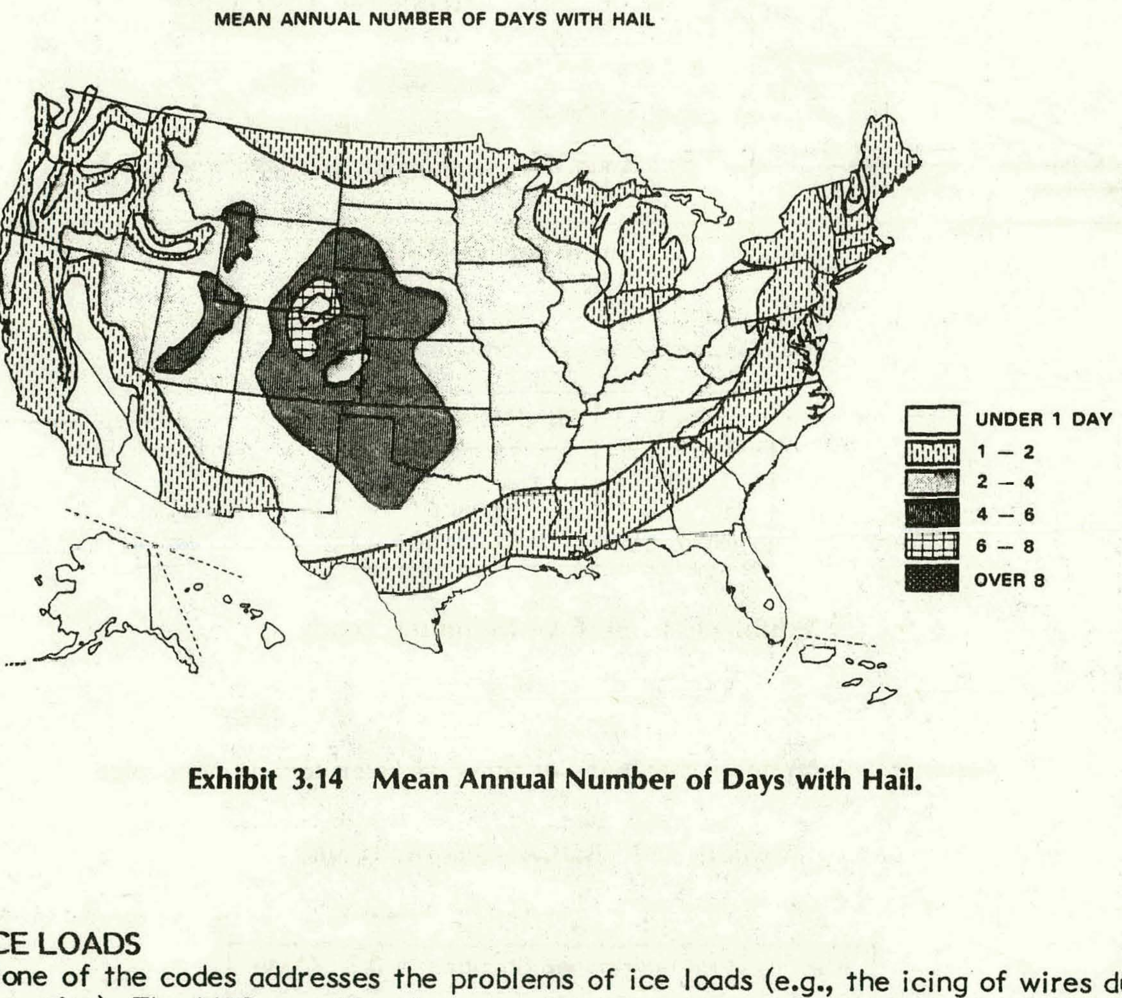


Exhibit 3.14 Mean Annual Number of Days with Hail.

3.4.5 ICE LOADS

None of the codes addresses the problems of ice loads (e.g., the icing of wires during freezing rains). The NBS specification uses the map shown in exhibit 3.16 for the mean number of days/year with freezing rain. The table in exhibit 3.17 indicates the corresponding thicknesses of the ice layers on wires exposed in each of these map areas.

DIAMETER IN.	WEIGHT GM	WEIGHT LB	TERMINAL VELOCITY FT/SEC
½	0.98	0.002	51
¾	3.30	0.007	62
1	7.85	0.017	73
1¼	15.33	0.034	82
1½	26.50	0.058	90
1¾	42.08	0.093	97
2	62.81	0.138	105
2¼	89.43	0.197	111
2½	122.67	0.270	117
2¾	163.28	0.360	124
3	211.98	0.467	130

Exhibit 3.15 Values of Weight and Terminal Velocity, Computed for Smooth Ice Spheres.

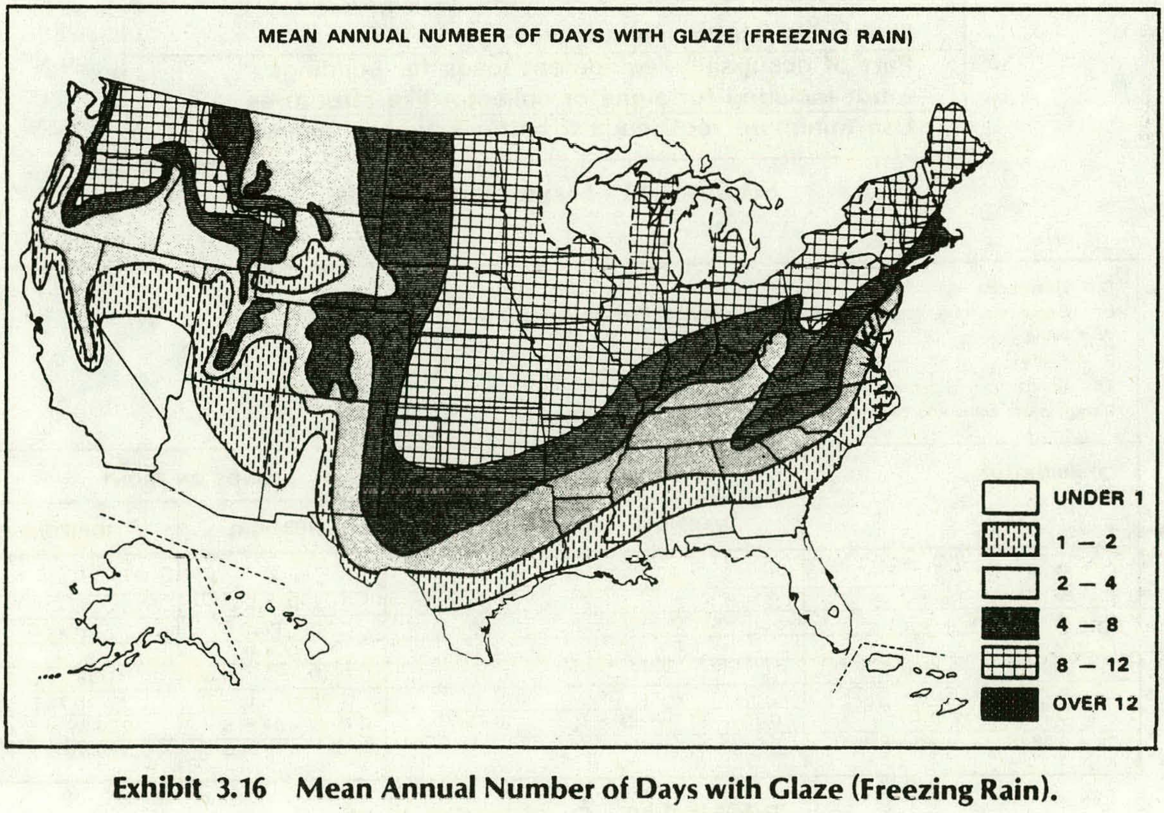


Exhibit 3.16 Mean Annual Number of Days with Glaze (Freezing Rain).

3.4.6 MAINTENANCE LOADS

Maintenance, occupancy, and equipment loads are included in the codes for structures that house people. None of the codes includes such loads on signs or collector-like structures. The designer must use his judgement.

Small collectors would have almost no maintenance loads (exhibit 3.18). Large collectors may have maintenance people climbing on walks or on the panels themselves. Unless details are available for estimating the maintenance load, the table of minimum loads shown in exhibit 3.3 can be used.

MEAN NUMBER OF DAYS WITH FREEZING RAIN	THICKNESS OF ICE—IN.
1	0.00
1 to 4	0.50
4 to 8	0.75
8	1.00

Exhibit 3.17 NBS: Ice on Wires.

3.4.7 COMBINATIONS OF LOADS

All of the foregoing loads do not act simultaneously; those that do, do not necessarily have a high probability of simultaneous occurrence. Exhibit 3.19 shows the design loads, C_i, as computed for various combinations of loads. The coefficients of 0.75 and 0.66 account for the reduced probability of occurrence. Each of the combinations, C_1 through C_8, must be computed for wind loads from each direction to determine which is the critical load that determines the design.

Live loads due to maintenance
Part of occupancy/equipment loads for buildings not included for signs or collector-like structures
Use minimum roof loads if better estimate unavailable

Exhibit 3.18 Maintenance Loads.

D = Dead Load
L = Snow, ice, rain, earth, hydrostatic, maintenance (not simultaneous with snow)
W = Wind
E = Seismic
T = Contraction, Expansion, Settlement
Design must withstand each combination.

COMBINATION	WINDS ON BACK		WINDS ON FRONT	
	VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL
C_1 = D	—	—	—	—
C_2 = D + L	—	—	D + L	O
C_3 - D + W or E	- 0.1 D + W	W	D + W or E	W or G
C_4 = D + T	T	o	D + T	T
C_5 = 0.75 (D + L + W or E + T)	—	—	0.75 (D + L + W or E)	0.75 (W or E)
C_6 = 0.75 (D + L + T)	—	—	0.75 (D + L + T)	0.75 T
C_7 = 0.75 (D + W or E + T)	0.75 (- 0.1 D + W + T)	0.75W	0.75 (D + W or E + T)	0.75 (W or E + T)
C_8 = 0.66 (D + L + W or E + T)	—	—	0.66 (D + L + W or E + T)	0.66 (W or E + T)

Exhibit 3.19 Combination Loads.

3.5 EXAMPLE OF THE USE OF THE BOCA CODE

Exhibit 3.20 illustrates an example of the use of the BOCA code. The collector (array) is assumed to be 25 feet long and 8 feet wide. This is approximately the largest collector that has been found cost effective in 1978. The collector is assumed to be installed in Albany, New York, at a tilt of 50^{o} to the horizontal. The weight of the collector is assumed to be 5 lb/ft^2. The area equals $25 \times 8 = 200\ ft^2$.

Data:	
Collector: 25′ long × 8′ high	
Location: Albany, NY	
Tilt: 50°	
Weight: 5 lb/ft	
Loads:	**Weight**
D = Dead Load = 5 lb/ft^2 × 25′ × 8′	= 1,000 lb
L = Maintenance: 12 lb/ft^2 × 25′ × 8′	= 2,400 lb
L = Snow: No drift: 25 lb/ft^2 × $\frac{50 - 30}{50}$ slope × 25′ × 8′ × 50°	= 1,286 lb
Drift: 19 lb/ft^3 × $\frac{8 \sin (50 - 27)}{2 \quad 27^\circ}$ × 25′ × 8′	= 3,508 lb
W = Wind: 15 lb/ft × 25′ × 8′	= 3,000 lb
E = Seismic, hail and ice	= 0
T = Deflection: check after design	

Exhibit 3.20 Example—by BOCA Code.

The dead load is the weight of the collector, 1,000 pounds. The maintenance load is computed from the minimum load of 12 lb/ft^2 and the area, yielding 2,400 pounds. The snow load without drift, but on the tilted surface, is: 25 lb/ft^2 multiplied by the tilt factor, the area, and the cosine of the tilt angle, or 1,286 pounds (exhibit 3.9). When drifting is included, the snow load can be as high as 3,508 pounds. In keeping with the BOCA code for signs, the wind load is computed from a wind force of 15 lb/ft^2 and the area, yielding a total load of 3,000 pounds. Seismic loads, hail, ice, and deflection-induced loads are assumed negligible. By mounting the collector so the bottom is clear of the ground, with a 2.5-foot gap below the collector, the effect ot dritting can be avoided.

Exhibit 3.21 shows the individual loads combined according to the scheme of exhibit 3.19. The most severe loads are circled. Wind from the front and wind from the back are considered separately. The wind from the back is frequently the most stringent, because it causes uplift and overturning. With the wind on the front, two conditions must be checked separately: C_3 gives the highest horizontal component; C_5 gives the highest vertical component and the highest resultant combination of the horizontal and vertical. The structure must withstand both C_3 and C_5. For the example, the resultant load is less than 20 lb/ft^2 vertically and 12 lb/ft2 horizontally. As will be seen in the following section, most commercially available structures have capabilities far in excess of these loads.

3.6 AVAILABLE STRUCTURES

Small structures, typical of most applications, will use pre-engineered structures. The cost of support structures will be approximately $40 per square meter of array. For a system requiring an average power of one kilowatt, the array size will be approximately 60 m^2, so the total structure cost will be $2,400. The cost of the structure will not only be a small part of the total system cost of nearly $200,000, but will also be small compared to the engineering cost that would be required to reduce the structure cost significantly. Only in systems above 10 kilowatts will structural optimization be worthwhile. Because the designs being considered in this seminar are all under 2 kWe, the pre-engineered structures are the only consideration.

Exhibits 3.22 through 3.25 illustrate some structural designs available from various manufacturers. The capabilities and typical dimensions are listed in exhibit 3.26. Many structures are capable of handling wind loads over 150 mph, well above any that can be expected. The force resulting from the 150 mph wind is approximately 56 lb/ft^2 which is also well above any snow load that might be expected, but the structural members are typically only 2 or 3 inches in diameter.

Perhaps the most important consideration in the selection of the structure is the selection of the material. Hot-dip-galvanized steel, aluminum and pressure-treated lumber are preferred to minimize maintenance, with the last two being most desirable because 20-year lives are common. Galvanized steel coatings are frequently chipped or worn off near fasteners, so the corrosion protection is lost.

Exhibit 3.26 also shows the foundations required for the various structures. Concrete footings that extend below the frost line will suffice, although some manufacturers claim that their structures are rigid enough to withstand several inches of frost heave, so they can be placed on slabs-on-grade or shallow footings. As is always the case, the foundations must be evaluated carefully in terms of the ground characteristics of the site. A soils engineer should normally be consulted.

COMBINATION	WINDS ON BACK		WINDS ON FRONT	
	VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL
C_1	—	—	—	—
C_2	—	—	1,000 + 3,686 cos 50 3,369 lb	
C_3	3.000 cos 50 - 0.1 1,828	3,000 sin 50 2,298	1,000 + 3,000 cos 50 2,928 lb	3,000 sin 50 2,298 lb
C_4	0 0	0 0	1,000 + 0 1,000	0 0
C_5	—	—	0.75 (3,369 + 3,000 50) 3,973	0.75 × 2,298 1,724
C_6	—	—	0.75 (3,369 + 0) 2,527	0.75 × 0
C_7	0.75 (1,828 + 0) 1,371	0.75 × 2,298 1,724	0.75 (2,928 + 0) 2,196	0.75 (2,298 + 0) 1,729
C_8	—	—	0.66 (3,973/0.75 + 0) 3,496	0.66 (1,724/0.75 + 0) 1,517

Exhibit 3.21 Combination of Loads.

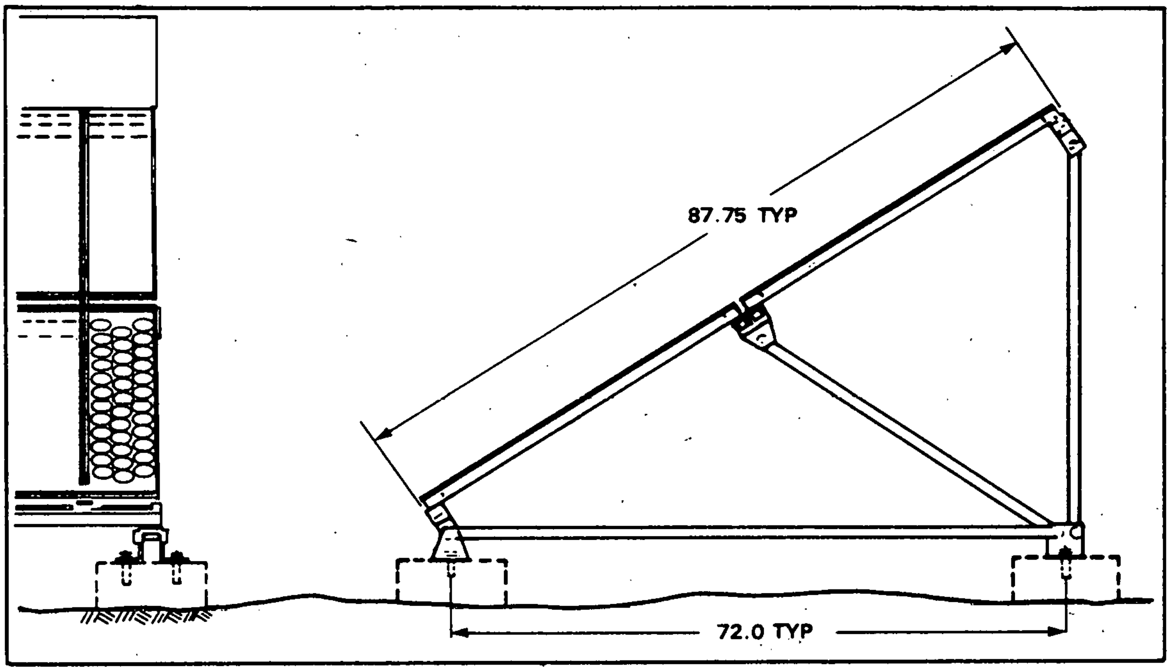


Exhibit 3.22 Truss Structure.

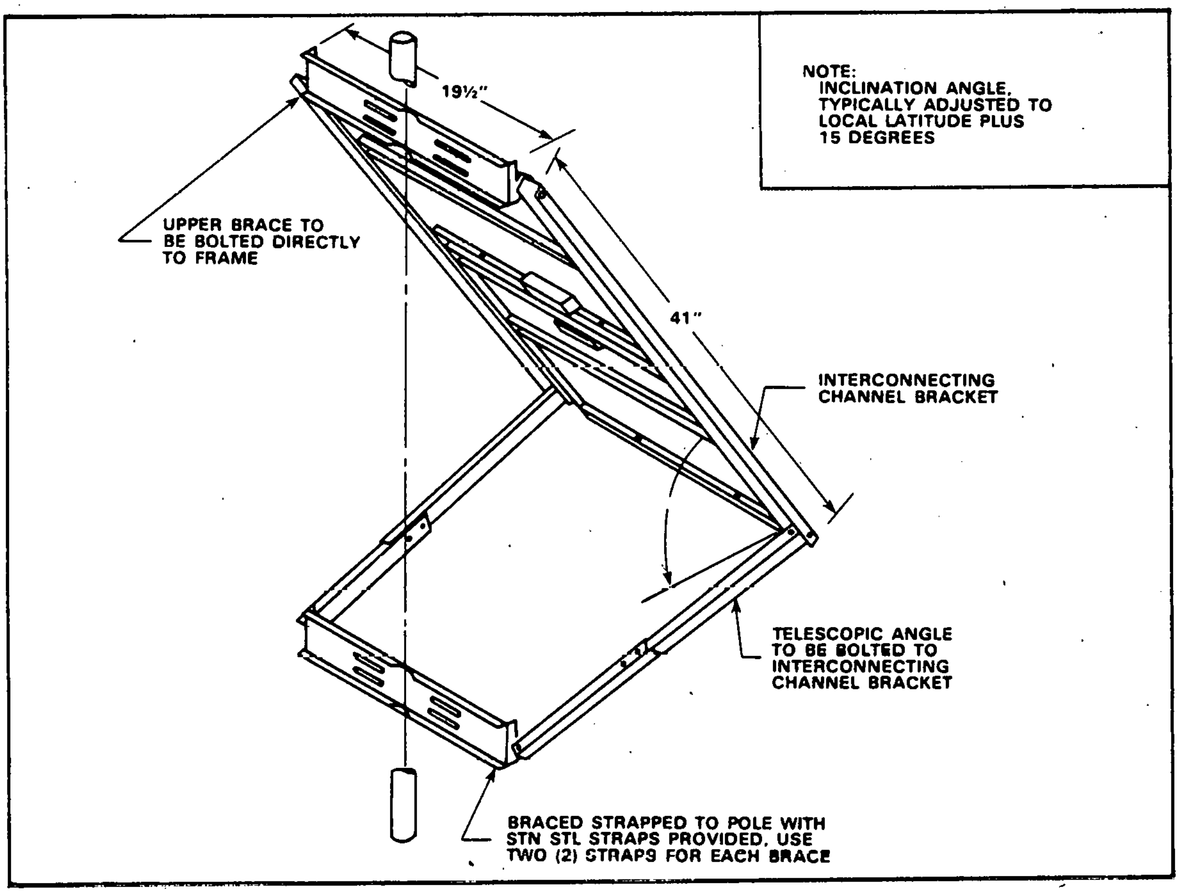


Exhibit 3.23 Truss Structure for Pole Mounting.

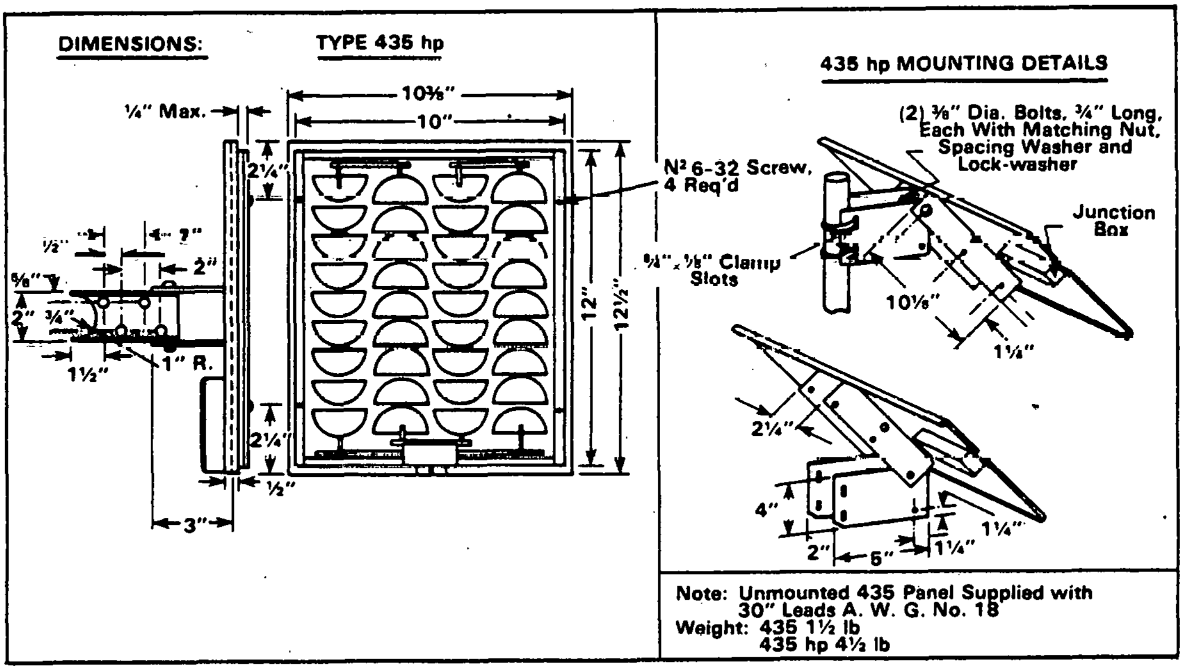


Exhibit 3.24 Structures for Pole Mounting.

ITEM / MFR.	ALLOWABLE NORMAL LOAD (LB/FT²)	FOUNDATION		APPROX. COST ($/M²)	MAT'L.	FACE DIMENSION (M × M)	LONGEST ELEMENT (M)	ELEMENT CROSS-SECTION ( )
		SLAB	FTG.					
Arco	100	X	12" × 12"	30	AL	2.2 × 0.22	2.3	2" × 2" × ⅛"
Solar Power	75							
Solarex—Truss	75-100	X	X	45[2]	AL	1.3 × 1.8	1.8	2½" × 1½" × ⅛"
Solarex—Pole	100			602[2]	AL	0.3 × 0.3	Pole	2" Typical
Solarex—Pole	100							

Exhibit 3.26 Typical Structures and Their Capabilities.

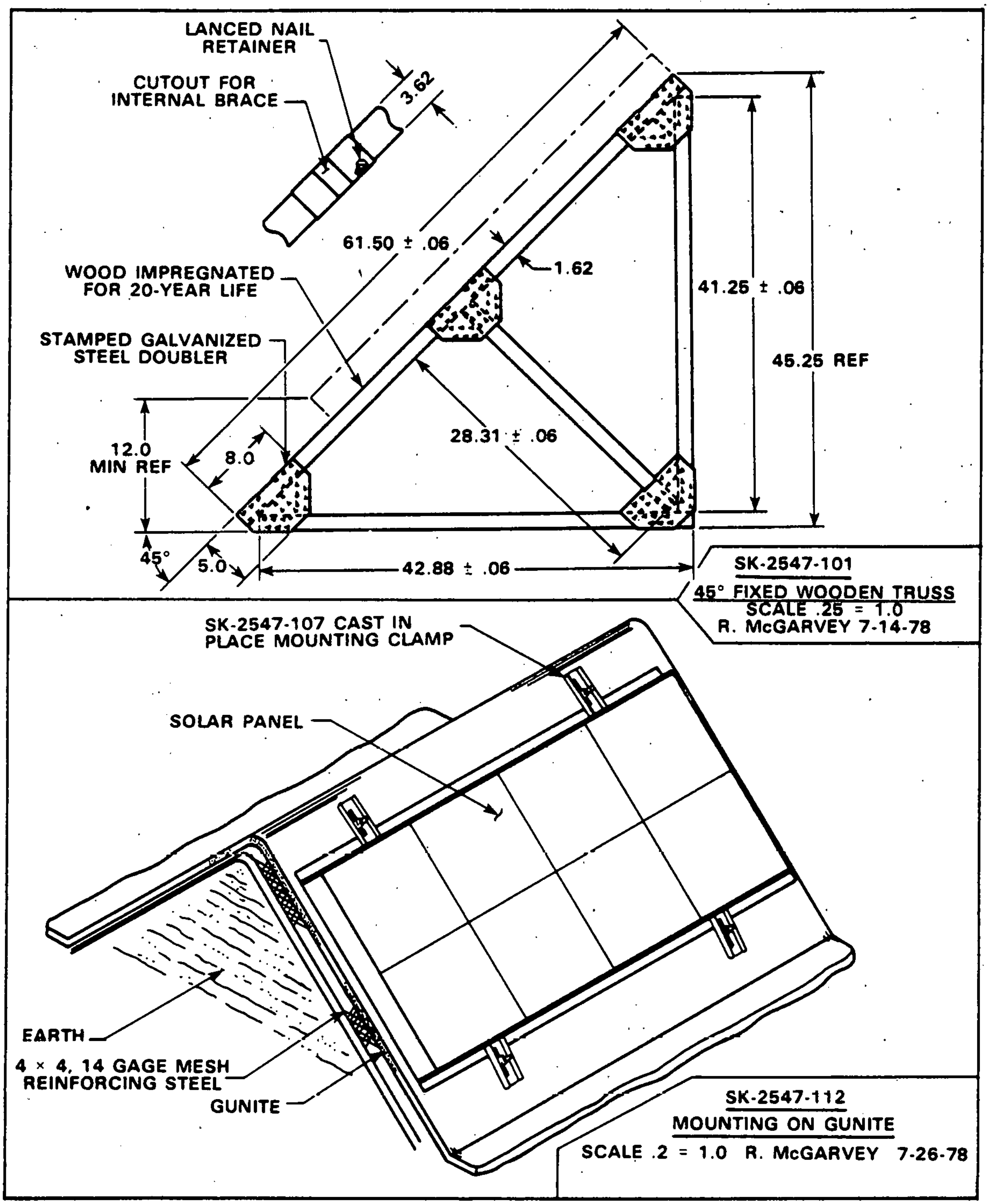


Exhibit 3.25 Proposed Structural Concepts.

3.7 THERMAL DESIGN

Designers have frequently proposed the solar thermal-solar cell total energy system. Solar cells are mounted integrally with thermal collectors, so the solar energy that is not converted to electricity might be used to generate heat useful for heating and cooling the building on which the solar cells are mounted. The properties of solar cells are such that they usually absorb less heat and emit more heat than the coatings often used in thermal collectors. As a consequence, the solar cells, when mounted on a thermal collector, can degrade the performance of the thermal collector. For the purposes of this seminar, only solar cells will be considered as being mounted on the array. Thermal collectors for total energy systems are being studied in the DOE/NASA/SERI solar thermal power systems program. Generally, total energy systems involve the cogeneration of electricity and heating/cooling or process heat. DOE/NASA/SERI are studying the solar photovoltaic total energy system also as well as the solar thermal total energy system.

Solar cells are cooled by natural convection or by wind. The power required to fan cool the cells far outweighs the added power obtained from operating the cells at the lower temperature available with fan cooling.

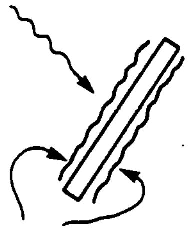
The temperature of the cell is computed from an equation that balances the energy input to the cell with the energy output. The computations can be done for a typical square foot of cell. The thermal output is equal to the solar input (insolation) multiplied by (l-n), where n is the electrical efficiency of the cell. This term is illustrated on the third line of exhibit 3.27. The thermal output from the cell is a combination of losses from the rear plus losses from the front. The panels are usually so thin that the temperature inside the panel is nearly equal to the temperatures at the surface of the cell. The maximum temperature of the cell occurs when the insolation is greatest, or approximately 100 W/ft^2. The convective heat transfer coefficients, h, depend on wind velocity as indicated by the equation obtained from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) handbook. With still air, the coefficient is 1 Btu/hr/sq ft/deg F. At 15 mph, the coefficient is 6.

With no wind but with a ground-mounted array, both the back and front of the panel are effective in removing the heat. Therefore, the total heat-loss coefficient is the sum of two for the front and two for the rear, for a total of 4 Btu/hr/sq ft/F$^{\circ}$. If this coefficient is divided into the energy that is not converted to electricity, the temperature is 74° F above the ambient temperature, or 174° F on a 100° F day. To be conservative, it is assumed that the glass surface has zero reflectivity. This assumption will be increasingly more accurate as the technology for antireflection coatings is improved. If a glass reflectance of 10 percent were used, the temperature of the cell would be 167° F, which is not significantly less, using the temperature differential of 74°F.

If the panel is root mounted, the back is not free to lose heat to the surroundings. Instead, the heat radiates to the roof and convects to the space between the roof and the panel. The panel should be mounted either flashed into the roof to prevent leakage, or 3 inches from the roof to permit air to circulate under the panel, thereby removing both heat and moisture. The heat transfer coefficient on the front is given by the same formula as for the freestanding collection. The heat-transfer coefficient for the rear is approximately 1.5. For the same no-wind case as analyzed above, the temperature of the roof-mounted panel would be 85° F above ambient, or 185° F (85° C) on a 100° F day.

ARRAY TEMPERATURE—FREE STANDING

SOLAR (I)



INPUT = OUTPUT

$(I - n)\ I = (h_{front} + h_{back})\ (T_{cell} - T_{air})$

Per ASHRAE:

$h = 2 + \frac{4}{15} \times$ mph Btu/hr - ft² - OF

$I \doteq 340$ Btu/hr - ft² (100 W/ft)

$n = 0.13$

With No Wind:

$T = T_{air} + (1 - 0.13) \times 340/(2 + 2)$

$T = T_{air} + 74°F\ (41°C)$

Array Temperature—Roof Mounted

$h_{front} = 2 + \frac{4}{15} \times$ mph

$h_{back} = 1.5$

(3" or more from roof)

With No Wind:

$T = T_{air} + (1 - 0.13) \times 340/(2 + 1.5)$

$T = T_{air} + 85°F\ (47°C)$

Exhibit 3.27 Typical Solar Array Temperatures.

In a 15 mph wind, the freestanding collector would be at a temperature of 125° F on a 100° F day, whereas the roof-mounted array would be at 146° F. The average roof-mounted cell temperature over the life of the cell would probably be close to 15° F above the ground-mounted temperature. The temperature of the cell is proportional to the insolation, so the above temperature differences can be modified to insolation values other than 100 W/ft^2 by a simple ratio.

Since the panel temperatures are well within the allowable temperature limits for most materials, they are of little concern. However, care must be exercised on still days to prevent personal injury from hot cells. In addition, the high cell temperatures will affect the cell life and, more importantly, the cell efficiency. The temperatures shown in exhibit 3.27 will result in a panel efficiency of 8 percent, as compared to the rated efficiency at 25° C of 12 percent.

3.8 FROST, SNOW, AND ICE

Because the panels face skyward, their temperatures will frequently be lower than the ambient dew point. As a consequence, frost will form on the panels, thereby obscuring some of the sunlight. Exhibit 3.28 shows the frost thickness that would not normally last past 10 a.m. on clear and average days. The sun will be bright enough so that, despite the high reflectance of the ice, the warmth of the sunlight will be sufficient to melt the frost. The same curve applies to ice and snow.

Under more severe conditions, the frost, ice, or snow thickness will be greater than could be melted by the sun. Electrical melting by a resistance heater in the panel could be used to de-ice the panel. Exhibit 3.29 shows the tradeoff between the energy required for de-icing and the energy produced from the de-iced cell. It is evident that de-icing will not be profitable under most circumstances, since the power required for de-icing (curves A and C) will not be regained by the array before the next snow fall (curve D).

Other possibilities exist for de-icing the panels. One promising method calls for heating the snow or ice at the surface of the panel, then allowing the upper layers of ice or snow to slough off (curve B in exhibit 3.29). This method is not effective if the panel has a lip at the lower edge, as many panels do. This lip serves as a snow retainer. More work is required to determine how effective surface melting would be.

Another area requiring further study is the partial melting of the ice/snow covering on the panel. If a strip of ice or snow is melted electrically, a strip of the panel will be exposed to direct solar radiation. As a consequence, the panel will be solar heated without the intermediate step of conversion to electricity. The strip will widen as the panel is heated, until the entire array is freed from snow and ice.

No matter what is done, on cold windy days, there is little hope of removing the ice cover. The experience of homeowners with icing of their southern windows will provide some indication of the severity of the ice problem and the persistence of the ice layer. At present, electrical heating of the panels does not appear worthwhile.

3.9 CONCLUSION

As a result of this chapter, agency representatives should be able to estimate the structural load that the collector must withstand, and be able to compare this with the given data on typical solar-panel structures, or with data supplied by the same or other manufacturers for more suitable structures. If the ambient temperatures and the local precipitation indicate ice and snow may cause a serious shortfall of solar-cell output, the ability of a manufacturer's collectors to retain ice and snow should be considered.

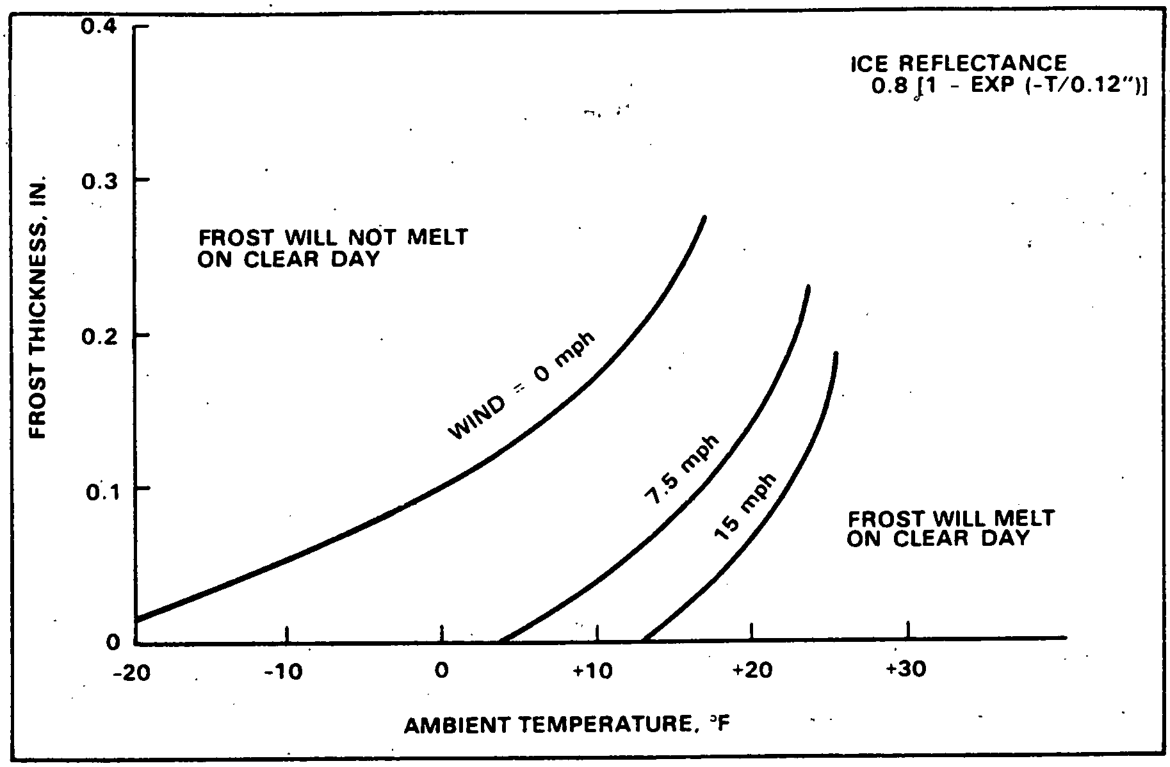


Exhibit 3.28 Frost Removal.

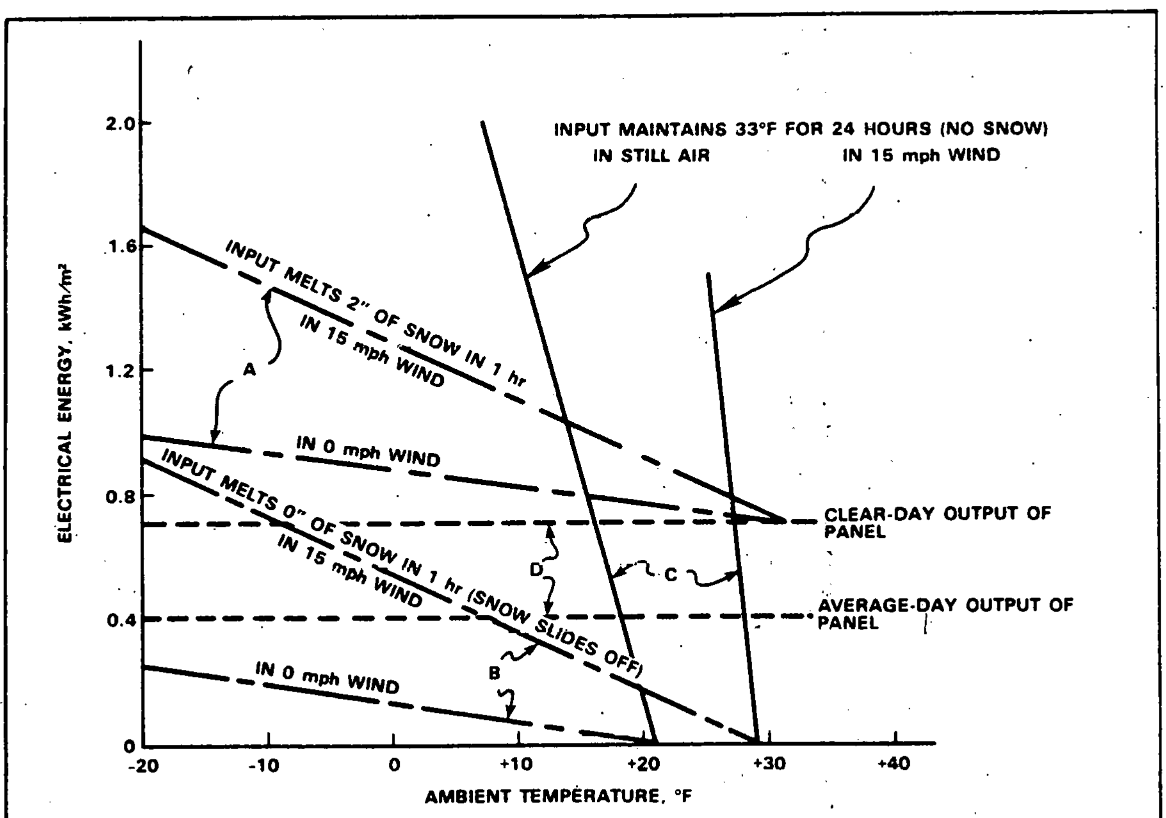


Exhibit 3.29 Thermal Snow Removal.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

SECTION 4
BATTERIES

4.1 ENERGY STORAGE

Due to the variations in insolation, and the possible utilization of energy under no-sun conditions, some form of electrical storage normally must be used in conjunction with the PV system.

Of the many possible energy storage systems available, most are not practical due to their high initial costs and energy storage capability mismatch (many can store much more energy than is required). Pumped hydroelectric, compressed air, thermal or hydrogen storage, super conducting magnets, and flywheel storage fall into this category. Chemical storage of electrical energy via batteries proves to be the most cost effective method of storing energy in connection with the PV system.

Batteries are storage devices that use chemical reactions to convert chemical energy into electrical energy. The quantity of available electric energy is a function of the inherent potential voltage and efficiency of electrochemical reactions, as well as the amount of active material in the battery. Many combinations of chemicals have been used as energy storage systems, each type possessing advantages and disadvantages with regard to physical and electrical battery characteristics. Energy density, expressed in either Wh/lb or Wh/in^3, is one important characteristic to consider. In many applications, energy cost, expressed in dollars per watt-hour, will be the overriding consideration.

4.2 TERMINOLOGY

Batteries are normally classified as either primary or secondary. Primary batteries are designed to be utilized only once because the active chemicals they contain are depleted during the chemical reaction which produces the output electrical energy. They are discarded when they are completely discharged. Secondary batteries are designed to be used repeatedly. Electrical energy, which can be applied to the output terminals, is electrochemically converted, stored as chemical potential energy, and, subsequently, reconverted to electrical energy.

Primary batteries are used in systems that require low current discharge rates and low first cost. The secondary battery, due to the reversibility of its chemical reaction, can be used repeatedly in high-power applications with a recharge included in the duty cycle. Types of batteries include: zinc-carbon, alkaline-manganese, mercury, and lithium for primary cells; and, lead-acid, nickel-cadmium, lithium-sulfur, sodium-sulfur, and sodium-chlorine for secondary application. Lead-acid and nickel-cadmium secondary batteries are the two types most suitable for use with PV systems due to their cost, operation, and availability (shown in exhibit 4.1).

In the following material, detailed discussions of types and operation of batteries are presented. It is expected that this material will allow the PV designer to choose the proper battery for the application at a cost suitable to the projects.

ACTIVE MATERIAL	TYPE	V/CELL	Wh/lb	FEATURES
Zinc-Carbon	Primary	1.5	35	Low-cost, wide variety of small sizes.
Alkaline-Manganese	"	1.5	42	Good low temperature operation, high efficiency under high-drain duty, more costly than zinc-carbon.
Mercury	"	1.3-1.4	56	Excellent high temperature performance. Relatively flat discharge characteristics.
Lithium	"	2.95	150	Highest energy density, temperature range and shelf life of primary cells, contains no water.
Lead-Acid	Secondary	2.0	12	Least expensive and most readily available of secondary cells.
Nickel-Cadmium	"	1.2	16	Excellent low temperature operation, low weight, low maintenance, higher initial cost than lead.
Lithium-Sulfur	"	≈ 1.5	≈ 60	Operate at high temperature, 400° C, not currently commercially available, projected costs $25/kWh
Sodium/Sulfur	"	2.2	≈ 95	Operate at high temperature, ≈300° C, very low self-discharge, projected costs are $20/kWh, should be commercially available in mid-80's.
Sodium/Chlorine	"	2.12	≈ 70	Not commercially available, projected costs $20 kWh with efficiencies of greater than 90%, operates at 200° C.

Exhibit 4.1 Types of Batteries.

Because electrochemical reactions usually produce potentials of no more than a few volts, several cells are usually connected in series to attain a more useful battery voltage. Cells can also be connected in parallel to obtain larger battery current capacity.

Cells are composed of three basic components: (1) the negative electrode that supplies electrons to the external circuit as it is oxidized during the discharge reaction; (2) the positive electrode which accepts electrons from the external circuit when it is reduced during discharge; and, (3) the electrolyte that completes the circuit by furnishing the ions (i.e., electrically charged atoms) needed for conductance between the two electrodes.

The capability of a battery in Ah is expressed as the quantity of discharge current available during a specified length of time and at a given temperature, since charge equals current x time. The output voltage decreases during discharge until the battery reaches a certain state where any further current draw will rapidly decrease the output voltage and possibly damage the battery. This state defines the "cut-off" voltage as shown in exhibit 4.2. During a cycle of use, the battery charge is dissipated and the battery voltage decreases. The energy capacity is the time integral (summation) of the product of the discharge current and voltage from full charge to cut-off voltage and is expressed in watt-hours, since energy equals power x time and power equals voltage x current. A charge or discharge rate is usually referred to as the energy capacity, where one watt-hour equals 360 joules of energy. For example, a battery which has a 150 Ah capacity, c, and is supplying 15 A continuously, will be completely discharged in 150 Ah/15 A, or 10 hours. This current draw equals c/10 for a 10-hour discharge rate. The percent of a battery's capacity that has been discharged is termed the depth of discharge. A complete discharge and subsequent recharge is referred to as a cycle. The number of such cycles a battery can undergo before degrading is termed the cycle life and is a function of both the battery type and the depth of discharge the battery is subjected to during the cycle. The deeper the discharge, the shorter the life, as a more complete utilization of the active materials in the battery will result in larger internal stresses. The interdependence of life cycles and depth of discharge is shown in exhibit 4.3.

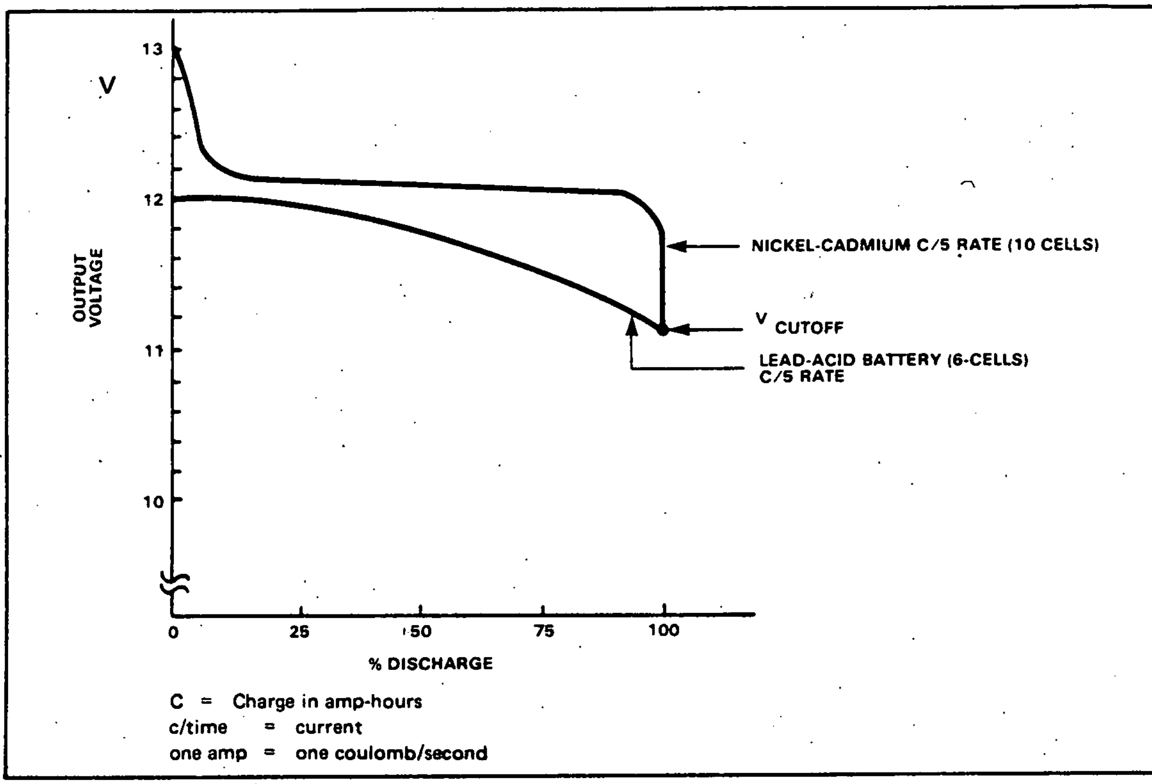


Exhibit 4.2 Comparison of Battery Output Voltages During Constant Discharge.

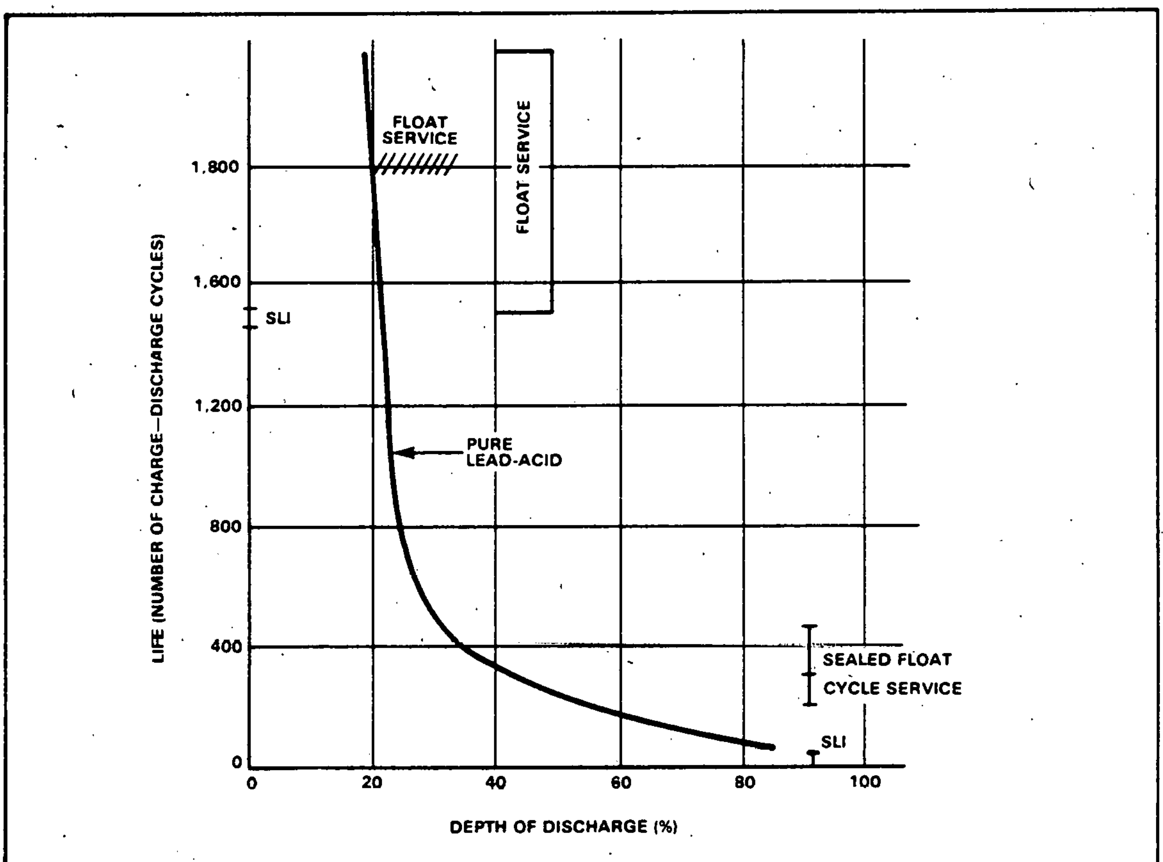


Exhibit 4.3 Battery Cycle Life vs. Depth of Discharge.

The coulomb is the common unit of electrical charge where one ampere equals one coulomb per second. In physical terms, the charge of an electron equals 1.6 x 10^{-19} coulombs. The actual number of free electrons in a battery cycle can be calculated by knowing capacity, and vice versa, for battery material choice and chemcial-electrical energy conversion sizing.

4.3 LEAD-ACID BATTERY

Lead-acid cells are comprised of lead negative electrodes and lead dioxide positive electrodes. The electrolyte used is an ionic conducting solution of sulfuric acid in water. During discharge, the active material contained in the electrodes is converted to lead sulfate. The equation for this reversible reaction is:

$$Pb + PbO_2 + 2H_2SO_4 = PbSO_4 + 2H_20$$

The ion is defined as an electrically charged atom or group of atoms, the electrical charge of which results when a neutral atom or group of atoms lose or gain one or more electrons during chemical reactions; the loss of electrons results in a positively charged ion and the gain of electrons in a negatively charged ion.

The electrolyte concentration of sulfuric acid decreases as the battery is discharged. Upon complete discharge, either the electrolyte or the active material in the electrodes is exhausted. Side reactions also occur, especially during overcharging. One such reaction is responsible for the production of hydrogen and oxygen via a method similar to electrolysis. Alloying materials or impurities in the electrodes can cause the evolution of toxic gases such as stibine (SbH_3) or arsine (AsH_3). In designing a lead-acid battery storage system, provisions must be made for venting these gases and for supplying additional water to the batteries. A catalytic converter can be incorporated in the battery cap, reconverting the hydrogen and oxygen into water.

An electrolyte is any substance which in solution or liquid form is capable of conducting an electric current by the movement of its dissociated positive and negative ions to the electrodes.

When recharged properly, lead-acid cells typically have coulombic efficiencies of 90 to 95 percent. For example, 111 Ah are required to recharge a 100 Ah battery with a 91 percent coulombic efficiency (100/0.91 = 111). Since recharge voltages are higher than discharge voltages, the energy efficiency is 70 to 80 percent. The coulomb is the common unit of electrical charge, and equals one amp-sec.

4.4 TYPES OF LEAD-ACID BATTERIES

At present, there are four types of lead-acid batteries, each of which possesses certain features critical to the type of service for which it is designed (see exhibit 4.4). One type of lead-acid battery is used in automobiles for starting, lighting, and ignition (SLI). These batteries are capable of delivering large amounts of energy in a short period of time, resulting in a low depth of discharge. For example, a typical 12 V car battery has an energy capacity of approximately 0.78 kWh. It typically delivers 300 A for about 20 sec/start, or 0.02 kWh (12V x 300A x 20/3600) kWh. This corresponds to a depth of discharge of 2.56 percent of rated capacity (0.78 kWh). When utilized in this fashion, an SLI battery will last 4 to 5 years. If the battery undergoes only three to five deep discharges (80 to 100 percent of capacity), failure may result. These batteries have thin plates that contain a high antimony content. Tin and arsenic have also been added to give strength and castability to the grids so they can withstand the large stresses caused by rapid discharge and recharge cycles, as well as mechanical stresses due to their environment in a moving vehicle. Automotive SLI batteries range in cost from $35 to $54/rated kWh in sizes from 0.95 to 1.2 kWh, respectively. Diesel SLI batteries cost approximately $50/rated kWh, ranging in sizes from 1 to 2.5 kWh. The high self-discharge rate and relatively short life of SLI batteries, especially when utilized to a deep discharge state, make this type of lead-acid cell unsuitable for many PV applications.

BATTERY TYPE		ENERGY COST rated $/kWh	ENERGY DENSITY rated Wh/lb	CHARACTERISTICS
SLI	AUTO	$35-54	15-21	High self-discharge, shallow discharge cycle, short life under deep discharge conditions.
	DIESEL	$50	16-18	
MOTIVE POWER	GOLF CART TYPE	$45-60	30-35	250 cycle life, high self-discharge, deep cycle.
	LONG LIFE	$160-220	7-11	1,000-2,000 cycle life, high self-discharge, deep cycle.
FLOAT SERVICE	PURE LEAD GRID	$80-130	14-18	Low self-discharge, low maintenance.
	LEAD-CALCIUM	$180-240	7-10	1,500 cycle life, low self-discharge, deep cycle capabilities.
SEALED	FLOAT SERVICE	$140	14-18	Low maintenance, low self-discharge.

Exhibit 4.4 Types of Lead-Acid Batteries.

4.4.1 CYCLE SERVICE BATTERIES

Another battery type may be categorized as providing "cycle" service. Motive power batteries, such as those used to power forklifts and golfcarts, allow greater depth of discharge. These batteries may survive one or more years (200 to 300 cycles) of daily deep discharge duty (90 percent of design capacity during an average work day). Plates for use in cycle batteries are made several times thicker than those used in SLI batteries and the number and size of these plates determine the battery capacity and weight. A massive positive electrode current collector (40 percent of the electrode) permits long life regardless of the use of high (5 percent) antimony grid alloys. As with the SLI batteries, most motive power-type batteries suffer from self-discharge problems and may lose up to 30 percent of rated capacity within several days, even if no power is drawn from them. Prices in the range of $45 to $60/rated kWh for a single motive battery are typical, with sizes ranging upward from a 2 kWh size. Longer life motive power batteries (1,000 to 2,000 cycles) are priced in the $145 to $220/rated kWh range and typically weigh three to five times as much as the less expensive motive batteries for the same kWh capacity.

4.4.2 FLOAT SERVICE BATTERIES

In float-type service, the battery is maintained in a state of low depth of discharge and only undergoes an occasional deep discharge. Batteries designed for such use have a very low self-discharge rate due to the use of pure lead or calcium alloyed grids, and a low rate of gas evolution (they require about one-tenth the makeup water needed in motive-power batteries). The positive grids are more corrosion resistant in the charge mode as they use no antimony. Therefore, the lifetime of these batteries typically exceeds 5 years' use. For maximum life, a discharge level of less than 20 to 30 percent of full capacity is recommended. These attributes make them ideally suited for use with PV power systems. Prices generally range from $80 to $130/rated kWh (higher for batteries smaller than 1 kWh), in sizes up to about 6 kWh.

Deep discharge, float-type batteries are also available at higher costs, with 0.4 to 0.8 percent calcium alloyed with the lead for added strength. This allows the battery to minimize self-discharge problems, thereby retaining a near full capacity for anywhere from 6 months to 1 year while permitting deep discharge cycles. For maximum life expectancy, a discharge level of less than 40 to 50 percent of capacity is recommended. Costs for batteries of this type (which also contain extra electrolyte to prevent damage at full discharge) range from $200 to $240/rated kWh per single battery, in sizes from 1 kWh and larger. Life expectancy is in the 1,500- to 2,000-cycle range.

4.4.3 SEALED FLOAT SERVICE BATTERIES

Sealed float service-type batteries are also now available in sizes up to approximately one-half kWh. These cells use grids composed of calcium and other proprietary alloys. Due to the calcium grids, there is a low rate of gas evolution, allowing the cell to be sealed, making it virtually maintenance free. Pressure relief valves are provided and will vent hydrogen if the battery is improperly charged. The life expectancy of the cells, as with most calcium grid designs, is 200 to 500 deep discharge cycles. Prices are in the $140/kWh range for 0.4 kWh batteries, with higher prices per kWh for the lower power ratings.

4.5 FAILURE MECHANISMS OF LEAD-ACID BATTERIES

A diagram of a lead-acid cell is shown in exhibit 4.5. The chemical conversion of metallic lead and lead dioxide to lead sulfate and vice versa causes internal volume changes

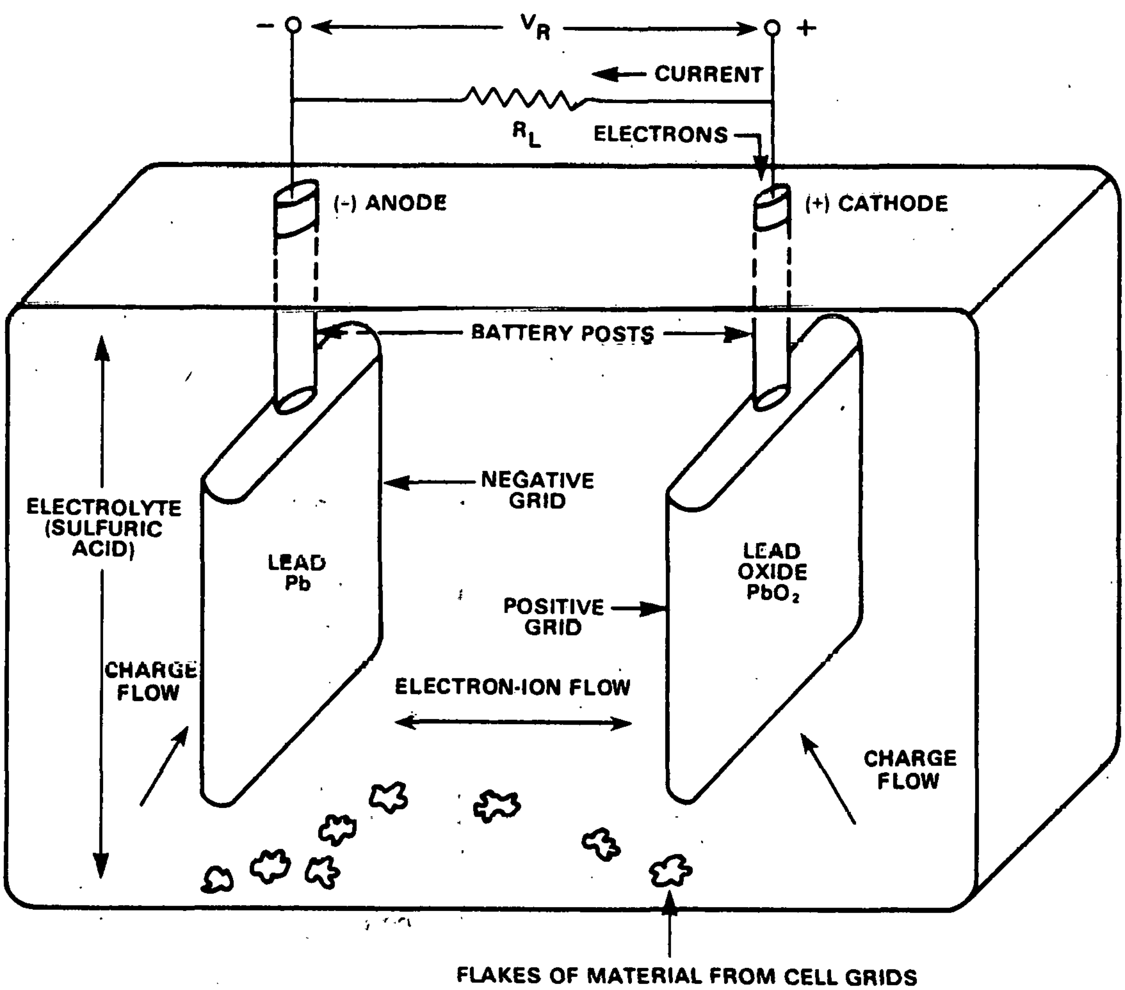


Exhibit 4.5 Lead-Acid Cell.

in the electrodes. These changes create stresses on the electrodes which may cause the active material to flake or shed from the collector grid, and eventually shorting the cell. This process causes the battery to lose capacity and increases the internal resistance. This degradation increases with depth of discharge and results in decreased energy density and current carrying capability. This is why motive batteries, which supply large power loads, have antimony and other alloys to strengthen the electrode grids.

Lead-acid cells will also fail if the quantity of electrolyte is allowed to fall to an excessively low level. This can be prevented by adding additional distilled water, as needed, to the cells and by not overcharging the cells, thereby avoiding outgassing.

Although a battery's capacity increases with temperature, high temperatures actually reduce a battery's life (see exhibit 4.6). While there is considerable disagreement on the exact correlation of life and temperature, a good estimate is that a battery's life is halved if the average temperature is raised from 75° F to 110° F. Energy conversion efficiency also decreases with increasing temperature due to internal loss processes, such as electrolyte resistance, which shows an exponential increase with temperature.

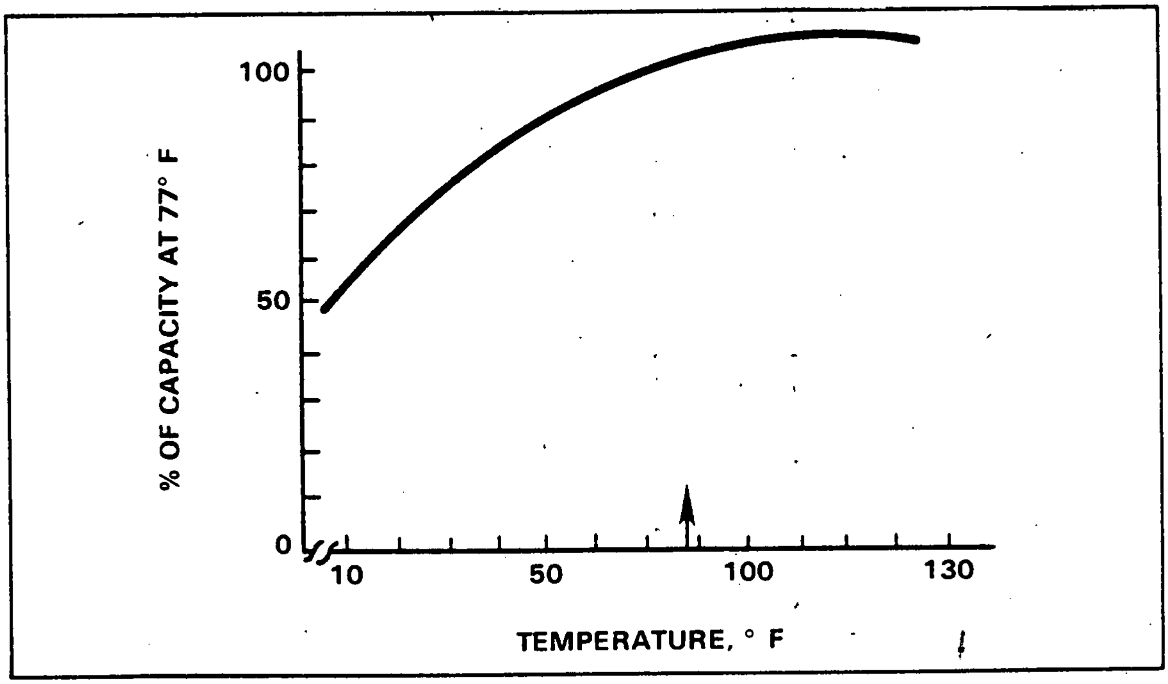


Exhibit 4.6 Relative Capacity of Lead-Acid Batteries as a Function of Temperature.

Care must also be taken to ensure that the batteries do not freeze in cold weather applications, as shown in exhibit 4.7; a fully-charged battery will freeze at approximately -60° F, depending on the concentration of the electrolyte. As the battery discharges, the electrolyte is consumed by the chemical reactions and the concentration decreases. A fully discharged cell will freeze at a temperature somewhat below 32° F. A high state of charge will prevent the batteries from freezing.

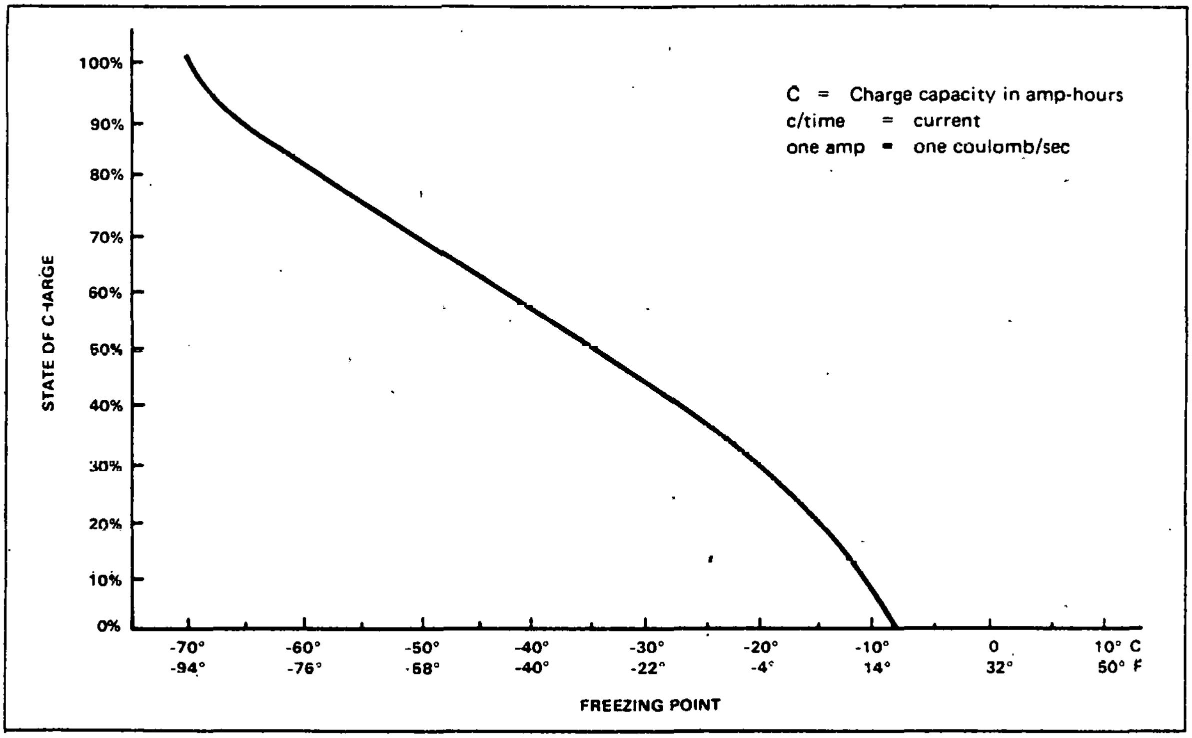


Exhibit 4.7 Freezing Point of Lead-Acid Battery as a Function of State of Charge. Specific Gravity of Electrolyte = 1.300 at 25° C at Full Charge.

4.6 DISCHARGE AND RECHARGE CHARACTERISTICS

4.6.1 LEAD-ACID BATTERIES

The voltage characteristics of typical lead-acid cells during constant current discharge are shown in exhibit 4.8. The higher the rate of discharge, the larger the cell voltage decrease. This is the result of connector and grid structure resistance and electrolyte concentration polarization. Use of different materials and manufacturing techniques will result in actual cells varying from these curves. To assure maximum battery life, discharge past a terminal voltage of approximately 1.8 V/cell should be avoided.

The same effects which lower the cell's output during discharge contribute toward increasing the required terminal voltage during recharge, as shown in exhibit 4.9. During recharge, efficiency and battery life will be lowered by excessive outgassing and high temperatures.

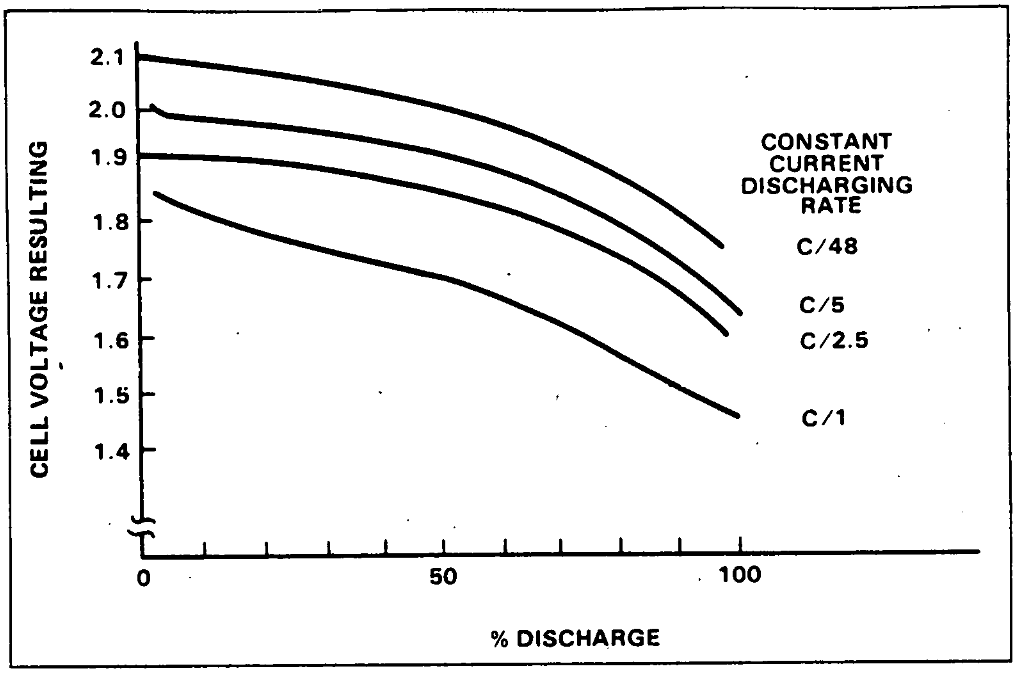


Exhibit 4.8 Typical Discharge Voltage Characteristics.

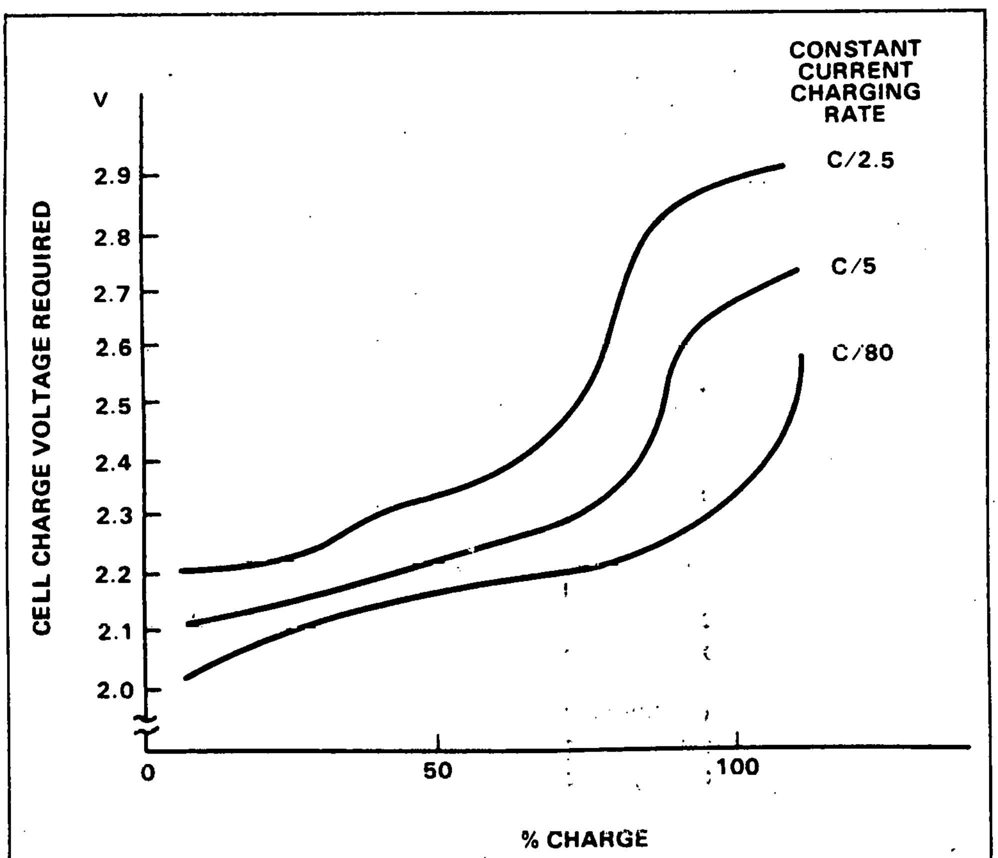


Exhibit 4.9 Typical Charge Voltage Characteristics.

For standby or float-type service batteries, the charge voltage should be held at 2.25 V/cell, or 13.5 V/12V battery. This will limit the effects of overcharging and significantly increase battery life. This method is commonly referred to as "float voltage" charging at constant voltage, whereas in trickle charging the charging current is held constant and may result in overcharging the battery.

For cyclic use, where the maximum number of recharge cycles is of paramount importance, the battery on-charge voltage should be maintained below 2.4 V/cell or 14.4 V/12 V battery. In applications where the batteries are used in both float and cyclic service, a charging voltage of between 2.30 and 2.45 V should be employed.

One of the simplest recharging circuits for small capacity batteries, a shunt-connected (parallel) zener diode, is shown in exhibit 4.10. This circuit uses an inexpensive, low wattage zener diode (sized to meet the needed recharge voltage) in conjunction with a current limiting resistor.

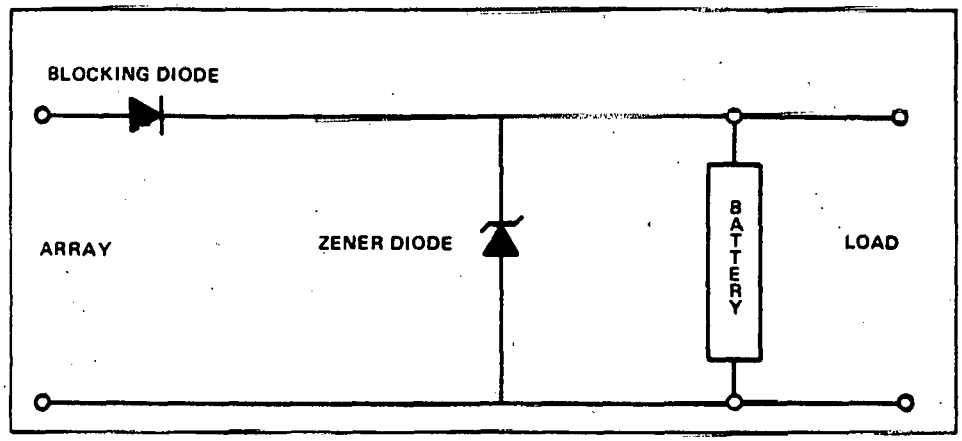


Exhibit 4.10 Battery Charging Regulator with Zener Dissipating Excess Energy.

Another popular circuit is the shunt (parallel connected) transistor regulator (see exhibit 4.11). This circuit allows a small zener diode to be used for all battery sizes, since only the transistor base current flows through the zener diode.

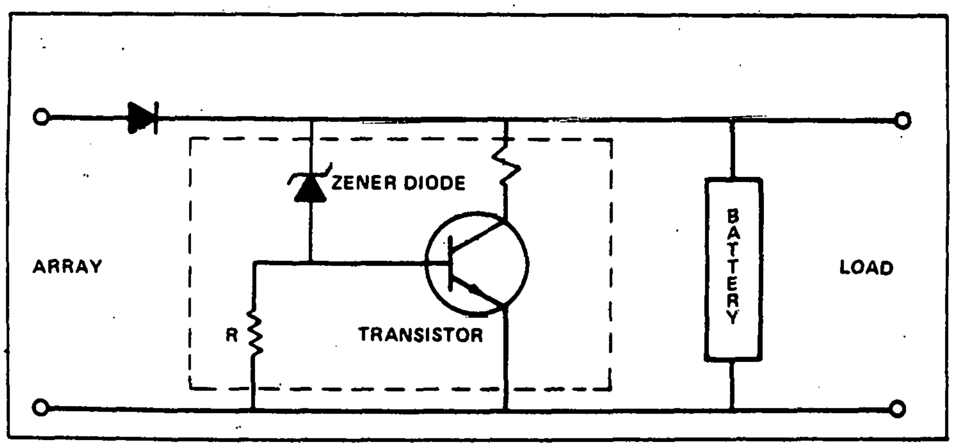


Exhibit 4.11 Battery Charging Regulator with Resistor Dissipating Excess Energy.

4.6.2 NICKEL-CADMIUM BATTERIES

Nickel-cadmium batteries are designed for use in lightweight, portable applications which require long operating lifetimes and little or no maintenance. The electrodes (see exhibit 4.12) in nickel-cadmium cells undergo changes in oxidation state without any changes in physical state. The active materials involved, insoluble in the alkaline electrolyte, remain as solids during oxidation state changes. This results in two favorable properties of nickel-cadmium cells: (1) because no chemical mechanism exists which would result in the loss of active material, the electrodes are long lived and (2) the cell potential is essentially constant throughout most of the discharge cycle. Oxidation is defined as the process of increasing the positive valence of or decreasing the negative valence of an element or ion. Electrons are removed from atoms or ions.

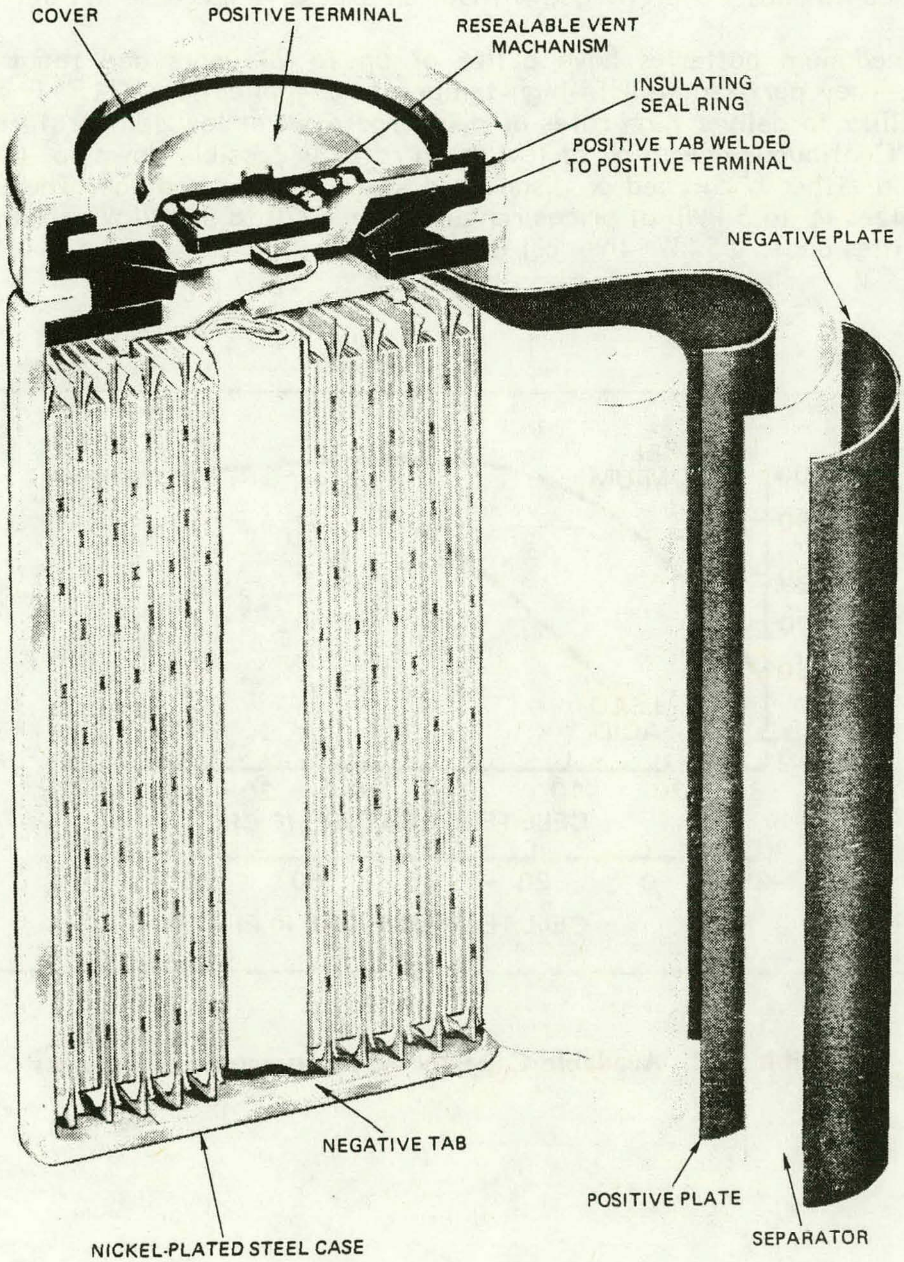


Exhibit 4.12 Cylindrical Sealed Cell Construction.

Nickel hydroxide (NiO (OH)) is the active material in the positive plate. During discharge, the charged NiO (OH) goes into a lower valence state, Ni $(OH)_2$, by accepting electrons from the external circuit. The negative plate, which is composed of cadmium, is oxidized to cadmium hydroxide and releases electrons to the external circuit. During charging, the reactions are reversed, as shown:

$$Cd + 2H_2O + 2NiOOH \rightleftarrows 2\,Ni\,(OH)_2 + Cd(OH)_2$$

These batteries do not vent hydrogen because the cells are constructed so the oxygen generated at the positive plate migrates to the negative plate, recombining with the hydrogen. The oxygen acts as a chemical short circuit within the cell, enabling the sealed battery to be continuously overcharged without an excessive increase in internal pressure.

Nickel-cadmium batteries have a life of up to 20 years and require virtually no maintenance. They perform well in high-temperature applications (115° F continuous) and retain the ability to deliver high rates of discharge even at low temperatures, as shown in exhibit 4.13. Continuous operation at low drain rates is possible down to -40° C. They also may be left in either a charged or discharged state without damage. These batteries are available in sizes up to 5 kWh at prices ranging from \$270 to \$320/kWh for over 1 kWh. For energy capacities under 0.5 kWh the cost is \$450/kWh.

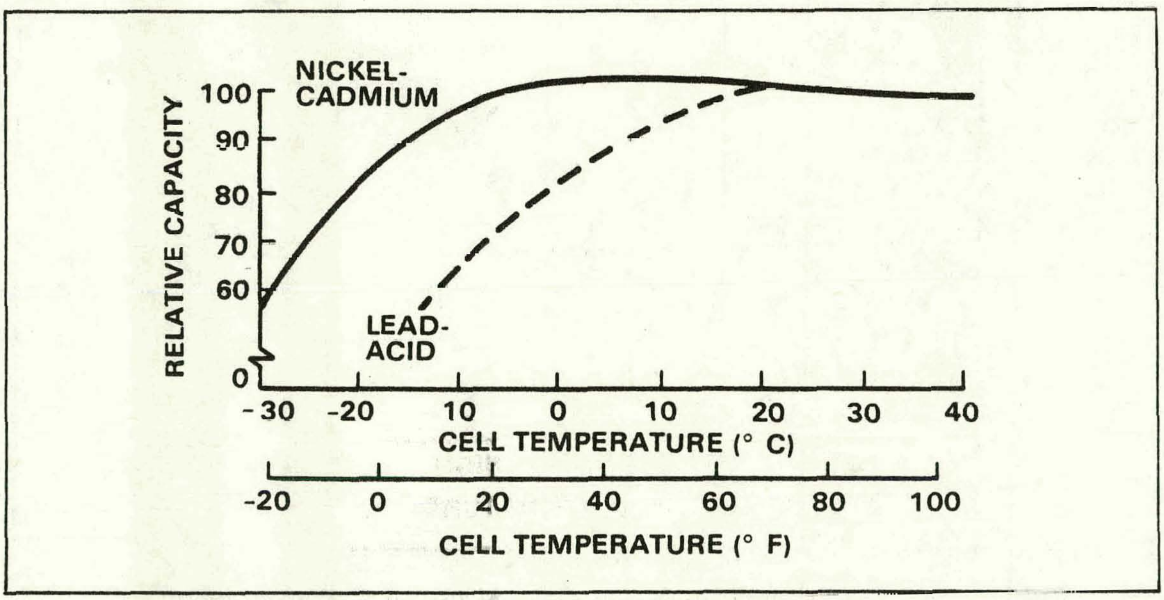


Exhibit 4.13 Available Capacity vs. Temperature of Batteries

4.7 FAILURE MECHANISMS

Failures generally result from either an internal short circuit or an excessive loss of electrolyte. Short circuits are generally created when two plates of opposite polarity, or their attached hardware, make physical contact. This results in the charging current passing through the partial short, forcing the cell voltage to zero almost immediately. The performance of nickel-cadmium batteries is not affected by small losses of electrolyte. However, moderate electrolyte loss will cause slight capacity degradation, which increases to almost complete loss of capacity when large amounts of electrolyte are lost.

Both internal shorts and excessive electrolyte loss are related primarily to time of usage and battery temperature during this period of time. Battery temperature is the most significant parameter in the life expectancy of the battery as high temperatures accelerate performance degradation by increasing self-discharge and reducing charge acceptance (input-output efficiency) as shown in exhibit 4.14. Prolonged exposure to high temperatures will also increase the decomposition of the separator material between the positive and negative electrodes, causing internal shorts. The performance of nickel-cadmium batteries at temperature extremes is superior to that of lead-acid batteries, making them the logical choice for high-temperature applications.

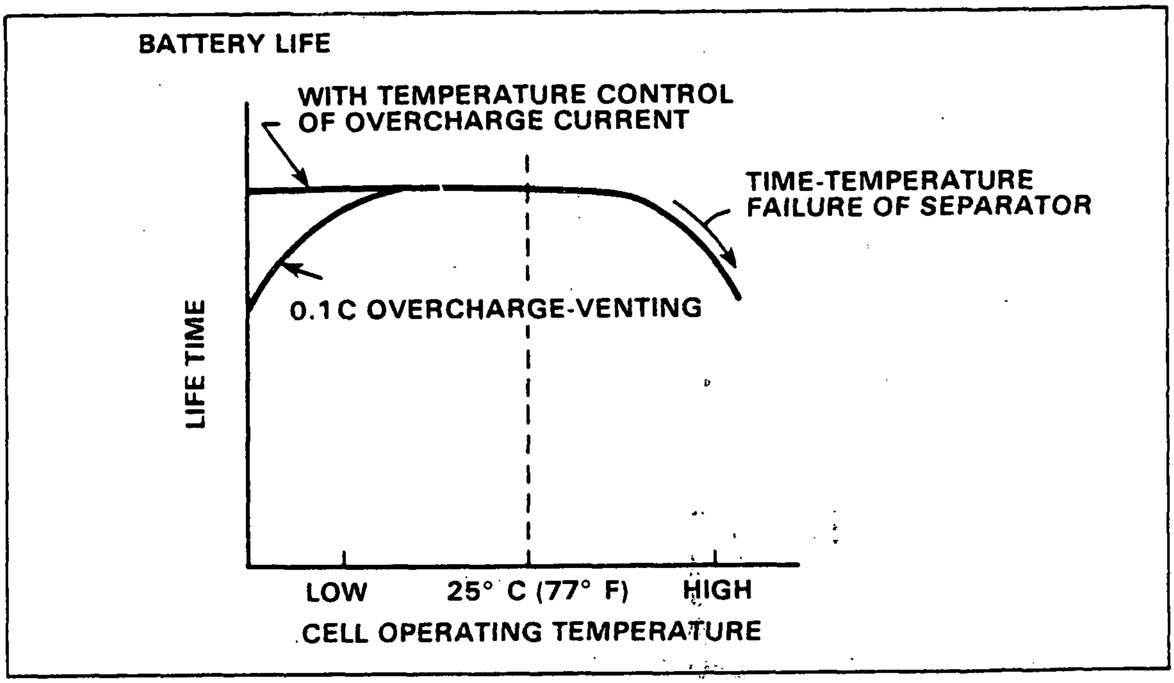


Exhibit 4.14 Life Expectance Relationship of Nickel-Cadmium Batteries vs. Operating Temperature.

Nickel-cadmium batteries which are subjected to a repetitive shallow depth of discharge tend to exhibit an apparent loss of capacity, commonly referred to as "memory loss." This problem can be mitigated by deep discharging of the battery and then recharging. The "memory" is thus erased and the original battery capacity restored. This memory problem is exhibited in sintered cell nickel-cadmium batteries but not in cells employing pocket plate construction.

Nickel-cadmium batteries can tolerate from 0.05 to 0.10 C overcharge for extended periods of time without damage or performance degradation (where C is the battery capacity in Ah). For example, a 220 Ah battery could be recharged with a constant current circuit (see exhibit 4.15) with a maximum charge current of 11 to 22 A. This slow charging rate has high reliability and low cost due to its simplicity, and will tend to minimize cell temperature rise and internal pressure during the recharge.

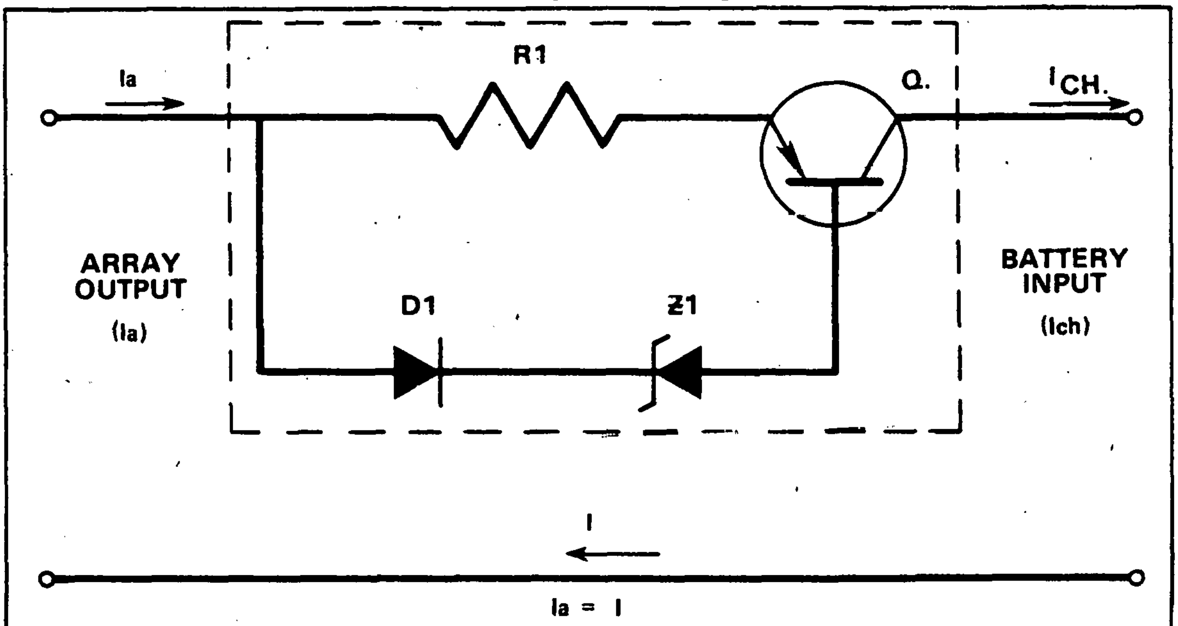


Exhibit 4.15 Constant Current Charging Circuit.

4.8 RECHARGING MULTIPLE BATTERY STRINGS

When recharging series-connected batteries to obtain higher system voltages, the possibility of slight differences in capacity between the individual cells exists. When a single voltage source is connected across the entire battery string, the same current will flow through all the cells. Due to differing characteristics of batteries, some may overcharge while others remain slightly undercharged. This results in both underutilizing the capacity of the batteries and prematurely aging them. To minimize these adverse effects, installations near hot spots (as temperature affects both cell voltage and capacity) and charging the batteries' string in more than 24 V battery groups (see exhibit 4.16) should be avoided.

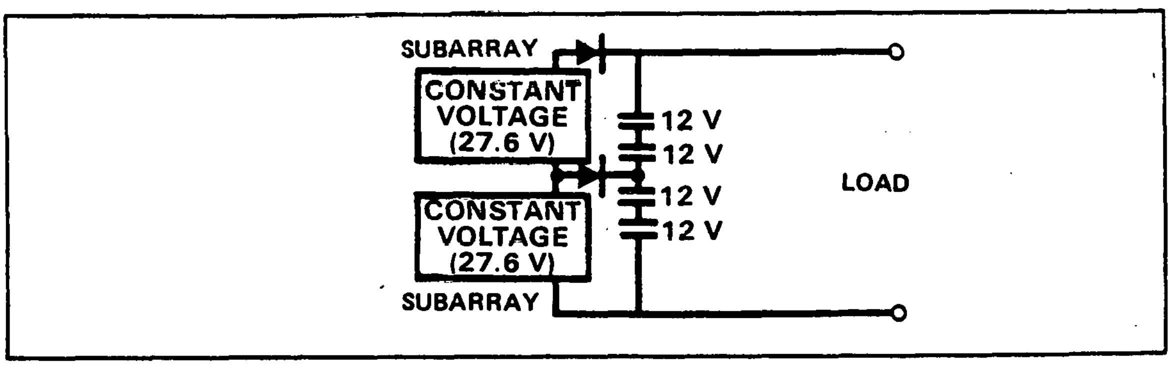


Exhibit 4.16 Charging High Voltage Battery System.

When connected in parallel, the current from the array will tend to divide equally between the batteries. If batteries of unequal capacity are being recharged, the current tends to divide between the batteries in the ratio of their capacities (due to internal resistance differences).

4.9 SAFETY PROBLEMS

Because batteries are hazardous devices and cannot be switched off, the potential hazard of DC electrical shock exists. A few of the considerations are as follows.

Shorting the output terminals by dropping a wrench across them can cause currents high enough to melt metal conductors and result in severe burns.

Lead-acid batteries also pose a hazard due to the acid electrolyte. Plastic squeeze-bottle eye-wash devices, sodium carbonate or similar neutralizing agents, and protective clothing (e.g., rubber gloves and aprons) should be kept on hand when servicing lead-acid batteries. Similarly, nickel-cadmium batteries contain a caustic base electrolyte. A mild acidic solution such as boric acid or vinegar should be kept handy as a neutralizing agent.

Battery storage systems generate hydrogen (which may explode) and other potentially dangerous gases such as stibine (SbH_3) or arsine (AH_3). A ventilation system and catalytic battery caps should be included in the housing design. Catalytic caps are currently available from various distributors for approximately $3.75 per cap.

There are existing standards which are more compulsory that ensure safety.

4.10 SUMMARY

Exhibits 4.17 and 4.18 provide a summary for the battery types that have been presented. Since system costs are directly related to the load requirements, current loss due to battery inefficiency and self-discharge can be very expensive. For this reason, the SLI lead-acid or motive-type batteries used in forklifts and golfcarts are generally unacceptable from the standpoint of cost and reliability.

Float-service, lead-acid batteries featuring lead-acid with calcium grid or pure lead grids are the most suited for general PV use. This is due to their very low self-discharge (typically 10 to 15 percent per year) and their high efficiency (80 percent electrical to chemical energy conversion). In extremely cold conditions, nickel-cadmium cells can offer advantages in increased capacity which may outweigh their higher costs. During electrical to chemical energy conversion, the batteries receive charge; and during chemical to electrical energy conversion, the batteries dissipate charge.

TYPE		rated $/kWh	rated Wh/lb	CHARACTERISTICS
SLI	AUTOMOTIVE	35-54	15-21	High self-discharge, short life under deep discharge conditions.
	DIESEL	50	16-18	
MOTIVE POWER	GOLF CART FORK LIFT	45-60	30-35	250 cycle life, high self-discharge.
	FORK LIFT LONG LIFE	160-220	7-11	1,000-2,000 cycle life, high self-discharge.
FLOAT SERVICE	LONG LIFE CALCIUM-GRID	200-240	7-10	1,500-2,000 cycle life, low self-discharge.
	PURE LEAD GRID	80-130	14-18	Low self-discharge, low maintenance.
SEALED FLOAT SERVICE		140	14-18	Very low maintenance, low self-discharge.
NICKEL-CADMIUM		270 up	10-15	Very low discharge, good low temperature performance, long life, "memory" problem.

Exhibit 4.17 Summary of Lead-Acid and Nickel-Cadmium Batteries.

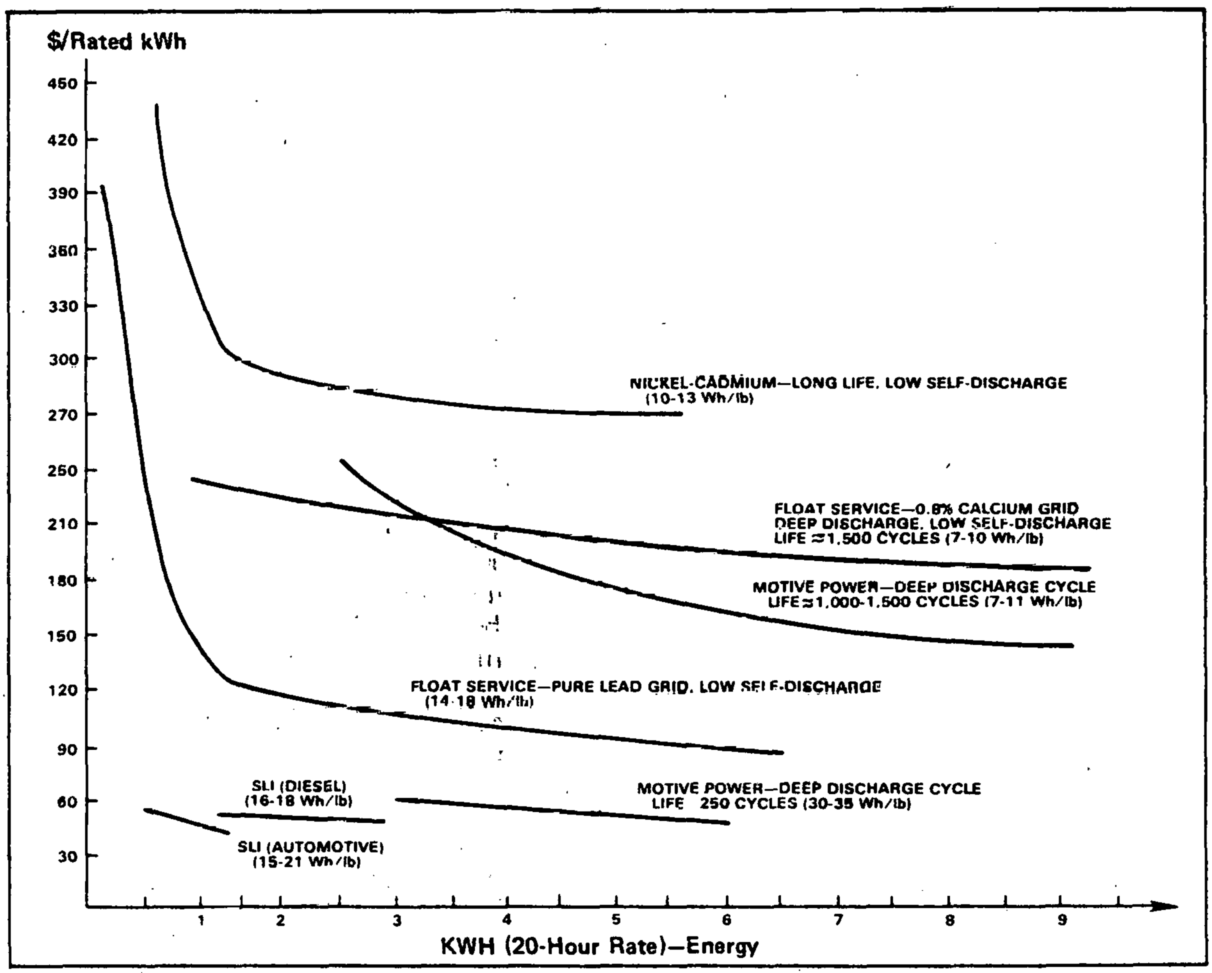


Exhibit 4.18 Comparative Battery Cost.

SECTION 5
POWER CONDITIONING

5.1 POWER CONDITIONING

The output from the solar array must match the requirements of both the load and the batteries. The power conditioning subsystem matches the load, batteries, array, and possible back-up energy by regulating the DC voltage and current input to the battery subsystem or converting the DC output of the array into AC at a specified voltage, if needed, or both. This section explains the basic operation of each type of power conditioning unit and its function within the electrical power system.

5.2 SELF-REGULATED PV POWER SYSTEMS

For the smaller, cost-effective power applications (normally under 2 kW_p capacity), the direct connection (through a blocking diode) of the array to the storage system and then to the load may prove to be the most cost-effective and require the least maintenance (refer to exhibit 5.1). Direct electrical connection of the array to the battery system without regulation is advisable only when the peak output current of the array is less than 5 percent of the charge capacity of the batteries (amp-hour rating) in the system (charge equals current x time).

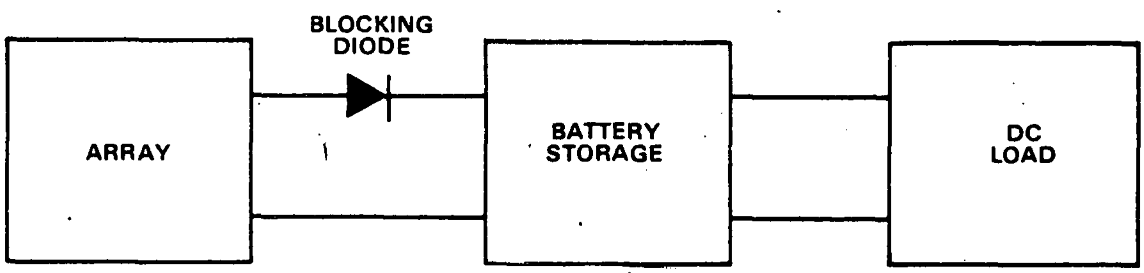


Exhibit 5.1 Self-Regulated PV System.

The operation of the system shown in exhibit 5.1 is as follows.

1. During periods of insolation, the batteries are charged by the power produced by the PV array at a voltage that causes current to flow from the array into the battery storage system while also supplying the load. When the voltage of the battery storage system equals that of the array (less the initial voltage drop across the blocking diode), current flow into the storage system would stop, with the batteries being at a full state of charge. (NOTE: A difference of potential is required for current to flow.) Voltage equals potential in an electrical energy system and the voltage drop (loss) across the blocking diode is basically current x diode resistance.

2. A battery storage system continually supplies load requirements. It should be recognized that this system design (see exhibit 5.1) places specific constraints on the selection of the PV array current and voltage operating conditions, resulting in the array operating at other than the maximum power point. These constraints

are centered around the charging voltage requirements of the battery storage system. The voltage range for a 12 V lead-acid battery under charge varies from 12.8 V (at 60 percent discharge) to 14.4 V (at full charge). To transfer the maximum power from the PV array to the storage system, the voltage-operating point for the array should be approximately 14.40 V plus 0.75 V (to account for the voltage drop across the diode) thus 15.15 V. The manufacturer's rated temperature of 27^{o} C would cause a different curve-displaced along the voltage axis, as shown in Exhibit 5.2. As shown in exhibit 5.2, for a slight increase in cell voltage above the nominal array operating voltage, cell current will decrease rapidly limiting the charging current. The I-V curve used corresponds to the array's characteristics at its nominal operating temperature.

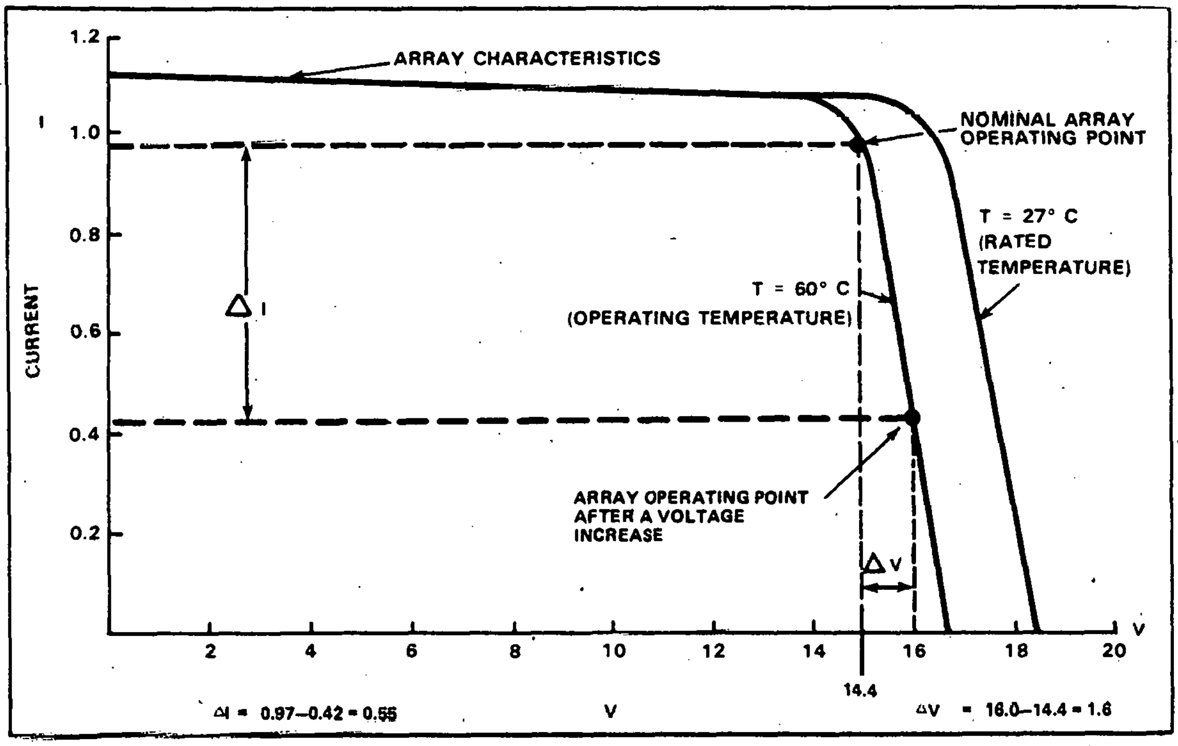


Exhibit 5.2 I-V Curve of PV Module Exhibiting Self-Regulation.

The possibility of battery gas production (and losses in electrolyte) are higher for a self-limiting system than for a system utilizing an active voltage regulator-battery charger. This is due to the variations in insolation causing instantaneous changes in array voltage and current, resulting in the possibility of overcharging the battery storage system. Setting the array operating point less than that required for maximum charging capability results in a larger and more costly battery storage system to meet the same load.

For the application of directly charging a battery storage system of 12 V, PV modules must be connected to produce approximately 15.15 V at the designed operating insolation and temperature. A self-regulated system usually operates away from the maximum power point, thereby wasting energy and array capability. Larger systems would use an active device to maintain maximum power utilization.

5.3 VOLTAGE REGULATED PV POWER SYSTEMS

Most PV systems utilize a voltage regulator, either in parallel or in series with the PV array, the storage system, and load (see exhibit 5.3). PV power systems are normally designed to recover quickly from worst-case load and weather conditions during their total useable life span. Under average weather conditions, this results in the arrays having excess power capability under normal load conditions, especially at the beginning of their lives. To regulate the voltage within required limits to prevent battery overcharge and outgassing, a voltage regulator must dissipate the excess available power.

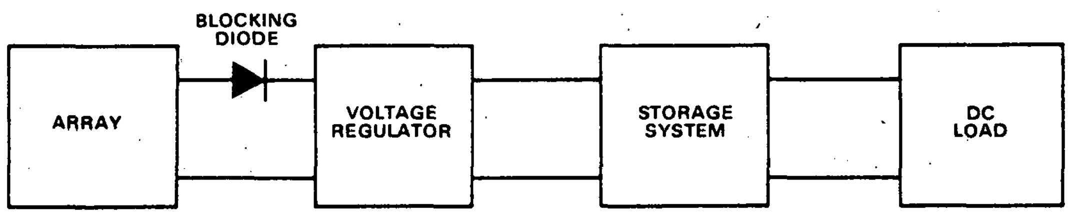


Exhibit 5.3 PV System Utilizing Voltage Regulator.

There are two types of voltage regulators available as off-the-shelf products. Series-type voltage regulators utilize a series transistor that electrically blocks the array when the battery reaches a full charge voltage and conducts when battery charging is required. A shunt-type regulator uses a transistor to shunt the excess current to the ground. Series regulators consume power at all times. Shunt regulators only dissipate that power not required by the storage system/load combinations. Exhibits 5.4 and 5.5 show simplified designs of series and shunt (parallel connected) regulators.

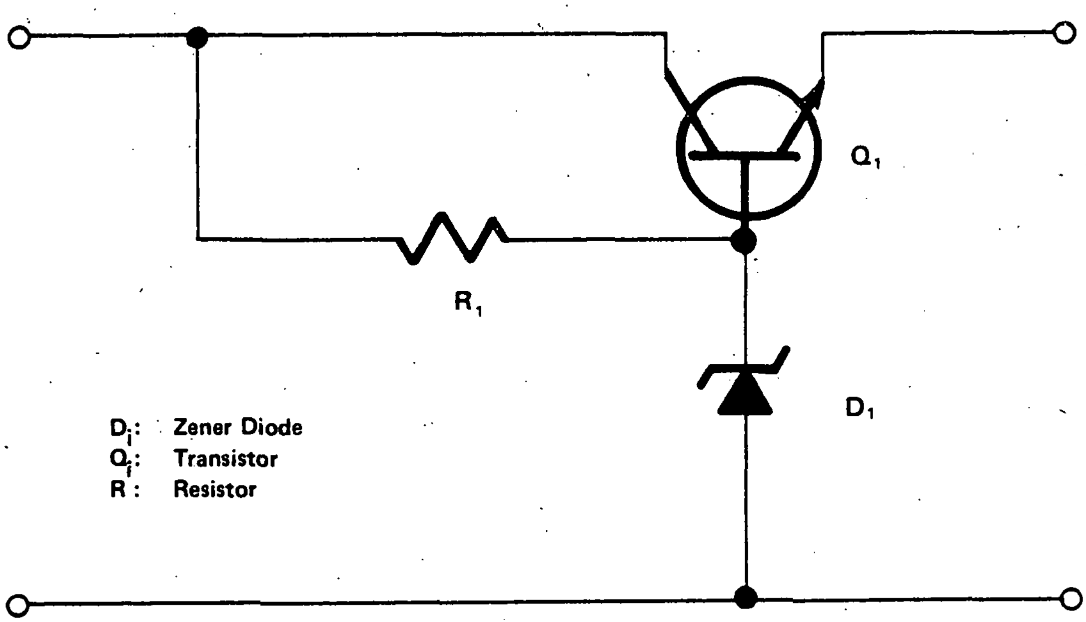


Exhibit 5.4 Series Regulator—Basic Design

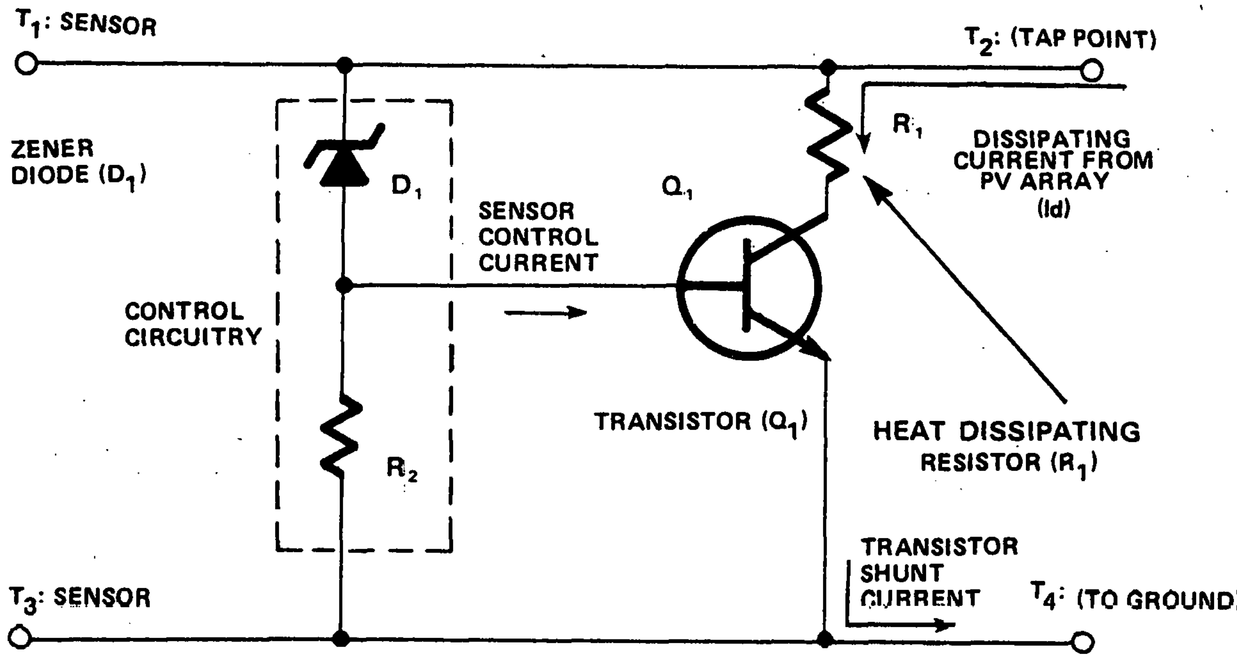


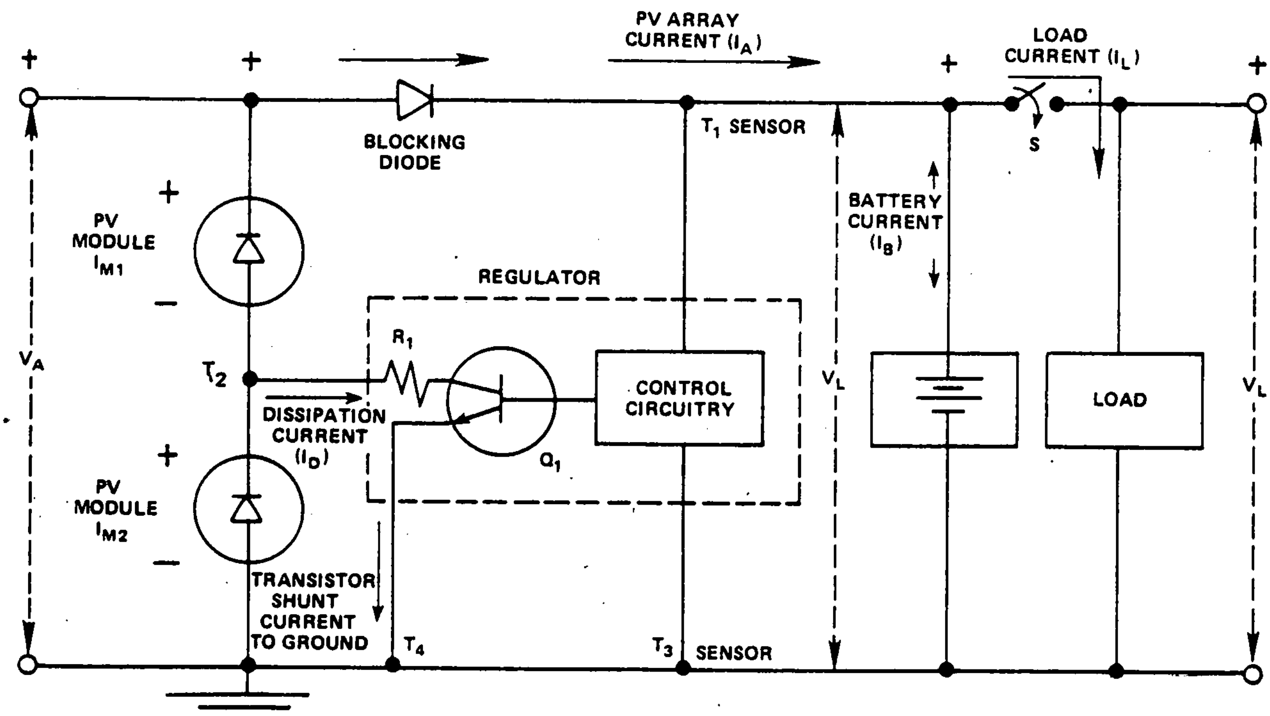
Exhibit 5.5 Shunt Regulation—Simple Design.

Series regulators operate by applying a set voltage to the transistor base, keeping the transistor output at a constant voltage over a large variation in current. All the load current passes through the regulator transistor in a series regulator design. This results in approximately a 1.2 V drop across the regulator transistor output, and a consequent loss in power (e.g., with a 10 A current, P loss = 10 A x 1.2 V drop = 12 W loss), where power equals I x V.

Exhibit 5.5 shows a simplified design of a shunt regulator. This type of regulator dissipates the excess power to ground. When the load utilizes all of the PV produced power, the shunt regulator consumes no power. Based on the output voltage, the regulator "shunts" current through a regulating transistor to keep the output voltage constant.

An alternative to using a full-shunt regulator is the partial-shunt regulator. Smaller heat dissipating elements and heat sinks are required, so the weight, heat management, and cost problems associated with these dissipating elements and accompanying power transistors are minimized. The partial-shunt regulator, which is connected across part of the array, shunts part of the array output at no load conditions; and is fully turned off at full-load, maximum operating temperature, and at the end of the designated life of the system. This type of shunt regulator dissipates less than one-half of the power dissipated in a full-shunt regulator (see exhibit 5.6).

For larger power systems (over several hundred watts), several linear-partial-shunt regulators can be employed, each of which regulates a separate portion of the array (see exhibit 5.7). In this system, the regulators would be operated linearly between saturation and cutoff, one at a time in a voltage-dependent sequence. At full load all the shunt regulators are off. At no load all regulators are in saturation, except one which is either in saturation or in its linear operating region, depending upon the array temperature. Typical costs for regulators are in the range of \$1/W. Linear operation refers to the output voltage function, cutoff refers to zero current, and saturation refers to maximum current.



$I_L = I_A + I_B$ AND V_L = REQUIRED SYSTEM VOLTAGE

$I_A = I_{M1} = I_{M2} - I_D$ AND V_A = ARRAY VOLTAGE

T_1 AND T_3 SENSE V_L AND I_A. I_D IS CONTROLLED SO THAT

$V_L = V_L$ (V_L IS DEPENDENT ON I_A WHICH IS DEPENDENT ON I_D)

Exhibit 5.6 Partial Shunt Regulation (T_2 on Im)

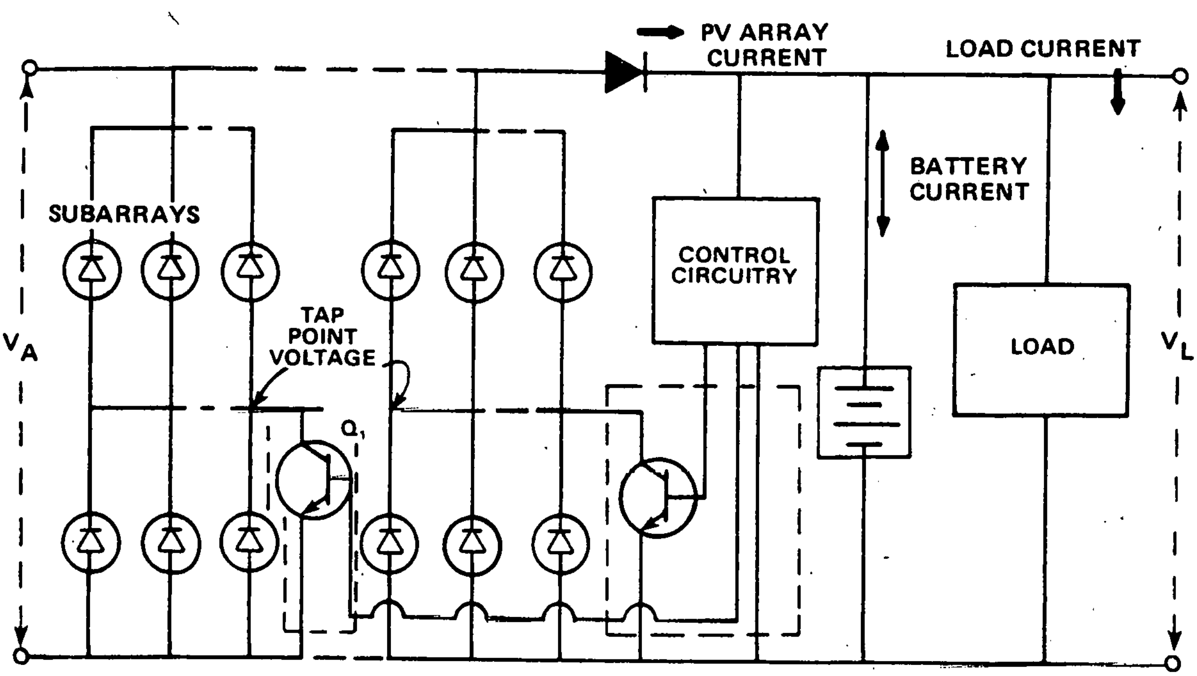


Exhibit 5.7 Partial Shunt Regulators for Multiple Subarrays.

5.4 SWITCHING REGULATORS

Switching regulators are complex, classical electronic devices (see exhibit 5.8) and have a distinct advantage over series or shunt regulators: low power dissipation in the main control device (especially at high power levels). The amount of current dissipated from the array is accomplished by electronic switching, feedback, and control. The transistor is the main element. Diodes, capacitors, inductors, and resistors are also employed, and series-parallel connections are used. The series part is either saturated or off, and has a low forward voltage drop to neutral when conducting load current and only leakage current flowing when it is not conducting. Power dissipation is small, resulting in high throughput efficiencies. To avoid stability problems, switching regulators must be employed in conjunction with a peak power tracker. They are not used in low power applications. Also, they are not currently available as off-the-shelf items. Series-parallel and delta-star connections are used.

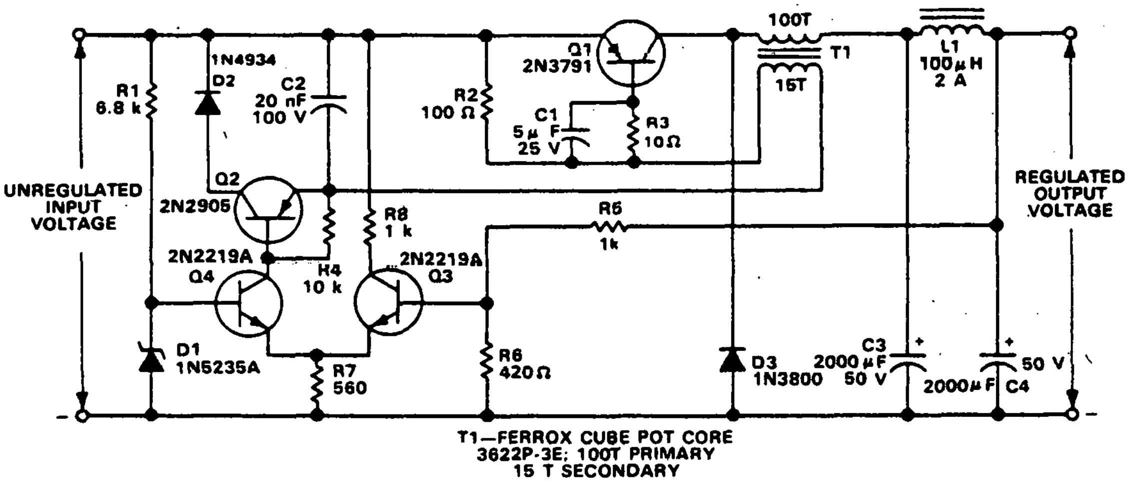


Exhibit 5.8 Electronic Switching Regulator

5.5 INVERTERS

An inverter changes DC voltage into AC voltage (see exhibit 5.9). Motor-generator sets, as well as other rotating equipment, have been used as inverters. Due to the maintenance problems associated with mechanical devices, only static, solid-state (electronic) inverters are considered here.

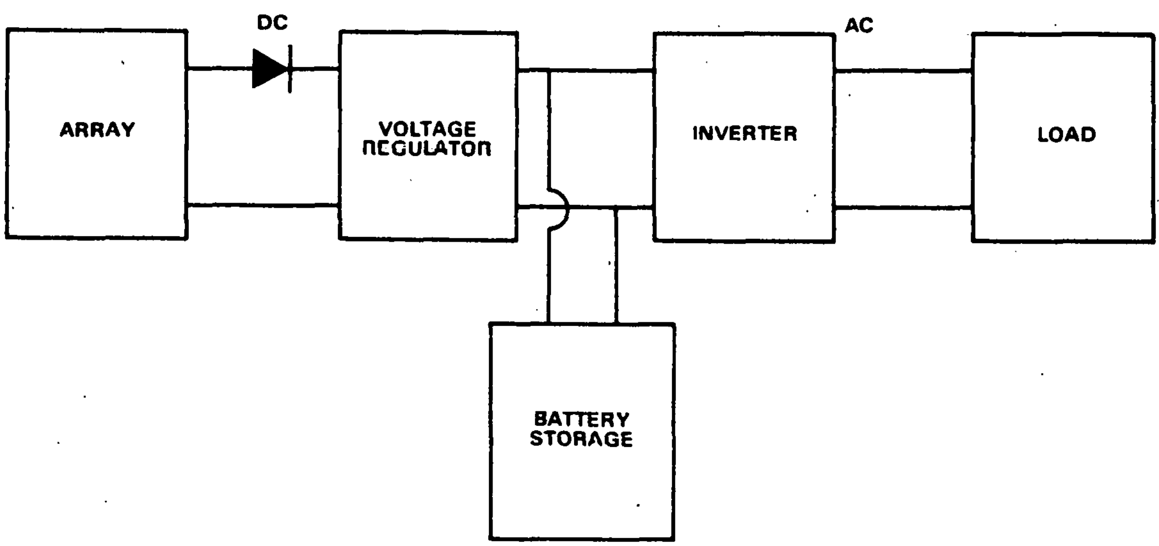


Exhibit 5.9 Regulated System Providing AC Output.

5.5.1 SOLID STATE INVERTERS

Power handling capability and efficiency make electronic switching-type inverters the most commonly used in power conditioning. The main circuit elements are alternately switched electronically between their on and off states. A simplified, single-phase bridge configuration is shown in exhibit 5.10. Electronic switching causes an alternating current, which is roughly equivalent to the pure sine wave of an alternator.

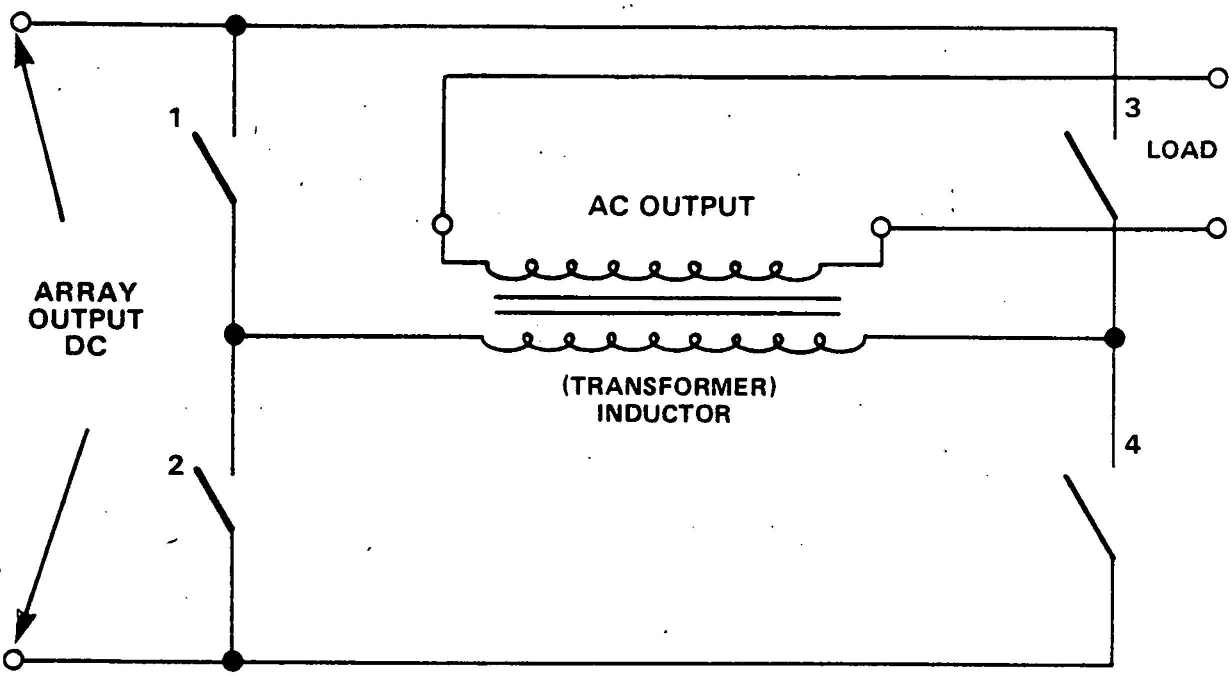


Exhibit 5.10 Conceptual Inverter Design.

Conceptually, switches 1 and 4 are initially closed while switches 2 and 3 are open. This causes a direct current to flow through the transformer winding. After 8.3 miliseconds (for 60 Hz AC operation), switches 1 and 4 are opened and 2 and 3 are closed, causing current to reverse direction in the transformer winding. This cycle is then repeated at the desired frequency to produce the AC output. In actual inverters, the switches are replaced by transistors or static controlled rectifiers. Rectifiers convert AC voltage to DC voltage.

Most low power inverters (less than 1 kW) utilize transistors as active electronic switching elements (see exhibit 5.11). Transistors are quiet, reliable, exhibit a low forward voltage drop to the base, and negligible leakage currents. Unfortunately, they require a relatively high control power. This effect can be mitigated by utilizing Darlington transistor configurations, although these devices are generally rated for lower power applications and are also more expensive. Typical efficiencies of commercially available DC to AC inverters range from 65 to 75 percent for 50 W units, costing $80 to $140, with less than 3 percent output harmonic distortion. A harmonic is an AC voltage whose frequency is some integral multiple of a fundamental frequency.

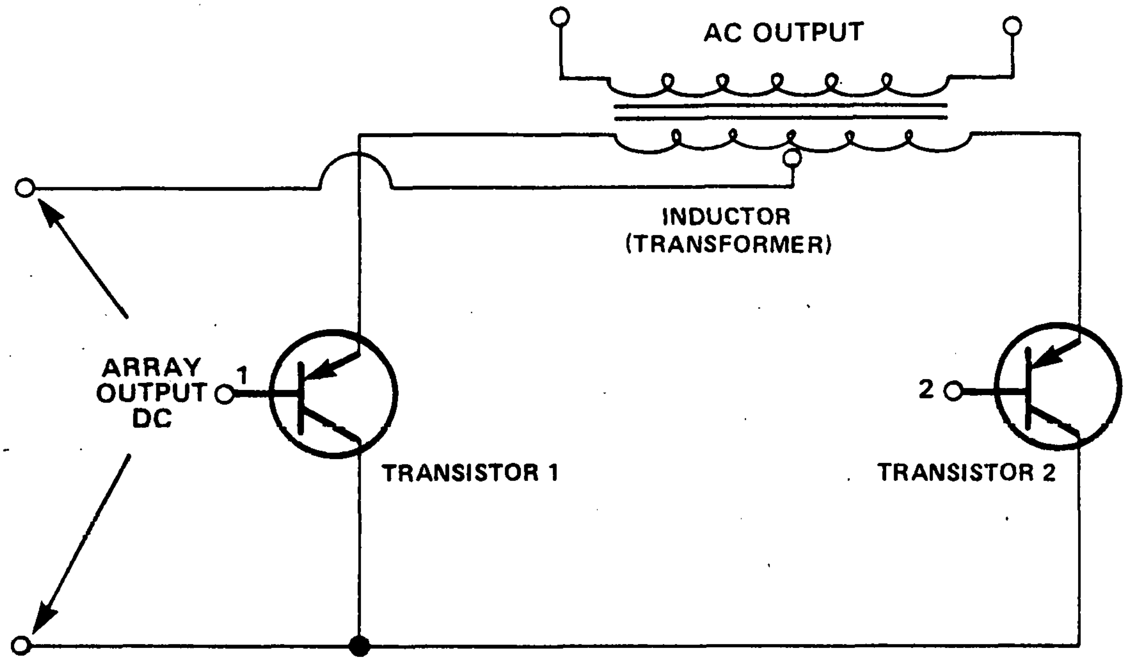


Exhibit 5.11 Actual Transistor Switching Inverter

Higher power inverters (greater than 1 kW) generally use static controlled rectifiers (SCR's) as the electronic switching elements. Very little control current, as compared with transistor circuits, is needed to switch the SCR into its "on" state. Unlike transistors, the current through the SCR must go to zero before the device can be turned off. The resulting AC voltage is not exactly equivalent to the transistor circuit AC voltage.

Inverter circuits can be divided into the two broad categories of line or self-commutated. (Commutation is the switching of current flow from one branch of a circuit to another.) Line-commutated inverters rely on control voltage from a fixed AC voltage bus to provide the electricity, (e.g., to turn off SCR's). This type of circuit is usually used in conjunction with utility line applications. Self-commutated inverters, however, rely on an internal control circuit to electronically switch the active elements on and off. Because transistors can be biased off by an external voltage, transistorized inverters are inherently self-commutating. SCR inverters can be designed for self-commutated service by the addition of internal circuits across the SCR bridge legs. Since output power is reduced, these circuits lead to higher costs, and lower efficiency. A summary of the utility of SCR and transistor inverter characteristics is tabled in exhibit 5.12.

SCR	TRANSISTOR
• USUALLY LINE-COMMUTATED	• SELF-COMMUTATED
• HIGH POWER, 1 kW	• LOW POWER, 1 kW
• HIGHER EFFICIENCY	

Exhibit 5.12 The Utility of SCR and Transistor Inverters

Because high efficiency inverters using electronic switching techniques are constant power devices, they exhibit a negative slope for input impedance. The equation V x I = P is a hyperbola for constant P, thus the negative slope. PV devices have a fairly sharp knee where the transition between being a voltage source and current source occurs. The peak power point from the source is found somewhere on this knee, and an optimized system should locate and track this peak point. This can be done either by analog tracking or digital tracking, or in combination. Analog refers to the manipulation of voltages and mechanical quantities by the slide-rule concept, whereas digital refers to the use of arithmetic.

Because PV systems cannot store energy and switching inverters (choppers) draw their current in short pulses, there must be a smoothing filter between the inverter and source. By using as data the modulation of the input current due to chopping, both the current and change in current can be measured. The voltage on the array multiplied by these factors determines both actual power and rate of change of power. By a basic arithmetic circuit, the operating power point can be found and tracked. Modulation is a variation in the amplitude, frequency, or phase of a wave in accordance with some signal.

If a hall effect generator were placed in the gap of a simple choke input filter, the hall generator's output would be proportional to current. The chopping or switching frequency itself would serve to modulate the current sufficiently to detect the operating point (see exhibit 5.13).

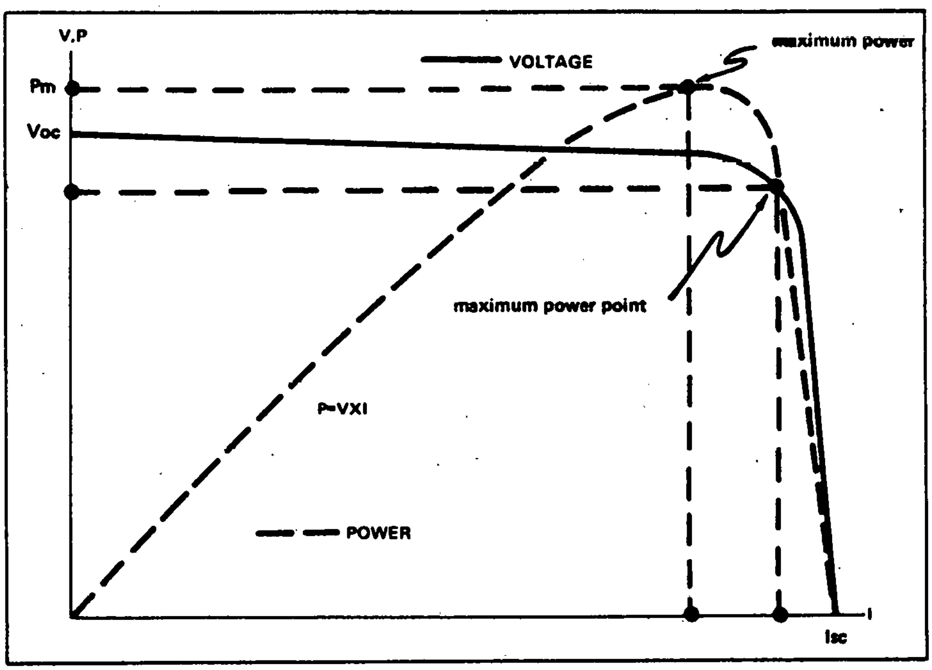


Exhibit 5.13 Peak Power Tracking.

Comparing the sign of the current modulation to the power determines at which side of the peak point the system is operating. If the current and power are increasing, operation is behind the peak. If current is increasing and power decreasing, it is operating beyond the peak. This information is fed back to the inverter to control the pulse width to either increase or decrease the current demand on the array. The pulse width is signal duration.

5.5.2 INVERTER TECHNOLOGY

In initial discussions of inverter technology, system constraints will not be considered; only methods will be considered. Inverter technology is extremely wide ranging and varied. The various techniques can be grouped, by implementation, into some basic classifications.

The simplest inverter technique, a power amplifier, is not widespread because of its low efficiency. Power amplifiers employ a hi-fi amplifier controlled by an oscillator, with voltage regulating feedback. Oscillators produce AC voltage of various frequencies. Hi-fi refers to an almost exact reproduction achieved by low distortion, and a wide range of reproduced frequencies.

Switching inverters, however, generally fall into the two basic classes of current generators and voltage generators. Each of these can be further divided into sub-classes by the techniques used.

Current generators usually feed pulses of current into a resonant electronic tank, which then oscillates electronically at its self-resonant frequency in a decaying sine wave. Control is achieved by varying the amount of electricity fed into the electronic tank so that, when the desired output voltage is present, the electric energy input is equal to the losses plus the electric load taken from the tank. When a power factor is included in the load, the electronic tank is detuned, changing the frequency of electrical oscillation. However, if the current pulses are synchronized to an external electronic clock, the tank is driven off electrical resonance, and the output electrical frequency is determined by the clock rather than the tuned circuit. Resonance in an electrical circuit occurs at an AC voltage input frequency which causes zero reactance. Reactance is the inductive-capacitive component of impedance. Power factor indicates the percent of resistive component.

Current can be fed into the tank at either a constant value and varying time (duty cycle), or at a constant duty cycle, with the magnitude of current varied. Usually, both duty cycle and current magnitude are varied in practical circuits, but they have a predictable interdependence. The effective value of an AC voltage is a function of amplitude and duty cycle.

Voltage generators, however, supply a voltage which is related to the source. In these devices, it is usual to have several voltages generated at differing time relationships to obtain the desired output. If two voltages are in phase and have amplitude of 1, the sum is 2. If they are 180° out of phase, their sum is zero; all intermediate conditions can be found by vector addition. The phase angle indicates the electrical waveform time displacement for starting time. Classical AC voltage analysis and synthesis is involved.

Synthesizing a waveform involves the sum of the outputs of many low-powered inverters. By implementation, certain fixed-phase relationships can be achieved that reduce the content of lower harmonics to levels requiring little or no filtering. Summation can be done magnetically with transformers or electrically from separate transformers. Transformers increase amplitude in this case by electromagnetic induction due to an AC voltage.

There are also techniques that require little or no output with a transformer operating at the output frequency. These generally can be considered as "carrier" systems. They are sometimes lumped into the synthesized waveform class, but they are different. A carrier is generated at a higher frequency (10 to 20 or more times the desired output frequency), and then modulated at the desired output frequency. Either FM or AM is used. With AM, there is a fundamental problem in that, theoretically, only 50 percent is in the sidebands. By several simple techniques, the AM can be converted to single sideband, suppressed carrier, so that all the power is in the sideband. Cyclo-converters fall within this carrier technology along with other circuits that obtain the same results by other techniques. FM refers to frequency modulation and AM refers to amplitude modulation.

The Ferroresonant inverter is the most popular lower priced system used today for sinewave outputs. These inverters should be considered as special cases of either voltage or current generators, with a different filter than the usual lumped, constant types.

Filtering of waveforms serves the purpose of separating the fundamental from the switched waveform harmonics in a nonloss manner. In concept, they are quite simple, but in practice they add considerable difficulty insofar as phase shift, dynamic response, and control stability are concerned.

5.6 INVERTER OUTPUT FILTERS

In most inverters, a square-wave voltage is produced at some point in the circuit because of the sudden switching action that occurs during the inversion process. Electricity travels as a wave at the speed of light. Changes often appear to occur instantaneously. For simple transistor or SCR-switch inverters, a square-wave voltage is outputed to the load. Square waves contain considerable harmonic content that will cause excessive heating in AC motor loads, resulting in increased motor losses without improving the torque output. Most inverters contain internal filters or resonant circuits that enable them to produce an output voltage that closely approaches a sine wave. Typically, total sinewave output harmonic distortion is less than 3 percent, which is comparable to utility standards.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

SECTION 6
ELECTRIC POWER LOAD ANALYSIS AND SYNTHESIS

6.1 INTRODUCTION

To prevent oversizing the solar PV power system (which is a stand-alone system) and unnecessarily increasing the cost, energy demand must be estimated as accurately as possible. As indicated in exhibit 6.1, the purpose of this section is to enable participants to estimate loads correctly, to reduce unnecessary loads, to determine whether the loads are best met by AC or DC voltage, and to anticipate potential problems that may occur when conventional loads are combined with the unconventional characteristics of the PV system. The load analysis also influences the selection and sizing of back-up systems in the areas of quantity and quality, including reliability and the need to maintain frequency stability for AC loads and possible utility grid-connected applications. All loads, generation, transmission, and distribution are analyzed and synthesized.

PURPOSES: To enable attendees to:
1. Estimate loads Reduce loads Define AC/DC needs
2. Anticipate problems of load/power-supply interactions
3. Analyze and synthesize all loads, generation, transmission, and distribution

Exhibit 6.1 Load Analysis.

6.2 ESTIMATING THE LOAD DEMAND

The first aspect of the load analysis is defining individual energy requirements. These are used to determine the total electric load demand profile. Exhibit 6.2 lists typical electric equipment for remote applications (e.g., fire water towers). The power requirement represents the maximum demand at any one time. Because some of the equipment is operated on a cyclic basis (including the refrigerator), the average demand (the energy demand) is considerably less than would be obtained by multiplying these rated demands by 24 hr/day, since energy equals average power x time. Exhibit 6.3 illustrates typical electrical energy requirements, based on the indicated duty cycle--the minutes per day the apparatus is drawing current. The 1.607 kWh per day energy requirement is only four percent of the 40 kWh per day that would be estimated if the peak demands were assumed to prevail for 24 hours, continuously. The size of the PV array and the cost would be approximately 4 percent of what might have otherwise been estimated. Energy per day (kWh/day) can be translated into average power (kW/day) by dividing by the duty cycle hours.

EQUIPMENT (12V DC)	MAXIMUM POWER REQUIREMENT (W)
A) Radio Communication (Transmit) (Standby)	25 1.08
B) Lighting (Fluorescent)	60
C) Water Pumping (5 gal/min, 50 gal/day)	12
D) Refrigerator (25% Duty Cycle)	60
E) Microwave Oven	1,450
F) TV	50

Exhibit 6.2 Estimating the Load.

ITEM \ LOAD	MAX. POWER	DUTY CYCLE		ENERGY/DAY
	LOAD (W)	min/hr	hr/day	Wh/day
A. Radio (Transmit)	25.00	10	8	33.33
(Standby)	1.08	50	8	7.20
(Standby)	1.08	60	16	17.28
B. Lighting	60.00	60	8	480.00
C. Water Pump	12.00	10	1	2.00
D. Refrigerator	60.00	15	24	360.00
E. Microwave	1,450.00	7	3	570.50
F. TV	50.00	60	4	200.00
TOTAL	1659.16	M	H	1607.31 Wh/day
Total Demand Daily, KwH =				1.607 kWh/day

Watt-hours per day = W x M x H x 1hr/60min
1 kWh = 1000 WH

Exhibit 6.3 Allowance for Duty Cycle.

CATHODIC PENETRATION		
Load Requirement, I & V	=	7 amps at 6V DC
Power Required, Watts,	=	42 Watts = I x V = 7 x 6
Energy Required/Day, WH,	=	7 x 6 x 24 = 1,008 wH/day
NAVIGATION LIGHTS, BELLS, AND HORNS		
Load Requirement	=	4 Amps at 24 V DC
Duty Cycle	=	10%
Power Required When On	=	96 Watts
Energy Required/Day	=	96 x 0.1 x 24 = 230 wH/day

Exhibit 6.4 Other Remote Applications.

Exhibit 6.4 lists the energy requirements associated with cathodic protection systems and navigational aids. Exhibit 6.5 shows typical energy requirements for pumping applications, including toilet flushers and domestic water supplies with two different flow/lift combinations. Battery storage sizing is heavily dependent on energy demand and duty cycle as well as peak power demand.,

TOILET FLUSHER

CATEGORY	UNIT	VALUE
1. Load Cycle 2. Load (I and V)	Amp, Volt	800 flushes/day, 55 sec/flush 7A, 24V DC pump motors
3. Power Required	W	7 × 24 = 168 W (I x V)
4. Energy Required/Flush	WH	$168 \times 55 \times \frac{1\ \text{hr}}{3600} = 2.567$ Wh
5. Energy Required/Day	WH	800 × 2.567 = 2053 Wh/day

WATER PUMPING

CATEGORY	UNIT	PUMP 1	PUMP 2
1. Flow Rate 2. Head	Gal/day Ft.	2,300 130	200 1,500
3. Pump Model No. 4. Manufacturer		ALTA-X 600 Pompes Guinard	50 W Jenson
5. Power Required (24 V) 6. Duty cycle	HP Hr/day	 5	¾ 5
7. Efficiency	%		75
8. Load requirement (a) (Line 5 ÷ Line 7)	W	600	746
9. Energy Requirement (Line 6 x Line 8) (b)	WH	3,000 Wh	3,730 Wh

a. Conversion Factor: 1 HP = 0.746 watts at 100% efficiency.
b. One watt-hour equals 3.3 Btu at 100% efficiency.

Exhibit 6.5 Pumping Applications

These computations for typical devices, as depicted in exhibits 6.2 to 6.5, can also be used as a guide in computing the energy demands for other applications. The peak demand must be known and the duty cycle estimated. Data obtained in the field indicate that some of the nameplate ratings of components can be substantially overstated. Although the overstatement is not important for conventional energy sources, the impact on the cost is enormous for PV systems sized to meet the nameplate ratings. The energy consumption of some equipment is only 40 percent of what the nameplate would imply, even at peak power. It is possible that the PV system will be seriously oversized, to the point of being noncost-effective, if nameplate readings are used directly. For marginal applications, measurement of the power input is advisable.

6.3 LOAD-REDUCTION STRATEGIES

When the energy demand of a potential PV system application is analyzed, methods for reducing system requirements are frequently discovered. Exhibit 6.6 lists the most frequent methods of reduction. First, components of the load profile can be operated cyclically. When the transmitter is operating at peak demand, the refrigerator can be shut off. This reduces the system peak power demand and, consequently, the sizes of the equipment and lines. The smaller sizes will result in higher system efficiency during off-peak operation and lower energy consumption. The cyclic operation of the components can be either manual or automatic, although the automatic system will be more costly and will introduce another power-consuming component into the system. The automatic systems will be cost-effective only if the existing peak power under simultaneous component operation is significantly greater than peak power under cyclic operation. At a ratio of approximately 3:1 (simultaneous to cyclic), the cyclic operation should be examined. If more than 1 kW is drawn, the cyclic operation should be examined, and the automatic system should be contemplated. (NOTE: The 3:1 and 1 kW figures are today's best estimates based upon anticipated past-load efficiencies. Both figures will decrease as the price of the automatic system is reduced.)

CYCLIC OPERATION OF COMPONENTS	
Diversity Load Shedding	Manual Automatic
Eliminate DC-to-AC Inversion	

Exhibit 6.6 Load Reduction Strategies.

Some of the losses that result from operating power-conversion equipment at less than maximum power can be circumvented if a separate power-conversion device is used for each load. For the most part, whenever the load is demanding power, the power converter will pass its rated capacity. In addition, if AC is needed for part of the load and DC for another part, the individual converters would be designed for the respective duties. This scheme's realized energy savings must be compared to the added cost of using individual power converters instead of one central converter. Because their power requirement is small, the individual converters can be simply made; thus, they may be no more expensive than the central unit.

Cyclic operation of a large number of components permits the undersizing of equipment on the basis of load diversity. When several components draw power from the system, it is unlikely all will draw current simultaneously. The power utilities make constant use of the low odds associated with their enormous systems. For example, suppose there are four components on the line drawing powers of 10, 20, 30, and 50 kW peak randomly with duty cycles of 50, 40, 30 and 20 percent, respectively. The probability that all four loads will operate simultaneously is 1.2 percent, as shown in exhibit 6.7. The system should be designed for the peak demand rather than cyclic operation under these circumstances, because the probability of overload is too great. (The 1.2 percent figure can be translated into 0.012 times 365 days, or four days/yr.) The total electric load demand profile is stochastic.

LOAD	ON-TIME
10 W	50%
20 W	40%
30 W	30%
40 W	20%
Probability of simultaneous operation = 0.5 × 0.4 × 0.3 × 0.2 = 0.012 = 1.2%	

PROBABILITY OF OTHER COMBINATIONS		
W	**Probability Calculation**	**Value**
10	0.5 × (1 - 0.4) × (1 - 0.3) × (1 - 0.2)	= 0.168
20	0.4 × (1 - 0.5) × (1 - 0.3) × (1 - 0.2)	= 0.112
30	0.3 × (1 - 0.5) × (1 - 0.4) × (1 - 0.2) + 0.5 × 0.4 × (1 - 0.3) × (1 - 0.2)	= 0.184
40	0.5 × 0.3 × (1 - 0.4) × (1 - 0.2) + 0.2 × (1.05) × (1 - 0.4) × (1 - 0.3)	= 0.114
50	0.3 × 0.4 × (1 - 0.5) × (1 - 0.2) + 0.5 × 0.2 × (1 - 0.4) × (1 - 0.3)	= 0.09
60	0.5 × 0.4 × 0.3 × (1 - 0.2) + 0.2 × 0.4 × (1 - 0.5) × (1 - 0.3)	= 0.076
70	0.2 × 0.3 × (1 - 0.5) × (1 - 0.4) + 0.2 × 0.4 × 0.5 × (1 - 0.3)	= 0.046
80	0.2 × 0.3 × 0.5 × (1 - 0.4)	= 0.018
90	0.2 × 0.3 × 0.4 × (1 - 0.5)	= 0.012

Exhibit 6.7 Load Diversity.

The probability of having loads ranging from 10 to 90 W is also indicated in exhibit 6.7. The probability of any one combination of loads can be computed in keeping with the following example: the probability that the load would be 20 W is equal to the product of the probability that the 20 W load is on and the probabilities that the three other loads are off, or 11.2 percent, according to the data in the exhibit.

The foregoing discussion brings us to the logical concept of load shedding. If the probability of simultaneous operation is low, or if the same functions are not critical, the peak demand can be limited by a controller that senses the demand and supplies power to the low-priority components only when the demand on the power system is low. Load shedding involves the automatic tripping of load center circuit breakers, usually in distribution switchboards, by use of relays triggered by sensors. Load shed tripping can also be initiated manually by remote control. The first loads shed are non-vital, then semi-vital, and finally the generators are tripped from the system. Closing is accomplished manually.

Reducing the peak load has such an indirect effect on the reduction in energy demand that it is difficult to estimate the energy impact without a computer that tracks system performance on a minute-by-minute basis. Even the simplest analysis can incorporate the energy-saving concept of eliminating DC-to-AC inversion. If the loads would conventionally require AC, there is always the option of replacing the AC components with a DC counterpart. Examples are: AC motors can be replaced by DC motors; other components that are normally supplied by AC but actually use DC, such as radio transmitters and receivers, can use the solar-produced DC directly. If DC is supplied directly, the losses associated with the DC-to-AC inversion (from the array/battery system to the load) can be eliminated, as well as the losses associated with the AC-to-DC conversion in the equipment itself. The overall reduction in energy demand can be as much as 40 percent. However, the tradeoffs between AC and DC must be examined in greater detail for each application, as is discussed in the next section. Modifying or manufacturing DC equipment that normally rectifies or transforms AC electricity prior to equipment use for DC electricity can be accomplished easily on a technological basis.

6.4 DC VERSUS AC POWER

An analysis was undertaken by a DOE contractor to assess the merits of directly supplying certain loads with the DC power available from the solar array/battery power sources rather than inverting the power to AC with losses resulting from inverter inefficiency. In making the assessment, the question of regulation was also considered. Although the inversion of DC to AC carries with it a nominal penalty of 12 percent inefficiency, relatively good output AC regulation can be achieved with the inverter within nominal limits of ± 5 percent. Regulating DC from an unregulated DC source (of which the array/battery combination is typical with a voltage range of 30 percent) also involves an inefficiency penalty of about 12 percent. Thus, power economy benefits would result only when unregulated DC is used. In section 6.4.1, typical loads are assessed as to their general operability with DC. Exhibit 6.8 presents the disadvantages of both AC and DC power. Transformers, whose purpose is to reduce or increase voltage for an isolated system or load, or just isolate a load or system, and motors rely on induction by electromagnetic fields. This induction can take place only with alternating current (AC) or modified direct current (DC).

WAVEFORM / INTERACTION	BUS	
	DC	AC
Motor Drive	Brushes wear	
Universal/Induction	More expensive	
Lights	Fluorescents less efficient Loss of incandescent and fluorescent reliability	
Electronics	Requires regulation	Requires regulation/rectification
PV Output		Requires inverter
Battery		Requires rectification
Controls	Contact wear	Requires rectification
Multiple Voltages	Not easily accommodated	

Exhibit 6.8 Disadvantages of DC and AC.

6.4.1 CLASSIFICATION OF LOADS

Electric loads can be classified by their type of electrical energy transformation. The four categories useful for PV system considerations are resistance elements, universal motors, induction motors, and induction-coupled loads (transformers).

The resistance elements include simple heat producers such as electric range elements and incandescent elements such as light bulbs. The universal motor is found in a great number of the portable appliances where the compact size and low cost are of primary concern. The universal motor can operate on DC or AC power. Where the low brush life or variable speed of the universal motor is objectionable, the induction motor is used. In long-life, low-maintenance applications, such as refrigerators and washers, the simple squirrel cage wound motor is used. Where accurate speed is needed, such as in timekeeping and sound reproduction, a synchronous induction motor is used where synchronous refers to the matching of electromagnetic fields and speed. The fourth class energy transformation utilizing induction coupling (transformers) is used in such items as fluorescent lamps, some electronics power supplies, and microwave oven supplies.

All electrical loads have impedance, which consists of resistance and reactance. Reactance consists of inductance and capacitance. The power factor indicates the percentage of resistance. The magnitude of impedance equals the square root of the quantity ($\text{resistance}^2 + \text{reactance}^2$). AC voltage equals current x impedance. The common unit of impedance, resistance, and reactance is the ohm, where one ohm equals one volt per ampere.

6.4.2 CLASSIFICATION OF CONTROLS

Loads are frequently controlled by two types of control elements. The simple contact pair is the most prevalent and is found in both dry and mercury wetted forms. The second type of control element is the thyristor. Both unipolar (SCR) and bipolar (Triacs) devices are used. The SCR is a static-controlled-rectifier (solid state-transistors). A triac is an alternating-current switch. Thyristors are semiconductor rectifiers.

The simple contact pair, found in nearly every appliance or circuit, guarantees complete line isolation when the appliance circuit is turned off. An extension of this control is the simple bimetal temperature control found in appliances such as irons and skillets. These switches are required to cycle on the order of four or five times per minute in most applications. A further extension of this technique is found in some universal motor speed controls where a miniature flyball governor is used to open and close contacts, thereby controlling the motor speed. Appliances and controls utilizing relays also rely on the contact pair. Many heating systems use relays for control and interlock functions. A governor is a mechanical device for automatically controlling the speed of an engine or motor by regulating intake power.

The thyristor controls are found in lamp dimmers and motor speed controls where phase control techniques control the effective voltage delivered to the appliance or lighting load. A new application of these devices will be in appliance temperature controls where the thyristor, used in the AC wave zero crossing mode, can eliminate unwanted conducted and radiated electrical noise inherent in contact opening and closing.

Relays are electromagnetic devices activated by a variation in conditions in one electric circuit and control a larger current or activate other devices in the same or another circuit.

6.4.3 APPLIANCE LISTING

The most common electric appliances are listed in exhibits 6.9 through 6.16. They pertain to climate control, food preparation, food preservation, home care, home entertainment, laundry, lighting, and personal care. Included in the listing are average rated wattage, type of electrical energy transformation employed, types of common controls, and average yearly energy usage. Electrical energy transformation involves resistance, reactance or a combination. The average rated wattage and average yearly energy usage figures were computed from the Niagara Mohawk Power Corporation, NPC 1970 estimate and CEQ 1973 estimate.

The major types of energy transformation and control types have been marked on the tables with an X. The minor types have been marked with an M. For example, the first entry in the Climate Control list (exhibit 6.9) is the Air Cleaner. It has X marks on the induction motor and transformer-coupled because there is usually an induction motor fan drive and, in the case of electrostatic air cleaners, a high voltage transformer. These units usually have simple on-off switches. However, room air conditioners are available with the three control types indicated. Most radiant heaters do not have air circulation fans, some do use a small induction motor to cool the metallic surfaces of the unit and provide some convection heating. Therefore, there is an M in the Induction Motor column. Induction involves the transfer of electric power by use of electromagnetic fields, and can serve to isolate circuits while reducing or increasing voltage, if necessary, as in transformers.

Demand / Appliance	Average Rated Load (W)	ENERGY TRANSFORMATION				CONTROL TYPE						
		Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	Average Yearly Energy Usage (kWh)
Air Cleaner	50			X	X	X						216
Room Air Conditioner	860			X		X	X	X				860
Bed Covering	177	X				X	X	X				147
Dehumidifier	257			X		X		X				377
Fan—Attic	370			X		X						291
Fan—Bathroom	105			X		X						
Fan—Circulating	86			X		X	X					43
Fan—Window	200			X		X	X					
Furnace Fan	294			X		X		X		X		
Heater—Radiant	1,250	X		M		X	X	X				176
Heat Pump	12,500	X		X		X		X				
Heating Pad	65	X				X	X					10
Humidifier	177			X		X	X	X				163
Oil Burner	263			X	X	X		X		X		

Exhibit 6.9 Climate Control.

Demand / Appliance	Average Rated Load (W)	ENERGY TRANSFORMATION				CONTROL TYPE						
		Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	Average Yearly Energy Usage (kWh)
Blender	386		X			X	X		X			15
Broiler	6700 1400	X		M		X	X	X				100
Can Opener	100		X	X		X						3
Carving Knife line	92		X			X						8
Carving Knife—battery	92				X							8
Coffee Maker	894	X				X		X				106
Deep Fryer	1667 1448	X				X		X				83
Dishwasher	1250 1202	X		X		X	X	X				363
Egg Cooker	500	X				X		X				
Frying Pan	1250 1106	X				X		X			M	186
Sandwich Grill	1250 1161	X				X		X				33
Hot Plate	1257	X				X		X				90
Microwave Oven	1450			M	X	X		X				190
Range w Oven	12,200	X		M	M	X	X	X		X		1,175
Range Self-Clean	12,200	X		M	M	X	X	X		X		1,205
Roaster	1,333	X	M	M		X	X	X				205
Toaster	1,250 1,146	X				X		X				39
Trash Compactor	400		X	X		X						50
Waffle Iron	1,116	X				X		X				22
Waste Disposal	445		X	X		X						30

Exhibit 6.10 Food Preparation.

Appliance \ Demand	Average Rated Load (W)	ENERGY TRANSFORMATION				CONTROL TYPE						Average Yearly Energy Usage (kWh)
		Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	
Freezer 15 cu ft	341	M		X		X						1,195
Freezer (frostless) 15 cu ft	440	M		X		X		X				1,761
Refrigerator 12 cu ft	238 241	M		X		X		X				728
Refrigerator (frostless) 12 cu ft	333 321	M		X		X		X				1,217
Refrigerator/Freezer 14 cu ft	326	M		X		X		X				1,137
Refrigerator/Freezer 14 cu ft (frostless)	615	M		X		X		X				1,829

Exhibit 6.11 Food Preservation.

Appliance \ Demand	Average Rated Load (W)	ENERGY TRANSFORMATION				CONTROL TYPE						Average Yearly Energy Usage (kWh)
		Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	
Clock	2			X								17
Floor Polisher	312 350		X			X						15
Germicidal Lamp	20	X			X							170
Sewing Machine	75		X			X			X			11
Vacuum Cleaner	630		X			X	X					46
Water Pump	454			X		X		X		X		
Circular Hand Saw	800		X			X						
Table Saw	800		X			X						
Drill—Hand	250		X			X			X			
Soldering Iron	125	X			X	X						
Garage Door Opener			X	X		X				X		

Exhibit 6.12 Home Care.

Appliance \ Demand	Average Rated Load (W)	ENERGY TRANSFORMATION				CONTROL TYPE						Average Yearly Energy Usage (kWh)
		Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	
Radio	71				X	X						86
Radio/Record Player	109				X	X						109
Television—B&W	160 55				X	X						350 120
Television—color	300 200				X	X						660 410
Slide Projector	300	X		X		X	X					
Movie Projector	600	X		X		X	X					

Exhibit 6.13 Home Entertainment.

Demand / Appliance	Average Rated Load (W)	ENERGY TRANSFORMATION: Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	CONTROL TYPE: On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	Average Yearly Energy Usage (kWh)
Clothes Dryer	4,856	X		X		X		X				993
Hand Iron	1,000	X				X		X				144
Washing Machine—automatic	500 512			X		X						103
Washing Machine—manual	286			X		X						76
Water Heater	2,500	X						X				4,219
Quick Recovery	5,000	X						X				4,811

Exhibit 6.14 Laundry.

Demand / Appliance	Average Rated Load (W)	ENERGY TRANSFORMATION: Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	CONTROL TYPE: On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	Average Yearly Energy Usage (kWh)
Incandescent—interior	75	X				X	X	X	X			
Incandescent—exterior	150	X				X		X				
Fluorescent	20				X	X						

Exhibit 6.15 Lighting.

Demand / Appliance	Average Rated Load (W)	ENERGY TRANSFORMATION: Resistance Element	Universal Motor	Induction Motor	Transformer Coupled	CONTROL TYPE: On-Off Switch	Push Buttons	Bimetal Relay	Phase Control	Magnetic Relay	Zero Crossing Switch	Average Yearly Energy Usage (kWh)
Hair Dryer	380	X	X	M		X	X					14 low
Heat Lamp	250	X				X	X					13
Curling Iron		X				X		X				
Heated Curlers		X				X		X				
Shaver	14		X		X	X						1.8
Sun Lamp	279	X				X						16
Toothbrush			X		X	X						.5
Vibrator			X			X	X		M			2
Water Pic			X			X						

Exhibit 6.16 Personal Care.

6.4.4 OPERATION ON DC VOLTAGE

The operation of the appliances will be discussed with respect to the suitability of the basic electrical energy transformation means to utilization of DC voltage and the suitability of the various controls to operation on DC voltage.

The loads with resistance element energy transformation can operate on DC voltages, as can the universal motor. The induction motors and induction-coupled appliances (transformers) rely on periodic voltage reversals to function (alternating current). These appliances cannot operate on DC voltage.

Of the resistance element loads, those most suitable for DC are the simple heat producers. These units follow a square law relationship between voltage and electric power transformed into heat. The heat flow equals $I^2 \times R = V^2/R$ which results from $P = V \times I$ and $V = I \times R$ (ohm's law). Many of these appliances have thermostatic controls such that the DC voltage might vary moderately (±10 to 20 percent), while the control would compensate for the input power variation. For example, an electric frying pan set for 350° F may only have power supplied to the resistance heater for the first 15 seconds out of a minute during which time the temperature of the load is raised to some upper limit, say 375° F. During the following 45 seconds, the temperature will decrease to some lower limit, say 325° F, at which time the bimetal controller applies voltage to the resistance element to start the cycle again. With a low input voltage, the cycle might be 25 second on, 35 second off, while the high input case would result in 10 seconds on and 50 seconds off. Voltage equals energy per charge and current equals charge per time (1 amp = 1 coulomb per sec). Power is the heat rate in this case (one watt equals one joule per second which equals one volt x one amp).

Due to the square law power conversion of these elements, the most significant variable in performance of these controlled resistance elements would be a low maximum output at low input voltages. Simple uncontrolled heaters, such as hot plates and radiant units, also suffer from this poor regulation. A 10 percent reduction in voltage from the normal operating voltage would result in a 20 percent reduction in heat flow, since $p = V^2/R$, and <u>change</u> in power (heat flow) equals $2 \times V/R \times$ change in voltage.

Incandescent lamps (lightbulbs) can operate on DC voltages; however, two phenomena must be considered. First energy output is proportional to the second power of the operating voltage. As the energy output decreases so does the temperature; therefore, the amount of energy emitted in the visible spectrum--the light output--decreases more rapidly. For example, the overall effect of a 10 percent reduction in voltage is a 40 percent reduction in the light output.

The second phenomenon is metallurgical in nature. The incandescent tungsten filament in a lamp undergoes a grain boundary modification on DC operation. This results in a reduced life from some lamps when operated on DC voltage. This grain boundary modification is quite temperature sensitive. Lamps operated above 2,800° K show little of this phenomenon during life. Lamps operated in this temperature range are used for general household illumination. Long-life lamps and very low wattage types, such as night lights, operate at reduced filament temperatures (below 2,700° K) which make them susceptible to this effect. However, the majority of the lamps used in residences will be unaffected by the DC operation. K = C + 273, and F = 1.8c + 32. 2800°K = 2527°C = 4548.6°F.

Fluorescent lamps suffer from an approximate 20-percent loss in efficiency when operated on DC voltage. In addition, the direction of the DC voltage must be reversed approximately once per day to avoid the degradation and premature failure of the electrodes due to ion bombardment. The output of a fluorescent lamp is considerably less sensitive to voltage variations than the incandescent lamp.

Universal motors do not rely on the periodic voltage reversal (AC) to operate. Even though these units can operate from either AC or DC voltage, most motors incorporated in present appliances have been optimized for AC operation because DC is not readily available. When the motors are operated on DC, they exhibit accelerated negative-brush erosion, resulting in a 50 percent decrease in life. Brushes, commutators, and slip rings, and other methods are used to transfer electricity from a moving conductor in which voltage has been induced.

Some AC-equiped systems, such as refrigerators, are hermetically sealed. Because the brushes of a DC motor must be accessible for repair, hermetic sealing is not feasible when these systems are DC equiped. Therefore, there will be a loss in system reliability when DC is used.

The speed of these motors is also dependent on the input voltage. A 10 percent decrease in voltage would result in a 10-percent decrease in speed. In most blower applications, this would result in a 10-percent reduction in flow rate and a 20-percent reduction in output pressure.

The induction motor and transformer-coupled devices rely on the periodic sinusoidal voltage reversals to operate. If these units are connected to a DC bus, a heavy current will be drawn with resultant appliance failure, since the reactance component of AC impedance becomes negligible under DC voltage. Power factor indicates the percentage of resistance.

If universal motors are excluded due to life considerations, the controlled resistance elements are the only residential loads suitable for operation with DC voltage.

The contact pair, as used in the typical residence, has been optimized with respect to cost and function. To reduce the cost of contact material and mechanical actuators, switches have been designed for AC operation only. The arc (which is established as the contact pair opens) is extinguished during the periodic current reversal. At the instant of zero current, the arc can be extinguished quite easily with inexpensive contact materials and small gap spacings. A DC switch must be designed to extinguish an established arc with both voltage and current available to sustain it. Therefore, more massive erosion-resistant contacts are needed with an increased spacing for DC operation.

Appropriate controls are required for the operation of any appliance on DC. Even the simple on-off switches of most appliances would need modifications to operate safely. Arc-arresting capacitors should be considered for all DC switches.

Electronic equipment, such as radios and environmental sensors, operate on DC, internally rectifying the AC usually available from the utility. Many devices also operate directly on a battery power supply. Therefore, these devices are ideally suited to operation with a regulated DC output from a PV system. A solar array, if not regulated, may produce operating voltages ranging from 17 V when new and fully illuminated to 0 V when dark. Early in the morning, when the sun is just above the horizon, the operating output voltage may be only 10 V. Therefore, the unregulated input to the electronic equipment will range from 10 to 17 V. The same range may prevail if a battery provides the only means of regulation, because it operates from nearly 17 V when fully charged to approximately 10 V when fully discharged. Many electronic devices will not operate properly over this voltage range and, therefore, will require a system voltage regulator for proper operation.

6.4.5 CONCLUSIONS

Voltage regulation will be required under most circumstances. DC voltage control is usually established by designing the solar array voltage higher than the load requirements. The higher voltage is reduced to match the load and system through losses controlled by and incurred in the voltage regulator. AC and DC regulation can be accomplished by a motor/generator set. The motor/generator set converts array electric power to electric power for the load and has built in voltage regulators, power regulators, and frequency control. It is often used to supply systems of different frequency than the main system, including DC/AC inversion and AC/DC conversion. AC regulation can also be accomplished by thyristor control (rectifiers). The methods of regulation must be evaluated for each application to determine which is the most economical. This is especially important because the cost of some AC equipment, such as induction motors, is much less than for the corresponding DC equipment. It does appear that electronic equipment is best driven by DC voltage from the array/battery system.

6.5 LOAD/POWER SYSTEM INTERACTIONS

Many problems which may be encountered when common components are connected to AC and DC power lines remain to be identified. Exhibit 6.17 lists the various problem areas.

LOAD	POTENTIAL PROBLEM
AC Motors	Insufficient starting current (torque) Varying frequency Overvoltage Nonsinusoidal wave form
DC Motors	Insufficient starting current (torque) Overvoltage
Incandescent Lights	Sensitivity to voltage
Fluorescent Lights	Sensitivity to voltage Lower efficiency
Electronics	Discontinuous voltage changes from voltage regulator Sensitivity to voltage
Battery (Charging)	Overvoltage Overcharging

Exhibit 6.17 Load/PV Interactions.

6.5.1 AC MOTORS

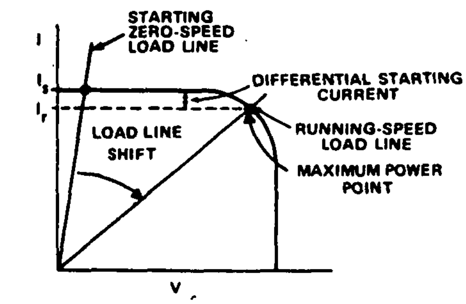
AC motors would be driven from the array/battery combination through a DC-to-AC inverter. If a battery were used, the power system would probably have sufficient current capacity to start the motor. If no battery were used, the array would drive the motor directly and the output current of the array would be limited by the insolation. The problem is illustrated in exhibit 6.18. When the motor is started, there is no back EMF generated, so the input impedance is very low. EMF is the electromotive force in volts. As a consequence, the load line is as indicated for high current and low voltage. When the motor is running at full speed, the load line is as indicated, corresponding to the higher load impedance due to reactance (back EMF). The zero-speed current is much higher than the running current (the starting current is very brief and looks like a spike function). As a consequence, the starting torque will be nearly equal to the running torque for some types of motors, such as synchronous and squirrel-cage. For universal motors, the zero-speed output torque could be too low to start the motor, especially if the motor were started under load. The load would be picked up as operating speed is approached.

Because permanent-magnet motors and series-wound motors have starting torques somewhat higher than running torques, they are the preferred motors to use with PV systems. The series-wound have a tendency to overspeed under light loads because the field strength is too weak at low currents.

AC motors are designed for a specific frequency, such as 60 or 400 cycles/sec. If the frequency deviates from the design value, the efficiency of the motor will decrease. Frequency deviations of 10 percent would result in an increase in heat generation of 10 to 20 percent.

Waveform is another source of potential difficulties with AC motors. If the inverter does not produce a perfect sine wave, the motor will be less efficient and may overheat. Exhibit 6.19 illustrates this problem. If the motor uses only the square wave equivalent of the sine wave, most of the square wave will not be useful in producing work output. Therefore, the difference in the electric power input from the sine wave and the power input from the square wave must be dissipated as heat. As indicated in exhibit 6.19, the heat dissipation with a sine wave is 15 percent of the output mechanical power (for an 85 percent efficient motor); but the heat dissipation with a square wave is 115 percent of the output power, as an approximation. For a 1.0 hp load, the motor must be rated for this extra input. As shown in exhibit 6.19, the input electric energy must be 2.15 times the mechanical output for a square wave, so the dissipation is 1.15 times the output. Compensation for this much heat dissipation requires a motor size 7.67 (1.15/0.15) times what would be required with a sine wave, or 7.67 hp for the illustrated case. There is a possibility that a capacitor could be built into the motor to decrease this effect; in fact, the inductive aspect of the motor impedance will provide some filtering, so the dissipation will be somewhat less than shown in exhibit 6.19. Capacitance decreases the reactance component of impedance.

Finally, some difficulties can be expected if the input voltage is allowed to vary significantly. Motors normally can tolerate a ± 10 percent change; however, for the PV system without a battery, the voltage swing will be from 0 V to possibly 17 V. The synchronous and squirrel-cage motors will stall at low voltages because the load torque will exceed the pull-out torque. The universal motor will rotate at a speed proportional to the input voltage. If the motor is designed for 12 V and the solar intensity is high enough to produce 17 V, the high motor voltage could cause overheating, overspeed, and motor failure. Under most circumstances a voltage regulator is required.



CONVENTIONAL STARTING CURRENT = 6 · RUNNING CURRENT

MOTOR TORQUE: Proportional to Current
- Synchronous
- Squirrel Cage
- Series Wound

Proportional to Current and Voltage
- Shunt Wound
- Compound Wound

$I_s = 6 \times I_r$, thus $I_s - I_r = 5\, I_r$.

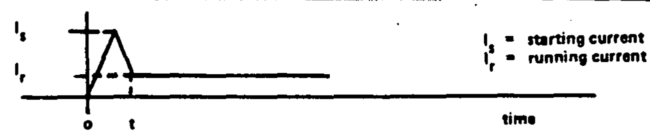
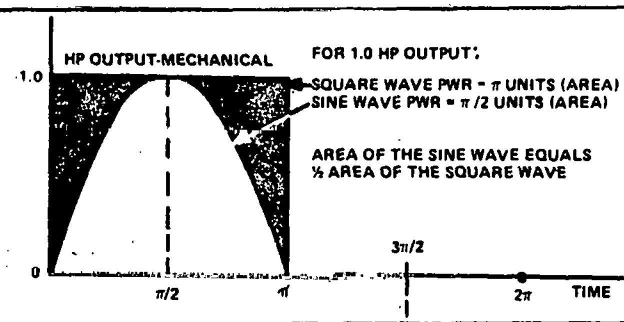


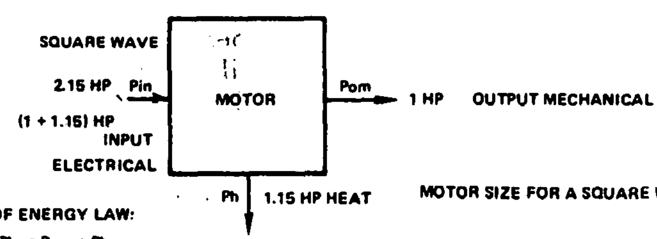
Exhibit 6.18 AC Motor Starting.



HEAT DISSIPATION

SINE WAVE: $2/\pi \times (0.15 \times \pi/2) = .15$
SQUARE WAVE $7.67/\pi \times (0.15 \times \pi/2 + \pi/2) = 1.15$

MOTOR EFFICIENCY = 85%, SO 1-85% = 0.15
HEAT DISSIPATION = Pin (1-efficiency) = Ph



MOTOR SIZE FOR A SQUARE WAVE = $\frac{1.15}{0.15}$ = 7.67 HP

CONSERVATION OF ENERGY LAW:
Pin = Pom + Ph
85% EFFICIENCY: Pom = 0.85 Pin
Ph = 0.15 Pin

π = 3.14 (The ratio of circle circumference to diameter): the electrical output of a generator is related to the rotation of the shaft.

Exhibit 6.19 Estimated Derating for AC Operation Utilizing a Square Wave.

6.5.2 DC MOTORS

DC motors encounter the same startup problems as AC motors. In addition, the lack of voltage control will cause similar problems. Wave form problems pertain only to AC motors.

6.5.3 INCANDESCENT LIGHTS

The output of lights is highly sensitive to the input voltage, so an unregulated DC source--even a battery operating from 11 to 14 V--will cause a significant variation in light output. Over-voltage will seriously shorten the light life; a drop from 14 V to 11 V will result in a drop in intensity to approximately 15 percent of the 14 V value. As with the motors, a voltage regulator is a good investment. In most designs the voltage regulator is placed upstream of the battery, so the same 11 to 14 V range will still occur. A separate voltage regulator for the lights might prove necessary.

6.5.4 FLUORESCENT LIGHTS

A fluorescent light is a glass tube or bulb coated on the inside with a fluorescent substance that gives off light when mercury vapor in the tube is acted upon by a stream of electrons from the cathode (negative terminal electrode).

Fluorescent lights need a high voltage to start, but then can run with low voltage. (A 12 W DC fluorescent is available.) A starting coil, similar to an automobile ignition coil, is needed to develop the initial high voltage to start the lamp. The coil is usually triggered by a thermal switch. Under DC operation, the efficiency of the fluorescent is approximately 20 percent lower than that attainable with 60-cycle AC. In addition, if the ions migrate in one direction only, as they do under DC, the life of the electrodes is seriously degraded. Ions are positive charge atoms or molecules missing an electron. They do not necessarily move physically but rather transfer electrons. The effect is positive charge motion opposite the transfer of electrons. Reversing the direction of the DC on a daily basis is recommended; however, if the thermal switch is an electronic switch, DC reversal is not possible. The 11 to 14 V range may also prove troublesome for maintaining light output.

6.5.5 ELECTRONICS

Because the PV system produces DC and electronic equipment normally use DC, powering of electronics is ideally suited to PV systems. Most electronics require voltage regulation within 1 or 2 percent, so the variation of array output voltage can be mitigated only with a regulator. If the regulator is of the electronic switching type, there may be some radio interference from the array itself or from the noise introduced through the power lines to the electronics, because the switching produces square voltage pulses superimposed on the input voltage.

6.5.6 BATTERIES

Batteries represent a load during the charge period. If the array is sized to yield 17 V, the voltage will be too high when the battery is fully charged. Overcharging, overheating, electrolyte boil-off, and battery failure can result. If the array voltage is designed for a lower voltage, the charge rate may be too small to permit recovery the next day from overnight discharge when the solar intensity is low. In most cases, the battery capacity will span many days, so the recovery rate need not be high; however, there is a definite tradeoff between battery size and array voltage. If the array voltage is designed to be as high as 17 V, a voltage regulator will be required to prevent the overcharging.

The problem associated with charging many batteries in series was discussed in section 4. The combination of needs: charging batteries in banks of low voltage, availability of DC components at low voltages only, and safety, may dictate that the PV system is best designed for low-voltage DC operation. DC-to-AC inverters would then be used for those isolated components requiring AC operation.

6.5.7 INVERTERS

DC-to-AC inverters can cause instabilities in the power system that could, when coupled with the output characteristics of the PV array, lead to loss of power. The stability criterion is that the power output of the power system must increase with voltage at a slower rate than the power consumption of the load. This instability can be exhibited by a PV system without a battery when operated at a voltage below the peak-power voltage. For this reason, and to permit operation of each power-conditioning component at its peak efficiency, there is a possibility that the most cost-effective system design will incorporate a DC-to-AC inverter at each AC-operated component.

6.5.8 CONCLUSION

Exhibit 6.20 provides a convenient checklist of potential problems that must be solved during the design phase of the project. The tradeoffs among the potential solutions will depend on the particular characteristics of each application.

MODULE CHARACTERISTICS:

Sensor Technology:	36 cells	19.8 Voc	0.25 Isc
Solarex (2 modules)	12 cells	6.6 Voc	1.2 Isc
ARCO	36 cells	19.3 Voc	1.2 Isc

QUESTIONS TO BE ANSWERED IN THE LABORATORY:

1. How can the I-V curve be determined for a module?
2. How can the I-V curve be used to judge the quality of the module?
3. How do Voc and Isc vary with insolation?
4. How do Voc and Isc vary when the module is shaded?
5. How can you judge the current capacity of the module when charging the battery?
6. How can you test the diode that protects the module?
7. How does the output of a CB radio vary with module shading?
8. How does the current demand of a CB radio change with transmit/standby operation?
9. How does the current demand of a permanent-magnet motor change with speed?
10. How does the output of a fluorescent lamp vary with voltage?
11. How can you test a module for open-circuit or short-circuit cells?
12. What is the I-V characteristic of similar modules when connected properly in parallel? When connected improperly?
13. What is the I-V characteristic of similar modules when connected properly in series? When connected improperly?
14. What is the I-V characteristic of an array consisting of grossly mismatched modules when connected in series and parallel, properly and improperly? (Sensor Technology and one Solarex)
15. Describe the hot-spot problem. Can it be demonstrated with the four modules provided with the laboratory?

Exhibit 6.20 Checklist and Laboratory Analysis of Arrays and Systems.

6.6 LOAD ANALYSIS LAB

The primary purpose of the laboratory portion of the seminar is to demonstrate PV hardware and subsystems, its construction, operating peculiarities, and potential problems in applications. Solutions to applications problems will be suggested. These solutions are not expected to be the final definitive answers, since PV technology is evolving rapidly. Exhibit 6.20 summarizes the questions the reader should be able to answer via the laboratory.

A series of demonstrations and experiments are planned to highlight various aspects of PV applications. After these demonstrations, there will be an opportunity for the participants to explore problems that have not yet been addressed by the seminar. Three kits of modular components and detailed instructions will be available for tests or experiments. Other seminar resources will be available. Participants should feel free to inspect the equipment and subsystems more closely, run their own tests with the demonstration kits, or ask questions during this question and answer session.

Exhibit 6.21 outlines the planned demonstrations and experiments. First, PV arrays have been set up outside to power several pieces of equipment. Lighting, pumping, and communications equipment are represented because the participants may be expected to deal with these applications.

Following the inspection of these PV powered systems, the effects of over-and under-voltage on both incandescent and fluorescent lighting will be demonstrated. Exhibit 6.22 shows the circuit arrangement that has been set up to explore the sensitivity of lighting to voltage. While it is unlikely the lights will be powered directly from a PV array, the batteries used in the system can be expected to depend on their state-of-charge, exhibiting voltage swings similar to those of the PV array.

The same circuit, as shown in exhibit 6.22, will be used for showing the effects of voltage variations on a television receiver. It should be noted that, for convenience, the arrays have been set up here to produce a nominal 12 V output because a variety of 12 V, DC equipment is made for the boating and recreational vehicle markets.

Next, the effects of over- and under-voltage and the performance of DC motors driving different types of loads will be explored (exhibit 6.23). In particular, a centrifugal water pump is used to typify a load characterized by zero torque at zero speed. A diaphragm-type positive displacement pump typifies a full-torque-at-starting load. Because PV arrays are inherently current-limited power sources, the concern is that some types of DC motors may not be able to turn the full-torque-at-starting loads. It may be desirable to specify series-wound permanent magnet motors, where available, or to use centrifugal pumps where the application permits.

EQUIPMENT

Sensor Technology, Solarex and ARCO modules
Ammeter (5 A DC), Voltmeter (25 V DC), Rheostat (100 ohms)
Batteries (2-6 V gel-cells)
CB radio, fan/permanent-magnet motor, fluorescent lamp

EXPERIMENTS

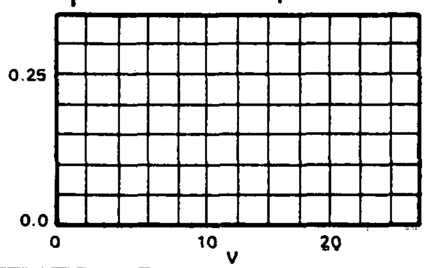
Description	Equipment	Measure	Results
1. I-V curve; Fill factor	S/T Rheostat	I, V with sun directly incident	I V
			
2. Insolation effect	S/T	Isc and Voc with sun at 45 degrees	Isc = Voc =
3. Shading effect	S/T	Isc and Voc with sun directly incident, some cells shaded	No. shaded = Isc = Voc =
4. Battery charging current	S/T	I, V with sun directly incident, (I, gt. 0.8* Isc when V. lt. 1.2* nominal voltage)	I = V =
5. Diode test	S/T	I when module is shaded and battery connected	I =
6. CB radio output and input required	ARCO	Listen to output when module is partially shaded I, V on standby I, V on transmit	V = Sound = I = V = I = V =
7. Fluorescent output	ARCO	Observe output when partially shaded	I = Intensity
8. Motor current draw	ARCO	I, V with locked rotor I, V at full speed	I = V = I = V =
9. Test for bad cells	Solarex 1	Isc with each cell shaded one at a time	Isc (good cell) = Isc (bad cell) =
10. Parallel modules + to +	Solarex 1 and 2	Voc, Isc	Isc = Voc =
11. Parallel modules - to -	Solarex 1 and 2	Voc, Isc	Isc = Voc =
12. Series modules + to -	Solarex 1 and 2	Voc, Isc	Isc = Voc =
13. Series modules + to +	Solarex 1 and 2	Voc, Isc	Isc = Voc =
14. Unequal modules + to + parallel	S/T and Solarex	Voc, Isc	Isc = Voc =
15. Unequal modules + to - parallel	S/T and Solarex	Voc, Isc	Isc = Voc =
16. Unequal modules + to - series	S/T and Solarex	Voc, Isc	Isc = Voc =
17. Unequal modules + to + series	S/T and Solarex	Voc, Isc	Isc = Voc =
18. Hot spot + to + parallel	S/T and Solarex	Voc, Isc; feel cell temperature; test Isc after hot-spot test	Isc = Voc = Isc =

Exhibit 6.21 Laboratory Experiments.

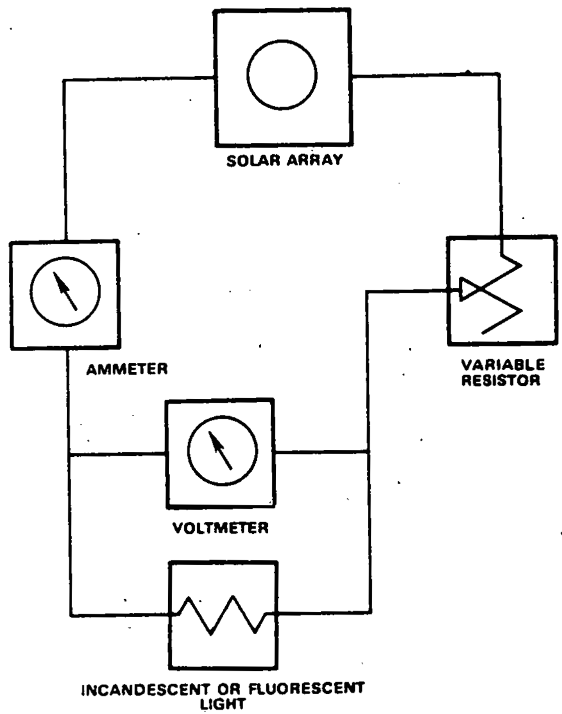


Exhibit 6.22 Effects of Variable Voltage on Lights.

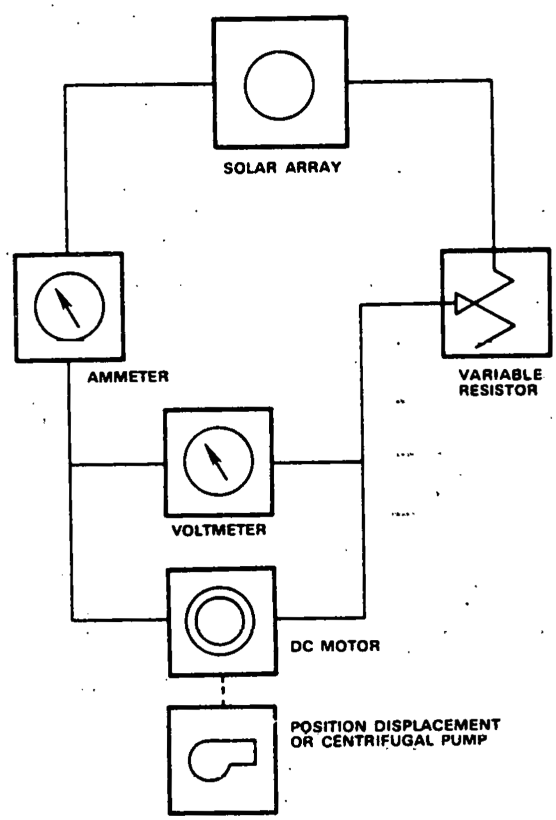


Exhibit 6.23 Effects of Variable Voltage on DC Motors.

Lastly, the effects of over-voltage and over-charging on batteries will be explored, because most applications will require batteries for energy storage. Batteries also have the capability to provide some degree of voltage regulation to the output of the PV array and to provide higher starting currents than the array alone could provide to motors and lights.

6.7 ELECTRICAL POWER FACTOR CORRECTION (SAME, AUGUST 1976)

Emphasis on the need for conserving energy in AC systems makes the electrical power factor a subject of continuing interest. When providing the consumer with electrical service, the utility supplier is actually furnishing two types of AC electrical energy. The major type is known as the active or real kilowatt component upon which the cost of service is based. This is the component that is usable and does the work. The other kind of energy is the reactive or magnetizing kilovar component and is needed to magnetize any electrical equipment that requires a magnetic flux from the power system to permit operations. This type of energy does not cause the disk of the watt-hour meter to rotate, although it is drawn from the power lines and furnished to the system. Every piece of electrical equipment or appliance whose operation is dependent upon a magnetic circuit requires a supply of exciting or magnetizing current. As an example, a transformer or a common induction motor receives magnetizing current through the alternating current distribution systems. Accordingly, it can be seen that all inductive equipment such as transformers, motors, and fluorescent fixtures need two kinds of current:

- o Working Current -- also known as usable, active and power-producing current - which is converted into useful work by electrical equipment, and,
- o Magnetizing Current -- also known as wattless, reactive, and nonusable current - which cannot be converted into useful work by inductive electrical equipment but which is needed for operation.

Power factor may be defined as the ratio of the working current to the total of the working current plus the magnetizing current. Low power factor means only that an excessive amount of magnetizing current is being drawn from the incoming power lines. During the past years when electrical power could be considered relatively cheap and in plentiful supply, the taking of magnetizing current from the A.C. lines was not considered objectionable if the effect of the extra current on voltage regulation was not too serious. However, as the total electrical load approaches the capacity of the utility supplier's generators, a low power factor will cause the generators to become overloaded and additional expensive generation equipment must be provided. Additionally, a low power factor results in the overheating of conductors and transformers and low voltage throughout the distribution system. This results in inefficient operation of electrical equipment and overheating of induction motors.

Clarification of the power factor principle can be demonstrated by the following calculations. The power flowing in a direct current (DC) circuit is the product of the volts times the amperes and is expressed in watts. A wattmeter will accurately register this value. If one considers an AC circuit, and the load is pure resistance, then again E (volts) x I (amperes) = watts. However, if the AC circuit contains an induction motor, the wattmeter reading is less than the product of E x I. A fraction of the total amperes is consumed in magnetizing the motor and the balance is used to perform work. Consider the following case: a 240-volt motor draws 10 amperes as measured by an ammeter. The product of volts times amperes would equal 2,400 watts; however, when the power is measured with a wattmeter, it is found to register only 1,920 watts. It is apparent the current is doing other than providing useful work. The current necessary to provide the useful work is:

$$\frac{1{,}920 \text{ watts}}{240 \text{ volts}} = 8 \text{ amperes}$$

Accordingly, the total current is 10 amperes, and the power factor, previously defined as the ratio of the working current to the total current is:

$$\frac{8}{10} = .8 \text{ or } 80 \text{ percent or as usually stated:}$$

$$\frac{\text{watts}}{\text{volts x amperes}} = \frac{1{,}920}{2{,}400} = .8 \text{ or } 80 \text{ percent}$$

In the preceding case, if it was found that the wattmeter had read 2,400 watts in lieu of 1,920 watts, then all of the current would have been performing useful work and the power factor would be 100 percent. This will not be found to be true, however, as the induction motor is a principal source of low power factor. All induction motors operate at considerably less than 100 percent power factor due to their magnetizing current requirements. Unfortunately, the magnetizing current needed is not proportional to the motor load and is very nearly the same at no load as at full load. Therefore, the power factor is dependent upon the load the motor is carrying and becomes lower as the load is reduced. The importance of selecting a motor according to the work it must perform is evident.

Most electrical systems contain quantities of working current and magnetizing current, and one type is just as effective in overloading the utility supplier's system as the other. The utility supplier must provide both, and the magnetizing current constitutes an addtional load without producing revenue. Many utilities compensate for this loss by including a charge for low power factor in their rate schedules. This is a penalty charge and is paid for by requiring the utility to provide magnetizing current as an extra service. A low power factor is not a desirable feature on an electrical distribution system and action should be taken to provide improvement or correction. This means neutralizing the effect of the magnetizing current by the addition of either:

- Synchronous motors, which do work while improving low power factor;
- Static condensors (capacitors), which are employed solely for power factor correction; or
- Solid-state devices, such as silicon-controlled rectifiers and thyristor switches, which are required where frequent and rapid variations in power factor correction are needed.

Of these, the capacitor is generally the most economical method for power factor improvement and usually pays back capital investment spent for installation in six months to three years. Capacitors may be considered as generators that supply the needed magnetizing current to inductive loads. A bank of serveral capacitors is usually needed and these are normally cluster or rack-mounted on a power pole as near the load as possible.

Power factor correction should be initiated to secure the following benefits:

- Reduction of losses in generators, transformers, and distribution lines to conserve energy;
- Reduction in the cost of electrical bills, particularly when a power factor penalty clause exists in the rate schedule;
- Increase in system capacity by elimination of excessive line current;
- Increase in voltage levels allowing efficient operation of all equipment; and,
- Increase in illumination from incandescent lamps.

The best solution to obtaining power factor correction is to have a qualified engineer survey the electrical system and select the proper location for the most efficient and economical equipment needed. Power factor calculations are slightly more complicated than indicated. Power factor is the cosine of the angle by which the current lags (or leads) the voltage in an AC circuit, complete with vector diagrams, plus the formula

$$w = \sqrt{3} \times E \times I \times \cos\Theta$$

where w = three phase AC watts, E = voltage difference between phases (volts), I = current (amps), $\cos\Theta$ = power factor, and $\sqrt{3} \times E = 3 \times V$ where V = the voltage difference between neutral and phase. Three phase power equals 3 x single phase power (phase to neutral).

SECTION 7
BACKUP SYSTEMS

7.1 INTRODUCTION

If the system requires continuous power, a backup system would be required. The purpose of this chapter is to enable the attendee to list possible backup systems and to evaluate each possibility for his application (see exhibit 7.1).

What Happens if the PV System Fails?

PURPOSE: To enable attendee to:

1. **List possible backup systems.**
2. **Evaluate pros and cons of each in context of the application.**

Exhibit 7.1 Backup Systems.

As shown in exhibit 7.2, the key question to be answered in analyzing the application is: is the occasional loss of power critical? If the loss is not critical, there is no need for the backup system with its attendant complexities. The duration of the possible outage is also part of the criticality. If the system is frequently inspected and spare parts and maintenance crew are nearby, there may be little need for a backup system. Even if the power need is not critical, a backup system may be desirable if the repair cannot be accomplished in a short time. A reliability analysis may be required by legal codes and regulations, and often involves standard protection requirements.

Is loss of power critical?

How long will loss last?

Exhibit 7.2 Need for a Backup System.

7.2 CAUSES OF POWER LOSS

Exhibit 7.3 lists the primary causes of power losses. At this time, there are insufficient data to estimate the frequency of the various interruptions for solar PV power systems. Available information does indicate that total system failures are rare; the major causes of power failures are nature, design deficiencies, and hardware failures.

One known outage due to lightning occurred at Meade, Nebraska. A 25 kW irrigation facility was struck during its first 15 months of operation. The exact failure mechanism is still unknown, even though lightning protection is a fairly routine analysis. Long periods of little or no sun are another cause of power losses. In the design process, as will be seen in section 8, an allowance is made for the maximum number of low-insolation days. The design will not be based on the worst possible condition, but the worst experienced over the past 10 to 20 years. There is always a possibility that there will be less sun than considered in the design. Unless a backup system is provided, insufficient energy will be possible at a high probability.

NATURAL

Lightning
Consecutive sunless days
Cold-weather effect on batteries

DESIGN

Less insolation than expected
More load than expected
Maintenance shutdown

HARDWARE FAILURES

Array short, open-circuit, full or partial failure
Optical degradation
Electronics—power conditioning
Batteries

Exhibit 7.3 Causes of Power Loss.

Cold weather, even if it does not cause battery failure, will cause a loss in battery capacity. This loss in capacity can result in deeper discharge of the batteries, with an attendant shortening of the battery life or a loss in the capability to store and later supply the needed energy. Cold weather is considered in the design, but nature may provide colder weather than anticipated.

Power may also be lost due to an inadequate design. In some cases, the engineering may be at fault. In other cases, basic data may not be sufficiently accurate to permit the development of an adequate design; for example, the insolation in many parts of the country can be estimated only to within 30 percent. Designing with a 30 percent margin may make the system noncost-effective; the designer must use the best available information, and then qualifies the variance. Similar design deficiencies may present themselves if either the user or the designer underestimates the energy needs of the load or if the load is added to the system subsequent to completion of the system design.

Finally, the user must expect occasional interruptions during scheduled maintenance periods, if only to protect the maintenance worker. In some cases, the power need may remain throughout the maintenance period and a backup system must be provided or already to go on-line instantaneously.

The various causes of hardware failure, either partial or total, are listed in exhibit 7.3 under the last category. Optical degradation of the outer surface is particularly important. In some circumstances, arrays covered with silicon rubber have experienced a 30-percent loss of power in 15 months. Cleaning restores much of this loss, although some ultraviolet degradation persists. Although an allowance is made in the design, loss of transmission through the optical coating could cause significant power losses and ultimately loss of the power supply to the load. Ultraviolet refers to sunlight of a particular energy level, and thus the optical effect on photoconductivity due to material propagation.

7.3 POTENTIAL BACKUP SYSTEMS

Exhibit 7.4 lists several backup systems that might be suitable for the applications envisioned for remote sites. In many cases, the loss of power will not be critical, so backup will not be necessary. In judging the criticality, one must recognize the time that will elapse before the power can be restored. Maintaining some inventory of spares will help keep the elapsed time to a minimum. The modularity of the array will keep the cost of spares, if required, low.

1. **None (e.g., visit daily, carry spares)**
2. **Manual (e.g., pumping, pedaling)**
3. **Engine/Generator**
4. **Primary Battery**
5. **Emergency Solar-Rechargeable Battery**
6. **Emergency Fossil-Rechargeable Battery**

Exhibit 7.4 Potential Backup Systems.

Manual backups are a viable, low-cost alternative. Hand pumping can be used for village water on an emergency basis, although provision must be made in the initial design for hand pumping. Centrifugal pumps cannot be manually operated, but positive-displacement pumps can. For small radio systems, pedal-powered generators can be used in emergencies.

For larger pumping operations or large-power operations, an engine can be justified for the backup system. If an engine is rarely used, it should be started regularly to prevent problems. The maintenance costs associated with the weekly operation must be factored into the analysis.

Battery backups can be the most desirable. Primary batteries, such as zinc-air batteries, can be used in some circumstances. Once discharged, the zinc-air batteries must be manually replaced, so the maintenance costs could be high. If standby rechargeable batteries are used, battery replacement can be avoided. For example, lead-acid batteries could be used that have their charge maintained by the solar cells, but are not connected to the main battery-storage system, which is used for nonemergency energy storage. The advantage of the solar-recharged battery is that it can recover from an emergency condition without separate servicing by a mechanic. The batteries might also be recharged by a portable generator carried by the mechanic. The portable generator would be especially useful as a backup in the rare circumstance of extremely low insolation for many days.

The various advantages and disadvantages just described are summarized in exhibit 7.5. Most of the systems would cost approximately $150 for 3 kWh/day applications, if servicing can be accomplished within 1 day. An engine-generator is the only device that could be considerably more expensive, because the sets do not come in small sizes (less than 500 W). Storage and safety of fuels for engine-generators and maintainability of the sets are some of the primary considerations in using portable generators.

A motor-generator set using electricity from a small electric utility consisting of a small transmission and distribution network is a secondary possibility. Natural gas utilities, and energy technologies such as the solar thermal-solar cell (PV) total energy system, and radioisotope powered photovoltaic cells are other secondary possibilities.

BACKUP SYSTEM	TYPICAL COST	LOAD--kWh	ADVANTAGES	DISADVANTAGES
1. None	—	3 kWh/Day	Simple	Noncritical applications only
2. Manual	$ 150	"	Simple, reliable	Require attendance
3. Engine	2,000	"	High power	Frequently won't start: high maintenance
4. Primary Battery	150	"	Can be remote Reliable	One-shot only
5. PV Recharged Battery	150	"	Can be remote Reliable	Cannot recover without sun
6. Fossil-Fueled Recharged Battery	150	"	Can be remote Reliable	Fuel, engine transport

Exhibit 7.5 Advantages and Disadvantages of Potential Backup Systems.

7.4 APPROPRIATENESS OF VARIOUS BACKUP SYSTEMS

The appropriateness of various backup systems depends on the application. The primary considerations are listed in exhibit 7.6. As shown, the first consideration is the remoteness of application. The second consideration is whether the loss of power is critical.

APPLICATION	UNATTENDED		INHABITED	
	CRITICAL	NONCRITICAL	CRITICAL	NONCRITICAL
Radio	Battery, alarm	None	Battery, pedal	None
Lighting	Battery, alarm	None	Engine	None
Pump	Battery, alarm	None, alarm	Engine	None
Refrigerator	Battery, alarm	None, alarm	Engine	None, alarm
TV	Battery, alarm	None	Battery, pedal	None
Cathodic Protection	Battery, alarm	None, alarm	Battery, alarm	None, alarm
Field Instruments	Battery, alarm	None, alarm	Engine, battery, alarm	None, alarm

Exhibit 7.6 Appropriateness of Various Backup Systems.

In many circumstances, the loss of power will be obvious because the equipment will not be working--the light will not come on, the radio will not receive or transmit. In other applications, the power loss will not be detectable. For example, because the refrigerator compressor operates cyclically, an observer will not know if the compressor is in an off period or is not being supplied by power. For these cases an alarm is needed to warn either that power has been lost or that the system is operating on emergency (backup) power.

Systems operating in a heavily traveled area and requiring large power consumption can use a gasoline or diesel engine for backup, because the engine operators and servicemen will be nearby. Under automatic startup, operation of the engine will be apparent; therefore, no alarm is needed in these cases.

7.5 INTEGRATION OF THE BACKUP INTO THE SYSTEM

Once the type of backup system has been selected, it must be integrated with the PV array. Means of integration are listed in exhibit 7.7. In monitoring or controlling an automatic actuator, a manual transfer switch is clean, direct, and involves no energy loss. The manual system requires inspection and onsite correction.

MANUAL TRANSFER SWITCH

- **Simple**
- **No energy loss**
- **Requires detection, onsite correction**

REMOTE MANUAL TRANSFER SWITCH

- **No energy loss**
- **Requires two-way telemetry**
- **Requires actuator**

AUTOMATIC TRANSFER SWITCH

- **Continuous energy loss—possible only when on backup**

Exhibit 7.7 Considerations for the Integration of the Backup into the PV System.

For remote sites, especially those with a telemetry system that transmits when the system is not performing properly, a second communication link can be supplied by which a person at a central station can radio to the site for the backup system to come on. A remote actuator will be required for this type of backup, although the actuator can be an electrical relay or solid-state electronic switch. A telemeter is any device which measures physical phenomena (temperature, radiation, etc.) at some remote point and transmits the values obtained to a distant indicator, recorder, or observer. Transmission is by radio or wire.

Automatic switchover is also possible, although the sensing and controlling function will then result in an additional power drain through the controller. It would be possible to have the relay or solid-state switch arranged so that power drain occurs only during those infrequent periods when the backup system is on, so the total energy loss would be insignificant. The relay would be the holding-coil type; the solid-state switch, a triac.

7.6 CONCLUSION

Except for a costly engine that might be required for a large-power backup supply, the backup systems add significantly to the reliability of the electric power supply system at minimal cost. Where required, the backup will add to the suitability of the solar PV system in remote applications. The use of back-up systems for supplement depends primarily on insolation, the electric load demand profile, and system capacity. Implementation involves the use of distribution switchboards or minor switching, and manual or automatic control. There are some applications which are not isolated but because of the importance of application and the duty cycle, require high reliability back-up regardless of remoteness.

SECTION 8
PV SYSTEM DESIGN

8.1 INTRODUCTION

This section presents an introductory detailed engineering method for the design of a solar PV system. This type of design is frequently used by system designers, however, it is too conceptual to be used as a design manual.

An overview of electric power system design was given in the Introduction to this seminar (see section 1). Since then, the discussion has been centered on each subsystem and component in the system and how they interact with the load. This section takes what was discussed in the previous chapters and integrates it into a system schematic and an analysis and synthesis of system performance, which involves basic, equivalent networks and block diagrams, load analyses, insolation computation, battery energy storage, and system capacity.

In designing an electric power system, one follows the sequence shown in exhibit 8.1. The load is analyzed according to the procedures discussed in section 6.

DESIGN SEQUENCE

1. **Load Analysis** — **Chapter 6**
2. **Quick Sizing of Components—Monthly Analysis**
3. **Computer Analysis of Performance**

Exhibit 8.1 PV System Design.

Exhibit 8.2 illustrates typical system schematics for PV power supplies. The top exhibit shows a system supplying DC; the bottom, AC. To illustrate the method for sizing a system and computing its performance, an example of a DC system will be provided. Power is sent from the solar array, through a protecting diode, either to a battery or directly to the load, or both. If the voltage being supplied by the array is too large (for example, over 14.4 V), the shunt regulator will be activated so the excess power is dissipated in the regulator and the output voltage is maintained at approximately the battery voltage (for example, 14.4 V). If insufficient power is being supplied by the array, the battery will supply the deficit.

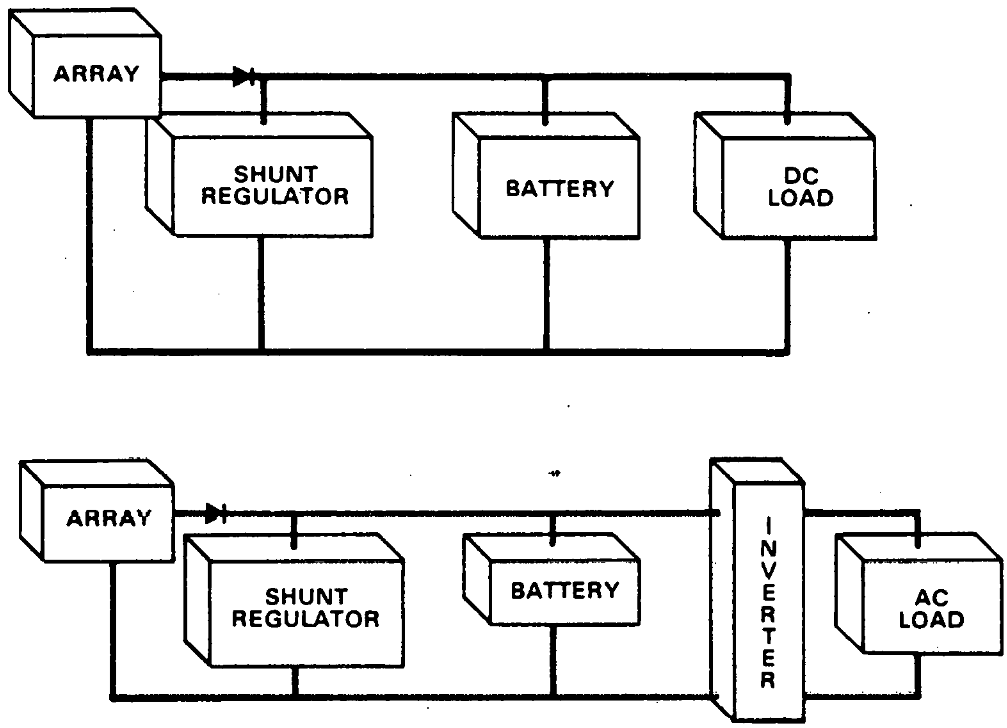


Exhibit 8.2 Representative PV System Schematic for DC and AC Loads

With the schematic now defined for the typical PV application, the sizing of the system and its subsystems and components can be addressed. An analysis and synthesis of the system performance will follow.

8.2 QUICK SIZING OF COMPONENTS AND SUBSYSTEMS

Exhibit 8.3 outlines the steps to be taken in estimating the sizes of the components. These sizes will be used in the detailed analysis of the system performance. Component sizing is an iterative process aimed at selecting the combination of sizes that minimizes the system life cycle cost. The collector tilt, collector area, and battery size are the key factors governing the minimization process. The collector tilt is a compromise among the seasonal demands and available insolation during each of the seasons. The tilt that maximizes the energy collected in January may provide too little energy in July, or may require such a large collector area that a combination of less tilt, less area, and larger batteries may be less costly. One-axis and two-axis tracking collectors are being studied in the solar thermal power systems program, solar heating/cooling, and solar total energy system programs. Insolation is the rate of solar radiation per unit of surface area.

SEQUENCE
A. Select array size, tilt
B. Compute insolation on average day for each month
C. Compute output of array
STORAGE REQUIRED
D. Compute costs of array, battery
E. Repeat for other array sizes, tilts until minimum cost is found.

Exhibit 8.3 Quick Sizing of Components.

The sequence illustrated in exhibit 8.3 calls for the estimation of the collector tilt and size. The computational procedure will yield the required battery size. The system cost can be computed on the basis of the array and battery sizes. As shown in step E, the process is repeated with other tilts and array areas until the minimum cost is determined.

The method for selecting array size is outlined in exhibit 8.4. First, the tilt angle must be estimated. If the tilt angle is equal to the latitude of the installation, the noon insolation will be the same in winter as in summer. However, the array will produce a high energy output during the summer, due to the longer summer days, and a low output during the winter. By increasing the design tilt angle to be 5^{o} to 20^{o} greater than the latitude angle, significantly more energy can be obtained at winter noon, partially offsetting the shorter day. The tilt angle should be selected as latitude plus 15^{o}. For illustrative purposes, the first tilt angle to be evaluated is 45^{o}, as indicated in exhibit 8.4. The insolation for this tilt angle is obtainable from available maps of insolation on tilted surfaces, such as shown in exhibits 8.5 to 8.8. For the first iteration, the collector size should be selected on the basis of the minimum insolation over a 4-month period. Data from the maps can be used to estimate this minimum, as will be illustrated in a subsequent section of this section, where the monthly insolation values are tabulated (see exhibit 8.19). The average of the three lowest months is shown in exhibit 8.4 (4.0 kWh/m^2 per day). Insolation is given as energy per unit area per day.

The electrical energy available to the load is equal to the incident solar energy times the electrical efficiency of the PV power system. The efficiency of the power system must be estimated taking the load demand into consideration. An initial estimate of the needed array size can then be made.

Exhibit 8.2 illustrates a system whose components display the following throughput efficiencies: PV cells - 7.5 percent; array interconnections and leads -95 percent; and, battery storage - 80 percent.

1. Select tilt of 45° for convenience, since data is readily available
2. Use the load computed according to the methods of Chapter 6, 3.6 kWh/day for this example
3. Compute the minimum 3-month insolation (or take it from charts such as exhibit 8.6: Insolation = 4.0 kWh/day - m²
4. Compute the average system efficiency For power directly from array to load 0.075 collector efficiency × 0.95 distribution efficiency = 0.07125 For power from array to battery to load 0.075 collector efficiency × 0.95 distribution efficiency × 0.8 battery efficiency = 0.057 Weighted average based on 8 hr direct and 16 hr via the battery: (8 × 0.07125 + 16 × 0.057) /24 hr = 0.06175
5. Compute array area Array area = load/ (insolation × system efficiency) Array area = 3.6 kWh/day load /(4.0 kWh/day - m² insolation × 0.06175 system efficiency) = 14.67 m²
6. Compute peak output from the array Peak output = 1.0 kW/m² peak insolation × 0.075 array efficiency × 14.67 m² array area = 1.1 kWp

Exhibit 8.4 Estimating the Array Size and Tilt.

Because the battery is bypassed during the daytime, a weighted average of the day and nighttime efficiencies must be used as an estimate of the system efficiency.

$$\text{Daytime efficiency} = (0.075 \times 0.95) \times 100\% = 7.125\%.$$
$$\text{Nighttime efficiency} = (0.075 \times 0.95 \times 0.80) \times 100\% = 5.7\%$$

If the load is constant and there is an average of 8 hours of daylight per day at this site, the overall efficiency of the system is:

$$\text{System efficiency} = \frac{7.125 \times 8 + 5.7 \times 16}{24} = 6.175\%$$

The initial estimate of the needed array size can now be calculated.

$$\text{Array size } (M^2) = \frac{(\text{Load demand/day (kWh/day)})}{\text{Efficiency x average insolation of the 4 lowest months (kWh/day-m}^2)}$$

$$= \frac{3.6}{0.06175 \times 4.0} = 14.67 \text{ m}^2$$

LINES SHOW INSOLATION IN kWh/m² · DAY

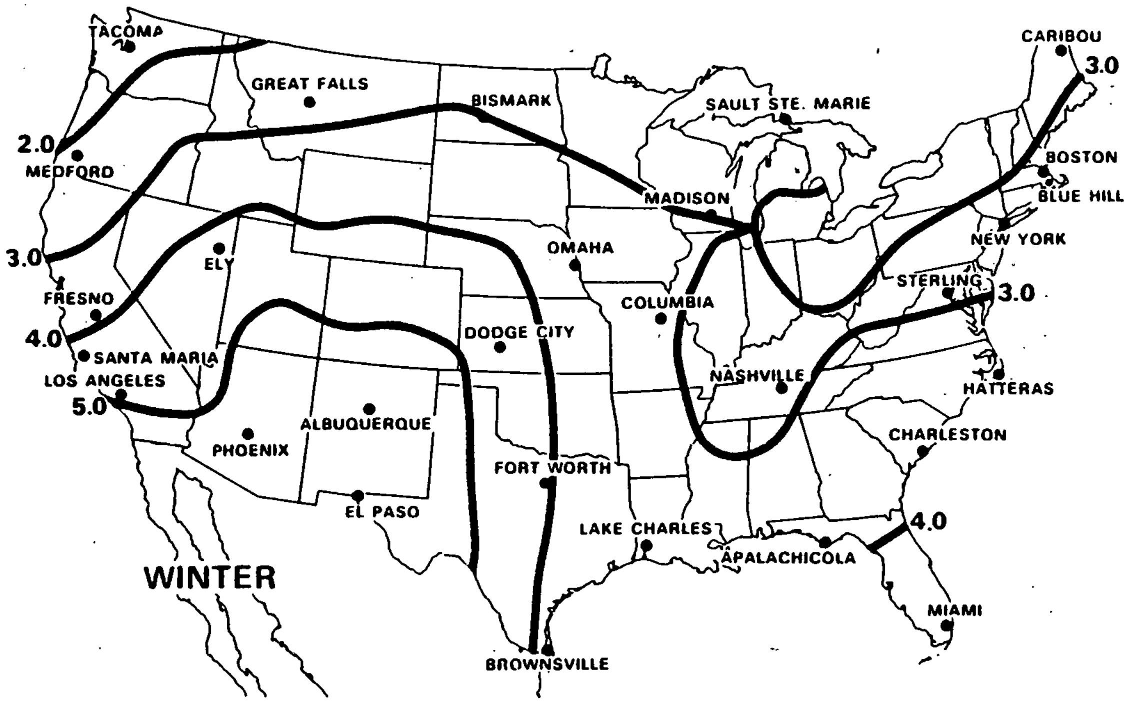


Exhibit 8.5 Total Insolation on a Collector Tilted 45° above the Horizontal: Winter.

LINES SHOW INSOLATION IN kWh/m² · DAY

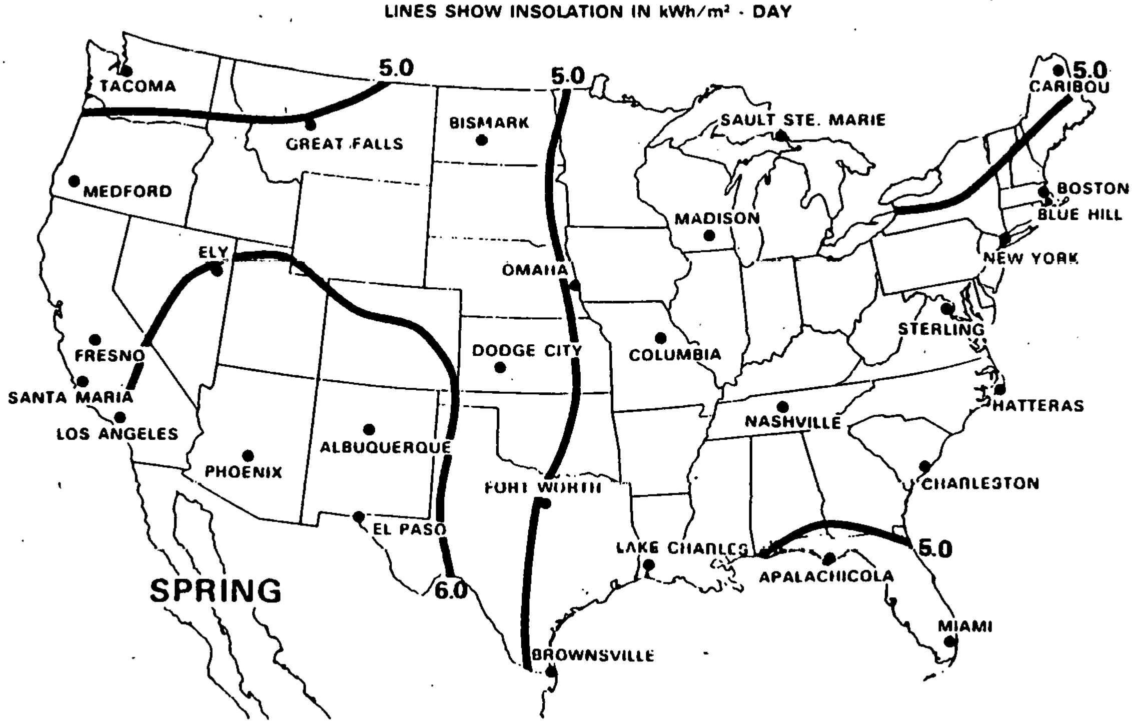


Exhibit 8.6 Total Insolation on a Collector Tilted 45° above the Horizontal: Spring.

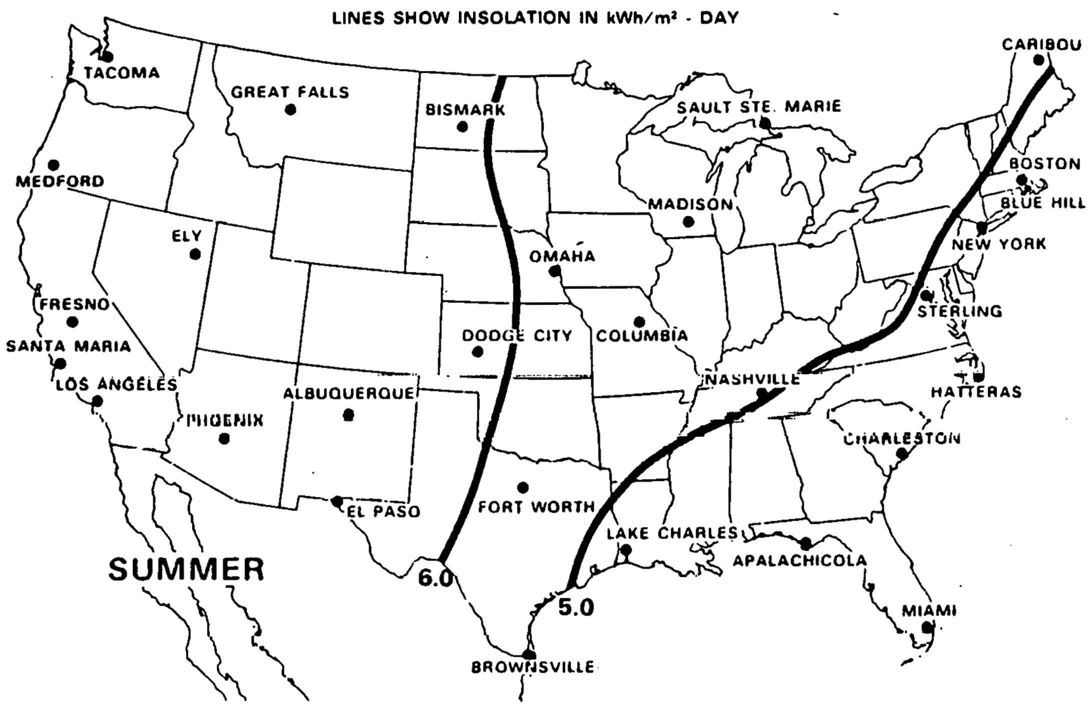


Exhibit 8.7 Total Insolation on a Collector Tilted 45° above the Horizontal: Summer.

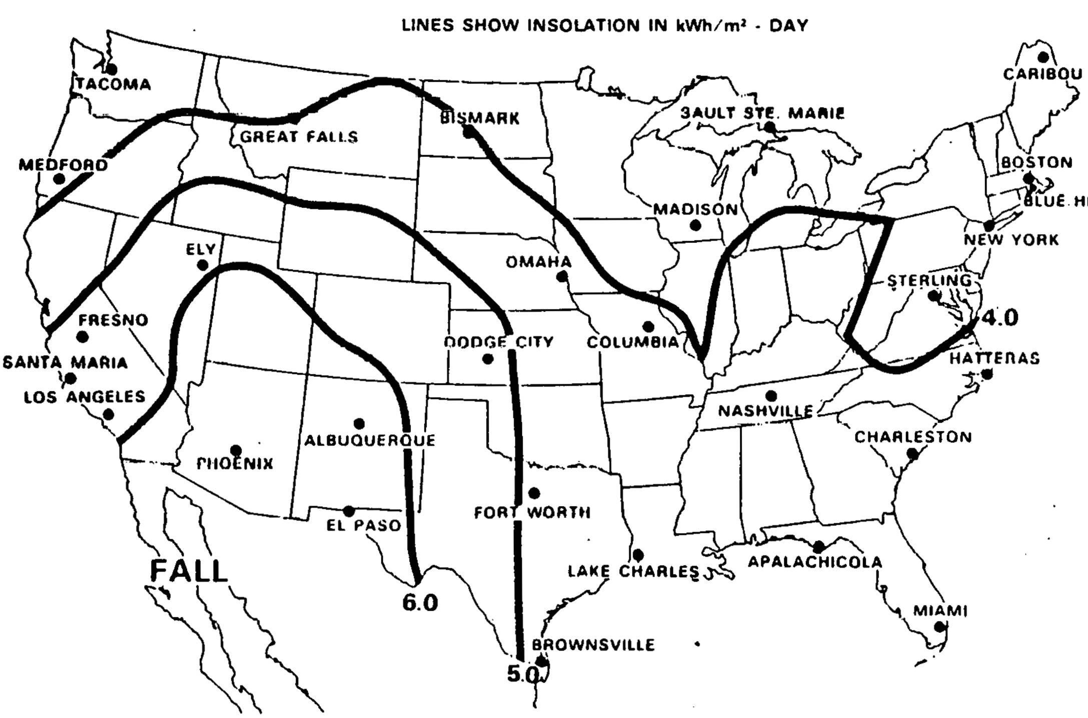


Exhibit 8.8 Total Insolation of a Collector Tilted 45° above the Horizontal: Fall.

The array size can also be expressed in terms of the peak electric power output when the insolation is 1.0 kW/m^2, a common rating point for arrays. In terms of output,

$$\text{Array size (KWp)} = \text{area} \times \text{array efficiency} \times 1.0 \text{ kW/m}^2$$
$$= 14.67 \times 0.075 \times 1.0,$$
$$= 1.10 \text{ kWp.}$$

This is the size and the tilt of the array that will be used in the first more-detailed computation of system performance.

The first step in estimating the system performance more accurately is to determine the insolation on the tilted array. This step was indicated as step B in exhibit 8.3. The computation of the insolation is perhaps the most complicated computation required to estimate the system performance in detail. The following section deals with an approximation for conceptual design, and incorporates resource assessment of the solar thermal power systems program, the solar heating/cooling and solar total energy systems programs.

8.3 INSOLATION COMPUTATION

8.3.1 INTRODUCTION

The output of the solar cells depends on the amount of sunshine striking the solar cells. One of the first steps in computing the system performance involves the computation of the solar input, or insolation (see exhibit 8.9). The procedure that will be followed here uses the method devised by Liu and Jordan and published by ASHRAE and is applicable to systems analysis and synthesis. The method was applied by Duffie and Beckman in the development of the insolation tables. After reading this section, the reader should be able to use these tables and compute the insolation on solar cells tilted at any angle, facing south (north in the southern hemisphere), at any location in the world. The data are most accurate in the United States, where some of the empirical functions were determined. For the present purposes, the method will be accurate enough anywhere.

OBJECTIVES:

To enable the reader to:

1. Use the tables of insolation.

2. Compute the insolation

On tilted collectors

Anywhere in the world.

Exhibit 8.9 Computation of Insolation.

The data for Fairbanks, Alaska are in total disagreement with the other data, apparently due to instrument error. The correlation between cloud cover, CC, and $\bar{K}_T$ is shown in exhibit 8.13. The scatter is considerably greater. If CC were 0.5, the $\bar{K}_T$ could be somewhere between 0.50 and 0.65, a 27-percent range. If F were 0.65, $\bar{K}_T$ would be between 0.51 and 0.61, a range of 18 percent. In estimating insolation, pyranometer data should be sought first, fraction-sunshine data second, and, as a last resort, cloud cover data.

TIME OF YEAR:

$$\bar{S} = 440\left(1 + 0.0167 \cos \frac{(D-284)\,360°}{365 \text{ days}}\right)^2$$

$$= 440 \text{ Btu/hr-ft}^2 = 129 \text{ W/ft}^2 = 1{,}388 \text{ W/m}^2 \quad \pm 3\%$$

TIME OF DAY:

$$S = S_{OVERHEAD}\,(0.85)^{1/\sin A} \quad \text{ON CLEAR DAYS}$$

Example (40° latitude, normal incidence)

DATE:	JAN	APRIL	JULY	OCT
S_{NOON}:	316	354	372	352
$S_{4\ PM}$:	138	308	335	243

EFFECT OF CLOUD COVER:

$$\bar{K}_T = \frac{\text{DAILY INSOLATION ON HORIZONTAL}}{\text{DAILY INSOLATION ON HORIZONTAL WITH NO ATMOSPHERE}}$$

$$0.04 < \bar{K}_T < 0.95$$

NOTE:

D = DAY OF THE YEAR (D = 2 FOR JANUARY 2)
A = SOLAR ALTITUDE ANGLE
S = INSOLATION ON PLATE FACING THE SUN

Exhibit 8.10 Variability of Insolation.

Possibly the best procedure for estimating insolation at a site with no pyranometer data is to find the closest station having pyranometer data. Then the correlations for fraction sunshine or cloud cover can be used to adjust the pyranometer data to the location of interest.

8.3.2 VARIABILITY OF INSOLATION

The computation of insolation must take into account the variation of insolation throughout the year, throughout the day, and throughout clear and cloudy days. Exhibit 8.10 shows the three effects and gives numerical evaluations of each. Because the distance between earth and sun varies throughout the year, the insolation varies plus or minus 3 percent over the year. Outside the atmosphere, on a plate held perpendicular to the solar rays, the solar flux is 129 W/ft^2 or 1,388 W/m^2, on the average over the year, where flux equals power per unit area.

Of more importance than the variation throughout the year is the variation throughout the day. At noon, the solar rays must penetrate the least amount of atmosphere, so the attenuation is least. On a clear day, the insolation at noon is approximately 85 percent of the insolation that would impinge on a plate outside the atmosphere. At times other than noon, the solar rays must penetrate a greater depth of atmosphere. The effect of the penetration distance is given by the simple power law shown in exhibit 8.10. If A is 30^o, sin A is 0.5 and the reciprocal of sin A is 2, then the atmospheric transmission is 0.85^2, or 0.5625 (approximately 56 percent). The table in exhibit 8.10 provides additional examples for a site at 40^oN latitude. It is evident that at 4 p.m. in January, the transmission is quite low, whereas at 4 p.m. in July, the transmission is still high. (The plate is assumed to be held perpendicular to the sun's rays and the numbers given are for the direct sunlight only. The total sunlight would be somewhat higher due to reflection from the same atmospheric particles that cause the loss in direct transmission.)

DEFINITION OF $\bar{K}_T$

Cloud cover has the greatest single influence on insolation. If a ratio, $\bar{K}_T$, is defined as the ratio of total flux on a horizontal surface over the entire day to the total flux that would be received if there were no atmosphere (called the extraterrestrial flux), then $\bar{K}_T$ would be found to range from 0.05 to 0.95, normal values being approximately 0.60. Thus, the clouds can cause the insolation to be only 5 percent of what might otherwise reach the surface of the earth.

8.3.3 MEASUREMENTS OF INSOLATION

The most accurate measurement of local insolation is obtained from a heat-flux meter called a pyranometer. The instrument measures the temperature reached by a blackened cavity when exposed to sunlight and protected from the ambient air by a glass dome. The instrument is calibrated by illuminating it with a beam of known intensity. Instead of a black cavity, some pyranometers measure the temperature difference between black and white strips and infer the insolation from this temperature difference. These black-and-white pyranometers are more difficult to calibrate and degrade more rapidly than the more precise black-cavity pyranometer. Intensity is defined as energy per unit time per unit area.

Few weather stations are equipped with pyranometers. As indicated in exhibit 8.11, some have Campbell-Stokes sunshine meters while others report the weatherman's estimate of the fraction of the sky that is covered by clouds. The Campbell-Stokes instrument focuses the sunlight onto a strip of paper, which is burned when the sunlight is bright enough. The length of the burn indicates the hours of sunshine. Actually, the instrument indicates the hours the sunshine was bright enough to burn the paper, so the hours are the hours of direct sunlight. Newer sun-actuated switches provide similar data. Exhibit 8.12 compares a correlation between (hours of sunshine as a fraction of possible sunshine F) to ($\bar{K}_T$). Good correlation is obtained with $\bar{K}_T = 0.85 \times F$.

Pyranometer — energy measurement

Fraction of Possible Sunshine — burning of paper

Cloud Cover - human visual observation, judgment

Exhibit 8.11 Measurement of Insolation.

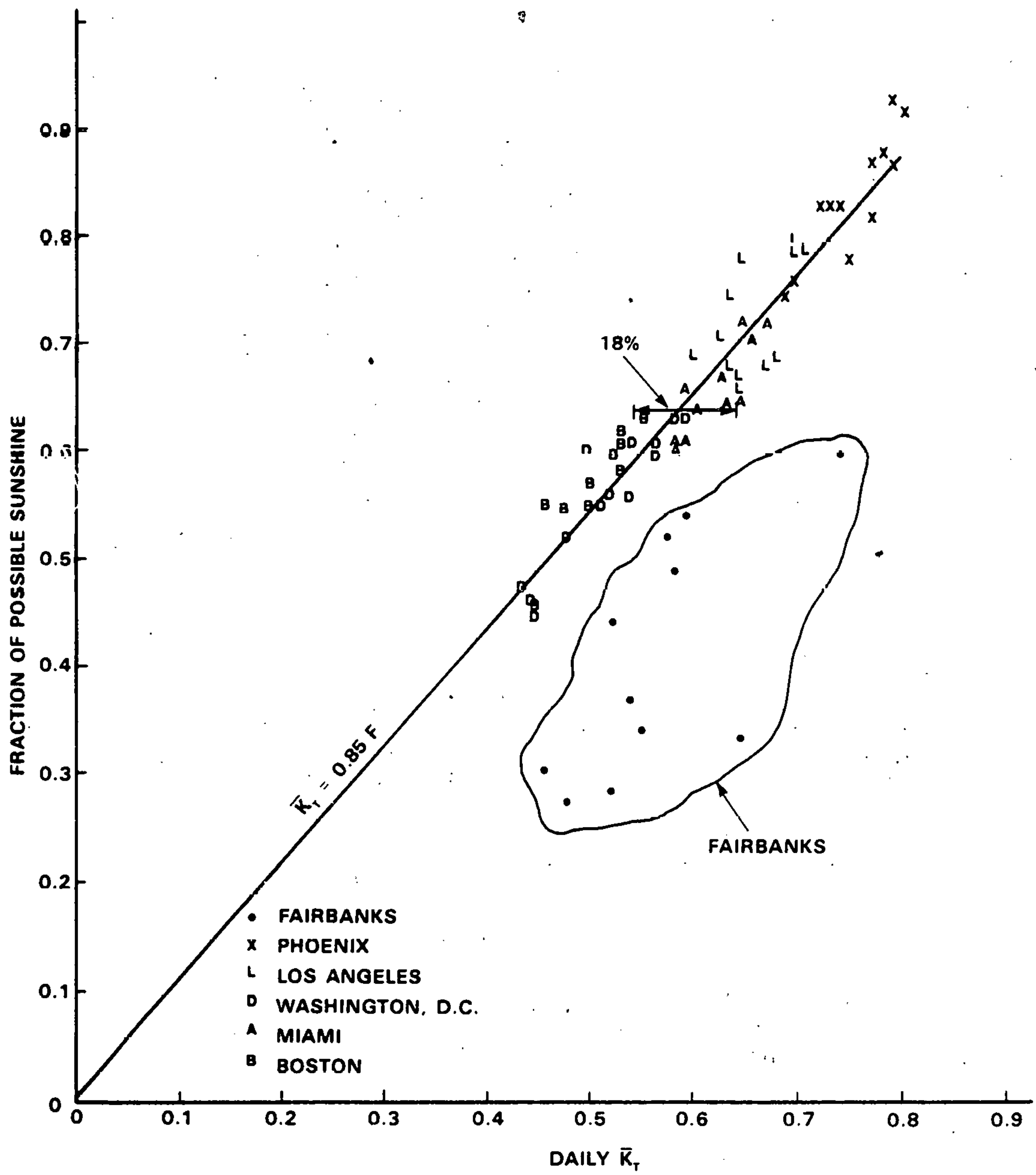


Exhibit 8.12 Correlation between $\bar{K}_T$ and Fraction of Sunshine.

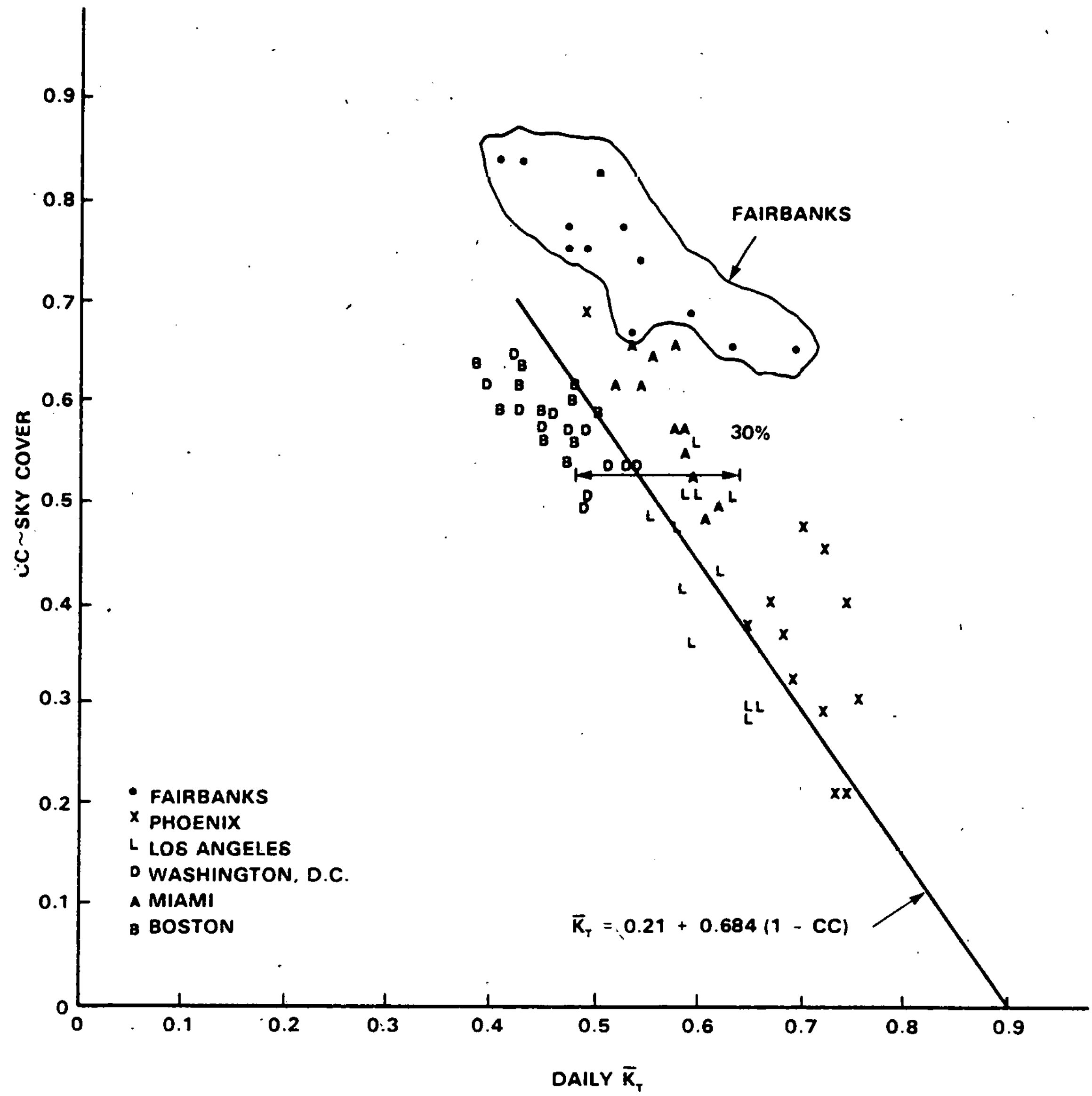


Exhibit 8.13 Correlation between $\overline{K}_T$ and Cloud Cover.

For example, suppose one needed $\bar{K}_T$ for location A and the closest pyranometer data were for location B, 100 miles away. Suppose both locations had data on fraction sunshine, as indicated in exhibit 8.14; 0.60 for A and 0.65 for B, with $\bar{K}_T$ at 0.52 for B. From exhibit 8.12, F = 0.65 and $\bar{K}_T$ = 0.52 are not consistent with the correlation curve. To adjust to location A, one can use the coefficient 0.85 of the correlation equation to write:

$$\bar{K}_T = 0.52 - 0.85 \times (0.65 - 0.60) = 0.48$$

AVAILABLE DATA			
LOCATION	$\bar{K}_T$	F	CC
A		0.60	
B	0.52	0.65	

Computation of $\bar{K}_T$ for Location A:

Correlation shows:

$$\bar{K}_T = \bar{K}_T(B) - (B) - 0.85\,[F(B) - F(A)]$$

$$= 0.52 - 0.85\,(0.65 - 0.60)$$

$$\bar{K}_T(A) = 0.48$$

Exhibit 8.14 Sample Computation Procedure.

8.3.4 VALUES OF $\bar{K}_T$

Values of $\bar{K}_T$ were derived from measurements of the National Weather Service and extrapolated by Duffie and Beckman in a manner similar to that just described to produce the tables for the United States (exhibit 8.15). These tables show not only the flux ratio, but also the horizontal flux, the average outdoor-air temperature for the month, and the number of heating degree-days accumulated that month, on the average. For world insolation see World Distribution of Solar Radiation, Report No. 21 by George O. O. Lof, John A. Duffie, and Clayton O. Smith, Solar Energy Laboratory, The University of Wisconsin, July, 1966. The insolation can be converted to $\bar{K}_T$ values by dividing by the extraterrestrial flux, as tabulated in exhibit 8.25 for each latitude and month. On exhibit 8.15, SI units have been used, so the degree-days, for example, are in C degrees. One MJ (megajoule) is equal to one million W-seconds of energy, where W represents watts of power.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
ABILENE	TX (LAT. 32.2)												
	$\bar{H}$ MJ/m^2	11.47	14.74	18.42	22.11	24.24	27.05	25.41	23.74	20.43	16.24	12.31	10.51
	$\bar{K}_T$	.58	.60	.61	.61	.61	.66	.63	.64	.63	.62	.59	.57
	T_a C	6.0	9.0	12.0	18.0	22.0	27.0	29.0	29.0	24.0	19.0	12.0	8.0
	DD C-DAY	367.	266.	197.	58.	6.	0.	0.	0.	0.	49.	187.	321.
ALBANY	NY (LAT. 42.4)												
	$\bar{H}$ MJ/m^2	5.19	7.65	14.34	15.22	18.44	25.22	22.37	18.65	13.05	10.75	9.20	5.86
	$\bar{K}_T$	.38	.40	.55	.45	.47	.61	.56	.52	.45	.51	.62	.48
	T_a C	-5.0	-4.0	.0	8.0	14.0	19.0	22.0	21.0	17.0	10.0	4.0	-2.0
	DD C-DAY	749.	646.	544.	302.	141.	22.	5.	12.	75.	234.	423.	673.
ALBUQUERQUE	NM (LAT. 35.0)												
	$\bar{H}$ MJ/m^2	12.88	16.31	21.41	26.35	28.77	30.90	28.86	26.60	23.67	18.69	14.13	11.75
	$\bar{K}_T$	.71	.71	.73	.74	.73	.75	.72	.72	.75	.75	.74	.71
	T_a C	1.0	4.0	7.0	12.0	17.0	22.0	25.0	23.0	20.0	13.0	6.0	1.0
	DD C-DAY	513.	389.	331.	157.	32.	0.	0.	0.	4.	121.	342.	496.
AMARILLO	TX (LAT. 35.1)												
	$\bar{H}$ MJ/m^2	11.93	15.24	19.17	23.61	25.83	27.38	26.75	25.12	21.23	16.83	12.98	10.72
	$\bar{K}_T$	.66	.66	.65	.67	.63	.67	.66	.68	.67	.68	.68	.65
	T_a C	2.0	4.0	8.0	14.0	19.0	24.0	26.0	25.0	21.0	15.0	8.0	4.0
	DD C-DAY	499.	393.	334.	153.	45.	6.	0.	0.	11.	114.	312.	457.
AMES	IA (LAT. 42.0)												
	$\bar{H}$ MJ/m^2	7.28	10.58	13.67	16.85	20.07	22.62	22.41	19.24	15.35	11.46	7.82	5.98
	$\bar{K}_T$	.53	.55	.52	.50	.51	.55	.56	.54	.53	.54	.52	.48
	T_a C	-7.0	-4.0	.0	9.0	15.0	20.0	23.0	22.0	17.0	11.0	2.0	-4.0
	DD C-DAY	794.	639.	539.	260.	106.	18.	0.	8.	58.	206.	463.	699.
AMHERST	MA (LAT. 42.1)												
	$\bar{H}$ MJ/m^2	4.85	7.40	12.55	14.51	18.02	21.49	21.58	18.40	13.80	10.45	6.40	5.19
	$\bar{K}_T$	.35	.39	.48	.43	.46	.52	.54	.51	.48	.49	.43	.42
	T_a C	-4.0	-3.0	1.0	8.0	14.0	19.0	21.0	20.0	16.0	11.0	4.0	-2.0
	DD C-DAY	713.	611.	515.	300.	139.	23.	4.	12.	68.	221.	403.	644.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
ANNAPOLIS	MD (LAT. 38.6)												
	$\bar{H}$ MJ/m^2	7.33	10.17	14.24	17.54	20.43	23.32	22.69	19.64	16.03	12.31	7.91	6.49
	$\bar{K}_T$	.46	.48	.51	.51	.52	.56	.56	.54	.53	.53	.46	.45
	T_a C	1.0	2.0	6.0	12.0	17.0	22.0	24.0	23.0	20.0	14.0	8.0	2.0
	DD C-DAY	526.	454.	376.	183.	58.	0.	0.	0.	16.	137.	293.	484.
ANNETTE	AK (LAT. 55.0)												
	$\bar{H}$ MJ/m^2	2.64	4.81	9.88	15.24	18.30	18.34	18.34	14.28	10.80	5.11	2.47	1.72
	$\bar{K}_T$	.43	.42	.51	.52	.49	.45	.47	.44	.47	.37	.34	.36
	T_a C	.0	2.0	3.0	5.0	9.0	11.0	15.0	14.0	12.0	8.0	4.0	2.0
	DD C-DAY	527.	465.	468.	381.	281.	187.	143.	124.	196.	315.	410.	499.
APALACHICOLA	FL (LAT. 29.4)												
	$\bar{H}$ MJ/m^2	12.25	15.22	18.44	23.00	25.47	24.71	22.62	21.20	19.24	17.48	13.93	11.04
	$\bar{K}_T$	.57	.59	.59	.63	.64	.61	.57	.56	.58	.63	.62	.55
	T_a C	12.0	13.0	15.0	19.0	23.0	26.0	27.0	27.0	26.0	21.0	16.0	13.0
	DD C-DAY	193.	144.	100.	18.	0.	0.	0.	0.	0.	9.	85.	177.
ASHEVILLE	NC (LAT. 35.3)												
	$\bar{H}$ MJ/m^2	9.21	12.48	16.03	20.51	23.28	23.78	23.24	21.56	18.25	14.86	10.47	8.46
	$\bar{K}_T$	.51	.54	.55	.58	.59	.58	.58	.58	.58	.60	.55	.51
	T_a C	3.0	4.0	8.0	13.0	18.0	21.0	23.0	23.0	19.0	14.0	8.0	4.0
	DD C-DAY	467.	398.	329.	155.	56.	8.	0.	0.	28.	149.	312.	453.
ASTORIA	OR (LAT. 46.1)												
	$\bar{H}$ MJ/m^2	3.85	6.52	11.17	15.51	20.49	20.16	22.37	19.07	15.01	8.82	4.77	3.26
	$\bar{K}_T$	.34	.39	.46	.48	.53	.49	.56	.55	.55	.47	.38	.33
	T_a C	5.0	6.0	6.0	8.0	11.0	13.0	15.0	15.0	14.0	11.0	8.0	5.0
	DD C-DAY	420.	333.	355.	287.	219.	142.	91.	84.	112.	210.	308.	382.
ATLANTA	GA (LAT. 33.4)												
	$\bar{H}$ MJ/m^2	9.53	11.88	15.77	20.24	22.37	23.17	22.50	20.99	17.23	14.64	11.08	8.41
	$\bar{K}_T$	.50	.50	.53	.56	.56	.56	.56	.56	.54	.57	.55	.48
	T_a C	6.0	7.0	11.0	16.0	20.0	24.0	25.0	25.0	22.0	17.0	11.0	7.0
	DD C-DAY	389.	311.	246.	80.	15.	0.	0.	0.	4.	76.	227.	371.

Exhibit 8.15 Values of $\bar{K}_T$ and Insolation for the United States.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
ATLANTIC CITY	NJ (LAT. 39.3)												
$\bar{H}$	MJ/m²	7.41	10.68	16.12	18.09	20.64	23.99	23.78	19.97	16.41	12.64	8.83	6.66
$\bar{K}_T$		.48	.51	.59	.52	.52	.58	.59	.55	.55	.56	.53	.47
T_a	C	2.0	2.0	5.0	10.0	15.0	21.0	23.0	23.0	20.0	15.0	9.0	3.0
DD	C-DAY	520.	461.	407.	242.	100.	8.	0.	0.	13.	111.	277.	470.
BALTIMORE	MD (LAT. 39.1)												
$\bar{H}$	MJ/m²	7.33	10.17	14.24	17.54	20.43	23.32	22.69	19.64	16.03	12.31	7.91	6.49
$\bar{K}_T$		.47	.49	.52	.51	.52	.56	.56	.54	.53	.54	.47	.46
T_a	C	1.0	2.0	6.0	12.0	18.0	22.0	25.0	24.0	20.0	14.0	8.0	2.0
DD	C-DAY	544.	470.	382.	189.	61.	0.	0.	0.	15.	139.	315.	512.
BARROW	AK (LAT. 71.2)												
$\bar{H}$	MJ/m²	.13	1.67	7.99	16.85	20.95	22.87	17.73	10.62	4.81	1.72	.29	.00
$\bar{K}_T$		.00	.79	.81	.76	.60	.54	.46	.39	.34	.42	.00	.00
T_a	C	-25.0	-28.0	-26.0	-18.0	-7.0	.0	3.0	3.0	.0	-9.0	-18.0	-24.0
DD	C-DAY	1398.	1296.	1371.	1080.	803.	547.	446.	467.	575.	833.	1095.	1271.
BETHEL	AK (LAT. 60.5)												
$\bar{H}$	MJ/m²	1.55	4.68	11.79	18.57	19.19	18.78	15.47	10.62	8.32	4.89	1.88	.96
$\bar{K}_T$		.49	.57	.72	.69	.53	.46	.40	.35	.41	.47	.44	.47
T_a	C	-14.0	-13.0	-11.0	-4.0	4.0	10.0	12.0	11.0	7.0	-1.0	-8.0	-15.0
DD	C-DAY	1057.	883.	919.	652.	448.	223.	177.	219.	340.	579.	797.	1037.
BIG SPRING	TX (LAT. 32.1)												
$\bar{H}$	MJ/m²	11.21	14.39	19.49	24.38	23.92	24.80	23.08	19.57	21.87	16.14	12.17	10.87
$\bar{K}_T$		.57	.58	.64	.68	.60	.61	.57	.52	.67	.61	.58	.59
T_a	C	6.0	9.0	12.0	18.0	22.0	26.0	28.0	28.0	24.0	18.0	12.0	7.0
DD	C-DAY	362.	260.	179.	50.	0.	0.	0.	0.	0.	48.	212.	329.
BILLINGS	MT (LAT. 45.5)												
$\bar{H}$	MJ/m²	6.62	9.92	15.03	19.09	22.65	25.62	26.63	23.32	17.75	10.68	7.24	5.57
$\bar{K}_T$		.56	.58	.61	.58	.58	.62	.67	.67	.65	.55	.56	.54
T_a	C	-6.0	-3.0	.0	7.0	12.0	17.0	22.0	21.0	15.0	10.0	2.0	-3.0
DD	C-DAY	742.	585.	558.	340.	185.	73.	6.	8.	123.	271.	488.	658.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
BINGHAMPTON	NY (LAT. 42.1)												
$\bar{H}$	MJ/m²	5.82	8.54	12.48	15.99	20.39	23.32	22.90	19.72	15.24	10.80	6.03	4.77
$\bar{K}_T$		.42	.45	.48	.47	.52	.56	.57	.55	.53	.51	.40	.39
T_a	C	-6.0	-5.0	.0	7.0	13.0	18.0	21.0	20.0	16.0	10.0	3.0	-4.0
DD	C-DAY	741.	657.	581.	338.	178.	42.	12.	22.	96.	253.	447.	682.
BIRMINGHAM	AL (LAT. 33.3)												
$\bar{H}$	MJ/m²	8.58	11.85	15.32	20.56	23.40	23.57	22.94	21.18	18.09	15.03	10.38	8.12
$\bar{K}_T$		.45	.49	.51	.57	.59	.57	.57	.57	.56	.58	.51	.46
T_a	C	7.0	8.0	12.0	17.0	21.0	25.0	27.0	26.0	23.0	17.0	11.0	7.0
DD	C-DAY	363.	287.	216.	64.	11.	0.	0.	0.	3.	76.	217.	341.
BISMARCK	ND (LAT. 46.5)												
$\bar{H}$	MJ/m²	6.61	10.50	14.68	18.78	23.04	24.55	25.59	21.66	15.98	11.42	6.73	5.19
$\bar{K}_T$		.59	.63	.61	.58	.60	.59	.64	.62	.59	.61	.54	.54
T_a	C	-13.0	-11.0	-3.0	6.0	12.0	17.0	21.0	20.0	14.0	7.0	-1.0	-9.0
DD	C-DAY	978.	801.	687.	367.	188.	68.	10.	19.	140.	313.	602.	851.
BLUE HILL	MA (LAT. 42.1)												
$\bar{H}$	MJ/m²	6.52	8.99	12.71	15.85	19.70	21.62	20.91	18.15	14.72	10.41	6.61	5.39
$\bar{K}_T$		.47	.47	.49	.47	.50	.52	.52	.51	.51	.49	.44	.44
T_a	C	-3.0	-3.0	1.0	7.0	13.0	18.0	21.0	20.0	16.0	11.0	5.0	-1.0
DD	C-DAY	654.	585.	520.	322.	148.	38.	0.	12.	59.	212.	383.	603.
BOISE	ID (LAT. 43.3)												
$\bar{H}$	MJ/m²	5.94	9.74	14.18	20.32	24.55	26.72	27.98	23.80	19.07	13.13	7.57	5.14
$\bar{K}_T$		.46	.53	.55	.61	.63	.65	.70	.67	.67	.64	.53	.44
T_a	C	-1.0	1.0	5.0	9.0	14.0	18.0	23.0	22.0	17.0	11.0	4.0	.0
DD	C-DAY	618.	474.	401.	243.	136.	45.	0.	0.	73.	231.	440.	565.
BOSTON	MA (LAT. 42.2)												
$\bar{H}$	MJ/m²	5.81	8.28	12.25	15.22	19.74	20.87	20.74	17.77	14.26	9.95	6.06	4.98
$\bar{K}_T$		.42	.43	.47	.45	.50	.50	.52	.50	.49	.47	.41	.41
T_a	C	-1.0	.0	3.0	9.0	15.0	20.0	23.0	22.0	18.0	13.0	7.0	1.0
DD	C-DAY	604.	540.	470.	285.	116.	20.	0.	5.	33.	176.	335.	546.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
BOULDER	CO (LAT. 40.0)											
$\bar{H}$ MJ/m^2	8.41	11.22	16.79	19.26	19.26	21.98	21.77	18.38	17.25	12.98	9.29	7.62
$\bar{K}_T$	.56	.55	.62	.56	.49	.53	.54	.51	.58	.58	.57	.56
T_a C	.0	1.0	3.0	9.0	14.0	19.0	23.0	22.0	17.0	12.0	5.0	2.0
DD C-DAY	551.	459.	449.	268.	131.	49.	3.	0.	77.	204.	383.	503.
BROWNSVILLE	TX (LAT. 25.5)											
$\bar{H}$ MJ/m^2	12.00	14.05	16.81	19.15	23.25	25.26	25.89	23.21	19.45	16.98	11.88	10.58
$\bar{K}_T$	.51	.50	.51	.52	.59	.63	.65	.61	.57	.58	.48	.47
T_a C	15.0	17.0	20.0	23.0	26.0	28.0	28.0	28.0	27.0	24.0	19.0	16.0
DD C-DAY	125.	84.	49.	0.	0.	0.	0.	0.	0.	3.	19.	81.
CAPE HATTERAS	NC (LAT. 35.2)											
$\bar{H}$ MJ/m^2	10.20	13.26	18.07	23.88	26.56	26.97	26.30	23.29	19.74	15.10	11.88	9.03
$\bar{K}_T$	.57	.58	.62	.67	.67	.66	.65	.63	.63	.61	.62	.54
T_a C	8.0	8.0	10.0	14.0	19.0	23.0	25.0	25.0	23.0	18.0	13.0	9.0
DD C-DAY	339.	299.	254.	104.	26.	0.	0.	0.	0.	42.	154.	298.
CARIBOU	ME (LAT. 46.5)											
$\bar{H}$ MJ/m^2	5.73	9.62	15.35	16.73	19.82	20.07	21.29	18.82	13.93	8.78	4.60	4.43
$\bar{K}_T$	.52	.58	.64	.52	.51	.49	.53	.54	.52	.47	.37	.46
T_a C	-11.0	-10.0	-4.0	3.0	10.0	15.0	18.0	17.0	12.0	7.0	.0	-8.0
DD C-DAY	939.	817.	727.	477.	260.	102.	43.	64.	187.	379.	580.	853.
CHARLESTON	SC (LAT. 32.5)											
$\bar{H}$ MJ/m^2	10.58	12.67	16.39	21.54	23.00	23.42	21.87	20.74	17.06	14.34	11.92	9.03
$\bar{K}_T$	.54	.52	.54	.60	.58	.57	.54	.56	.53	.55	.58	.50
T_a C	10.0	10.0	14.0	18.0	22.0	25.0	27.0	26.0	24.0	19.0	14.0	10.0
DD C-DAY	271.	216.	162.	30.	0.	0.	0.	0.	0.	33.	157.	262.
CHARLOTTE	NC (LAT. 35.1)											
$\bar{H}$ MJ/m^2	9.29	12.39	16.20	21.39	23.07	24.45	23.65	21.69	18.21	14.86	10.51	8.54
$\bar{K}_T$	.52	.54	.55	.60	.58	.59	.59	.59	.58	.60	.55	.51
T_a C	6.0	7.0	10.0	16.0	20.0	24.0	26.0	25.0	22.0	16.0	11.0	6.0
DD C-DAY	394.	327.	256.	81.	19.	0.	0.	0.	6.	84.	233.	388.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
CHATTANOOGA	TN (LAT. 35.0)											
$\bar{H}$ MJ/m^2	8.12	11.35	14.49	19.51	22.57	23.32	22.90	21.02	17.84	13.94	9.46	7.58
$\bar{K}_T$	.45	.49	.49	.55	.57	.57	.57	.57	.57	.56	.49	.45
T_a C	5.0	6.0	10.0	16.0	20.0	24.0	26.0	26.0	22.0	16.0	9.0	5.0
DD C-DAY	427.	347.	268.	92.	28.	0.	0.	0.	5.	101.	268.	410.
CHICAGO	IL (LAT. 41.6)											
$\bar{H}$ MJ/m^2	7.15	9.70	13.63	16.31	20.78	23.13	22.04	20.32	16.06	11.08	6.57	5.48
$\bar{K}_T$	.51	.50	.52	.48	.53	.56	.55	.57	.55	.52	.43	.43
T_a C	-3.0	-2.0	3.0	10.0	16.0	21.0	24.0	23.0	19.0	13.0	5.0	-1.0
DD C-DAY	701.	585.	486.	252.	116.	14.	0.	4.	32.	176.	410.	629.
CLEVELAND	OH (LAT. 41.2)											
$\bar{H}$ MJ/m^2	5.19	7.53	13.05	15.77	21.87	23.38	23.04	20.62	15.72	11.00	5.90	4.81
$\bar{K}_T$	.36	.38	.49	.46	.56	.57	.57	.57	.54	.51	.38	.37
T_a C	-2.0	-1.0	2.0	9.0	15.0	20.0	22.0	21.0	18.0	12.0	5.0	.0
DD C-DAY	656.	577.	498.	278.	136.	22.	5.	9.	53.	197.	390.	598.
COLUMBIA	MO (LAT. 38.6)											
$\bar{H}$ MJ/m^2	7.53	10.45	14.39	18.11	22.21	23.88	24.00	22.00	18.73	13.55	9.28	7.07
$\bar{K}_T$	.47	.49	.52	.52	.56	.58	.60	.60	.62	.59	.54	.49
T_a C	-1.0	.0	6.0	12.0	18.0	23.0	25.0	24.0	20.0	14.0	6.0	.0
DD C-DAY	598.	486.	398.	180.	67.	7.	0.	0.	30.	139.	362.	537.
COLUMBUS	OH (LAT. 40.0)											
$\bar{H}$ MJ/m^2	5.39	8.28	12.38	16.43	20.41	23.50	22.67	19.95	17.65	11.96	7.44	5.52
$\bar{K}_T$	.36	.41	.46	.48	.52	.57	.56	.55	.59	.54	.46	.41
T_a C	-1.0	.0	4.0	11.0	16.0	21.0	23.0	22.0	18.0	12.0	5.0	.0
DD C-DAY	604.	527.	449.	237.	95.	15.	0.	3.	47.	193.	397.	577.
CORPUS CHRISTI	TX (LAT. 27.5)											
$\bar{H}$ MJ/m^2	10.97	13.82	17.29	19.85	23.49	25.29	26.33	23.36	19.68	17.08	11.93	10.25
$\bar{K}_T$	.49	.51	.54	.54	.59	.63	.66	.62	.58	.60	.51	.47
T_a C	13.0	15.0	18.0	22.0	25.0	27.0	29.0	29.0	27.0	23.0	18.0	15.0
DD C-DAY	169.	111.	67.	0.	0.	0.	0.	0.	0.	4.	45.	122.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
CORVALLIS OR (LAT. 44.3)	H MJ/m²	4.22	5.81	11.75	16.89	21.24	24.30	28.02	22.87	16.69	9.83	5.86	3.39
	K_T	.34	.33	.47	.51	.55	.59	.70	.65	.60	.49	.43	.31
	T_a C	3.0	6.0	7.0	10.0	13.0	16.0	18.0	18.0	16.0	11.0	7.0	5.0
	DD C-DAY	451.	341.	336.	248.	163.	80.	34.	31.	67.	203.	328.	413.
DALLAS TX (LAT. 32.5)	H MJ/m²	9.67	12.85	16.49	19.01	21.81	24.91	24.62	22.52	19.17	15.20	10.93	9.25
	K_T	.49	.53	.54	.53	.55	.61	.61	.60	.59	.58	.53	.51
	T_a C	7.0	10.0	13.0	19.0	23.0	28.0	30.0	30.0	26.0	20.0	13.0	9.0
	DD C-DAY	338.	243.	174.	39.	0.	0.	0.	0.	0.	31.	158.	289.
DAVIS CA (LAT. 38.3)	H MJ/m²	6.61	10.71	16.81	22.08	26.60	29.36	28.86	25.55	20.83	14.55	9.03	6.19
	K_T	.41	.50	.60	.64	.67	.71	.72	.70	.69	.63	.52	.42
	T_a C	7.0	9.0	11.0	14.0	17.0	21.0	23.0	22.0	21.0	17.0	11.0	7.0
	DD C-DAY	324.	230.	184.	99.	40.	0.	0.	0.	0.	31.	178.	303.
DAYTON OH (LAT. 39.5)	H MJ/m²	6.78	9.38	13.90	17.46	21.69	24.07	23.61	21.52	17.75	12.94	7.83	6.07
	K_T	.44	.46	.51	.51	.55	.58	.59	.59	.59	.57	.47	.44
	T_a C	-2.0	-1.0	4.0	11.0	16.0	22.0	24.0	23.0	19.0	13.0	5.0	-1.0
	DD C-DAY	636.	538.	448.	229.	92.	7.	0.	4.	35.	171.	387.	587.
DENVER CO (LAT. 39.4)	H MJ/m²	10.68	14.15	18.25	21.73	24.37	27.38	26.50	24.79	20.68	15.49	10.97	9.13
	K_T	.69	.69	.67	.63	.62	.66	.66	.68	.69	.69	.66	.65
	T_a C	-1.0	.0	3.0	8.0	14.0	19.0	23.0	22.0	17.0	11.0	4.0	.0
	DD C-DAY	604.	501.	482.	292.	141.	44.	0.	0.	67.	227.	427.	558.
DES MOINES IA (LAT. 41.3)	H MJ/m²	7.03	9.92	13.48	17.79	21.52	23.78	23.78	20.93	16.96	12.60	7.91	5.78
	K_T	.49	.51	.51	.52	.55	.57	.59	.58	.58	.58	.51	.45
	T_a C	-7.0	-4.0	1.0	10.0	16.0	21.0	24.0	23.0	18.0	12.0	3.0	-4.0
	DD C-DAY	786.	634.	536.	258.	103.	14.	0.	7.	52.	194.	453.	689.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
DETROIT MI (LAT. 42.1)	H MJ/m²	5.44	8.33	12.52	16.20	20.89	23.24	23.36	20.26	16.03	11.39	6.20	4.81
	K_T	.40	.44	.48	.48	.53	.56	.58	.57	.56	.54	.41	.39
	T_a C	-4.0	-3.0	2.0	9.0	14.0	20.0	22.0	22.0	18.0	12.0	4.0	-2.0
	DD C-DAY	696.	597.	512.	288.	136.	20.	3.	9.	53.	209.	415.	629.
DODGE CITY KA (LAT. 37.5)	H MJ/m²	10.83	13.67	18.07	22.58	23.54	27.56	27.18	24.38	20.62	15.89	11.71	9.70
	K_T	.65	.63	.64	.65	.60	.67	.67	.67	.67	.67	.66	.64
	T_a C	-1.0	1.0	5.0	12.0	17.0	23.0	26.0	25.0	20.0	13.0	5.0	.0
	DD C-DAY	589.	463.	410.	191.	64.	12.	0.	0.	23.	137.	370.	544.
DULUTH MN (LAT. 46.5)	H MJ/m²	5.37	8.83	13.44	16.70	20.22	23.11	23.19	19.55	13.94	9.71	5.32	4.35
	K_T	.50	.53	.56	.52	.52	.56	.58	.56	.52	.52	.43	.45
	T_a C	-13.0	-11.0	-5.0	4.0	10.0	15.0	19.0	18.0	12.0	7.0	-2.0	-10.0
	DD C-DAY	973.	833.	718.	440.	269.	108.	37.	58.	177.	339.	810.	872.
EAST LANSING MI (LAT. 42.4)	H MJ/m²	4.81	8.36	12.29	14.18	19.65	21.70	21.37	18.44	14.76	10.12	5.39	4.31
	K_T	.35	.44	.47	.42	.50	.52	.53	.52	.51	.48	.36	.35
	T_a C	-5.0	-4.0	.0	8.0	13.0	19.0	21.0	20.0	16.0	10.0	3.0	-2.0
	DD C-DAY	730.	638.	553.	308.	156.	27.	5.	13.	74.	234.	443.	653.
EL PASO TX (LAT. 31.5)	H MJ/m²	13.84	18.07	22.96	27.39	29.90	30.53	28.02	26.72	24.05	19.32	15.35	13.09
	K_T	.69	.72	.75	.76	.75	.75	.70	.71	.74	.73	.72	.70
	T_a C	7.0	9.0	13.0	17.0	22.0	27.0	27.0	26.0	23.0	18.0	11.0	7.0
	DD C-DAY	381.	247.	177.	58.	0.	0.	0.	0.	0.	47.	230.	360.
ELY NV (LAT. 39.2)	H MJ/m²	9.95	13.93	19.40	23.59	26.10	29.61	27.10	25.43	21.70	16.43	12.00	9.20
	K_T	.64	.67	.70	.68	.66	.72	.67	.70	.72	.72	.72	.65
	T_a C	-4.0	-2.0	.0	5.0	10.0	14.0	19.0	18.0	13.0	7.0	1.0	-3.0
	DD C-DAY	727.	597.	543.	373.	253.	125.	16.	24.	130.	329.	522.	658.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
FAIRBANKS AK (LAT. 64.5)												
$\bar{H}$ MJ/m^2	.80	3.18	9.74	16.10	19.95	22.04	18.57	15.18	7.69	3.60	1.13	.25
$\bar{K}_T$	.61	.55	.70	.64	.56	.54	.49	.52	.43	.45	.51	.49
$\bar{T}_a$ C	-24.0	-19.0	-13.0	-1.0	8.0	14.0	15.0	12.0	6.0	-3.0	-16.0	-22.0
$\overline{DD}$ C-DAY	1311.	1056.	966.	593.	308.	123.	95.	184.	357.	668.	1018.	1252.
FARGO ND (LAT. 46.5)												
$\bar{H}$ MJ/m^2	5.32	8.92	12.89	17.54	21.10	22.02	23.19	19.89	14.57	10.13	5.48	4.94
$\bar{K}_T$	.48	.54	.54	.54	.55	.53	.58	.57	.54	.54	.44	.51
$\bar{T}_a$ C	-14.0	-12.0	-4.0	6.0	13.0	18.0	21.0	21.0	14.0	8.0	-2.0	-11.0
$\overline{DD}$ C-DAY	1018.	844.	703.	378.	186.	54.	7.	18.	130.	310.	607.	896.
FORT SMITH AR (LAT. 35.2)												
$\bar{H}$ MJ/m^2	8.25	11.30	15.11	18.80	22.02	23.61	22.86	21.86	18.13	14.19	9.80	7.83
$\bar{K}_T$	.46	.49	.52	.53	.56	.57	.57	.59	.58	.57	.51	.47
$\bar{T}_a$ C	4.0	6.0	10.0	17.0	21.0	26.0	28.0	27.0	23.0	17.0	10.0	5.0
$\overline{DD}$ C-DAY	448.	338.	262.	73.	9.	0.	0.	0.	0.	75.	243.	405.
FORT WAYNE IN (LAT. 41.0)												
$\bar{H}$ MJ/m^2	6.32	9.08	13.44	17.08	22.06	24.45	23.82	21.10	16.54	12.35	7.07	5.65
$\bar{K}_T$	.44	.46	.50	.50	.56	.59	.59	.59	.56	.57	.45	.43
$\bar{T}_a$ C	-4.0	-2.0	2.0	10.0	15.0	21.0	23.0	22.0	18.0	12.0	5.0	-2.0
$\overline{DD}$ C-DAY	684.	582.	491.	262.	120.	13.	0.	7.	50.	202.	413.	627.
FORT WORTH TX (LAT. 32.5)												
$\bar{H}$ MJ/m^2	10.54	13.42	17.77	12.25	23.46	26.85	25.59	24.59	20.91	16.48	12.46	10.20
$\bar{K}_T$	.54	.55	.59	.34	.59	.66	.64	.66	.65	.63	.60	.56
$\bar{T}_a$ C	7.0	9.0	13.0	18.0	22.0	27.0	29.0	29.0	25.0	19.0	13.0	8.0
$\overline{DD}$ C-DAY	341.	249.	177.	55.	0.	0.	0.	0.	0.	36.	180.	298.
FRESNO CA (LAT. 36.5)												
$\bar{H}$ MJ/m^2	7.78	12.38	18.32	22.79	26.64	29.15	27.93	25.34	21.03	15.68	10.08	6.69
$\bar{K}_T$	.45	.55	.64	.65	.67	.71	.69	.69	.68	.65	.55	.42
$\bar{T}_a$ C	7.0	10.0	12.0	16.0	19.0	23.0	27.0	26.0	23.0	18.0	12.0	7.0
$\overline{DD}$ C-DAY	336.	237.	186.	90.	34.	3.	0.	0.	0.	47.	197.	321.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
GAINESVILLE FL (LAT. 29.4)												
$\bar{H}$ MJ/m^2	11.63	15.35	18.61	22.54	24.51	22.75	21.75	21.24	18.57	15.39	13.30	10.62
$\bar{K}_T$	.54	.59	.59	.62	.62	.56	.54	.56	.56	.56	.59	.53
$\bar{T}_a$ C	13.0	14.0	17.0	21.0	24.0	26.0	27.0	27.0	26.0	22.0	17.0	14.0
$\overline{DD}$ C-DAY	164.	133.	73.	11.	0.	0.	0.	0.	0.	7.	69.	143.
GLASGOW MT (LAT. 48.1)												
$\bar{H}$ MJ/m^2	6.44	10.58	15.77	19.03	23.50	25.63	26.76	22.33	17.15	11.21	6.48	4.94
$\bar{K}_T$	.64	.68	.68	.60	.61	.62	.67	.65	.65	.63	.57	.57
$\bar{T}_a$ C	-12.0	-8.0	-3.0	6.0	12.0	17.0	21.0	21.0	14.0	8.0	-1.0	-7.0
$\overline{DD}$ C-DAY	951.	799.	659.	360.	186.	83.	17.	26.	150.	338.	613.	814.
GRAND JUNCTION CO (LAT. 39.1)												
$\bar{H}$ MJ/m^2	9.70	13.59	17.98	22.29	25.30	29.61	28.06	24.30	20.95	15.81	11.00	9.03
$\bar{K}_T$	.62	.65	.65	.65	.64	.72	.70	.67	.70	.69	.65	.64
$\bar{T}_a$ C	-3.0	.0	5.0	11.0	16.0	22.0	25.0	24.0	19.0	12.0	4.0	-1.0
$\overline{DD}$ C-DAY	672.	504.	405.	215.	81.	12.	0.	0.	17.	174.	437.	617.
GRAND LAKE CO (LAT. 40.2)												
$\bar{H}$ MJ/m^2	8.88	13.11	17.71	21.44	23.11	26.46	25.12	21.14	19.93	15.11	9.80	7.70
$\bar{K}_T$	.59	.65	.65	.63	.59	.64	.62	.58	.67	.68	.61	.57
$\bar{T}_a$ C	-9.0	-7.0	-4.0	.0	6.0	10.0	13.0	12.0	8.0	3.0	-3.0	-8.0
$\overline{DD}$ C-DAY	864.	734.	720.	525.	381.	250.	153.	174.	280.	446.	653.	820.
GREAT FALLS MT (LAT. 47.3)												
$\bar{H}$ MJ/m^2	5.77	9.58	15.14	17.94	21.91	24.71	26.56	22.12	16.89	10.96	6.44	4.68
$\bar{K}_T$	.54	.59	.64	.56	.57	.60	.67	.64	.63	.60	.54	.51
$\bar{T}_a$ C	-5.0	-2.0	.0	6.0	12.0	16.0	21.0	20.0	14.0	9.0	1.0	-2.0
$\overline{DD}$ C-DAY	749.	641.	591.	357.	213.	103.	16.	29.	143.	302.	512.	649.
GREEN BAY WI (LAT. 44.3)												
$\bar{H}$ MJ/m^2	5.74	8.79	13.10	16.08	20.47	22.69	22.52	19.34	14.78	10.05	5.82	4.60
$\bar{K}_T$	.46	.49	.52	.49	.53	.55	.56	.55	.53	.50	.42	.42
$\bar{T}_a$ C	-9.0	-8.0	-2.0	7.0	12.0	18.0	21.0	20.0	15.0	10.0	1.0	-6.0
$\overline{DD}$ C-DAY	854.	731.	627.	353.	188.	51.	12.	30.	106.	272.	515.	759.

Location \ Month		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
GREENSBORO	NC (LAT. 36.0)												
	$\bar{H}$ MJ/m^2	8.57	11.37	14.80	19.61	22.29	23.50	22.62	19.86	17.23	13.76	10.16	7.78
	$\bar{K}_T$	.49	.50	.51	.56	.56	.57	.56	.54	.55	.56	.55	.48
	T_a C	3.0	4.0	8.0	14.0	19.0	23.0	25.0	24.0	21.0	14.0	8.0	4.0
	DD C-DAY	453.	379.	302.	113.	33.	0.	0.	0.	13.	116.	278.	437.
GRNVLE-SPTNBRG	NC (LAT. 34.5)												
	$\bar{H}$ MJ/m^2	9.38	11.30	16.29	21.39	23.15	23.32	23.19	21.48	17.75	14.95	10.76	8.58
	$\bar{K}_T$	.51	.48	.55	.60	.58	.57	.58	.58	.56	.60	.55	.51
	T_a C	6.0	7.0	10.0	16.0	21.0	24.0	26.0	25.0	22.0	16.0	11.0	6.0
	DD C-DAY	391.	321.	250.	80.	16.	0.	0.	0.	5.	81.	233.	381.
GRIFFIN	GA (LAT. 33.1)												
	$\bar{H}$ MJ/m^2	9.95	12.63	16.23	21.70	24.13	24.25	23.38	21.87	18.27	15.56	12.04	8.78
	$\bar{K}_T$	.52	.52	.54	.60	.61	.59	.58	.59	.57	.60	.59	.49
	T_a C	6.0	8.0	11.0	16.0	21.0	24.0	25.0	25.0	22.0	17.0	11.0	7.0
	DD C-DAY	356.	289.	228.	61.	11.	0.	0.	0.	11.	61.	200.	339.
HARTFORD	CT (LAT. 41.6)												
	$\bar{H}$ MJ/m^2	6.62	9.46	13.73	16.12	19.85	22.36	22.15	19.22	15.24	11.05	6.91	7.91
	$\bar{K}_T$	.47	.49	.52	.48	.51	.54	.55	.54	.52	.51	.45	.62
	T_a C	-4.0	-3.0	2.0	9.0	15.0	20.0	23.0	21.0	17.0	11.0	5.0	-2.0
	DD C-DAY	692.	594.	506.	288.	126.	13.	0.	7.	59.	213.	395.	634.
HILO	HI (LAT. 19.4)												
	$\bar{H}$ MJ/m^2	11.71	15.47	18.73	18.02	18.73	24.00	22.33	20.49	18.90	14.18	12.63	11.00
	$\bar{K}_T$	.43	.50	.54	.48	.48	.61	.58	.54	.53	.45	.45	.43
	T_a C	21.0	21.0	21.0	22.0	22.0	23.0	23.0	24.0	24.0	23.0	22.0	21.0
	DD C-DAY	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
HONOLULU	HI (LAT. 21.2)												
	$\bar{H}$ MJ/m^2	15.20	17.67	21.60	23.40	25.83	25.75	25.75	25.62	23.99	21.23	17.84	15.53
	$\bar{K}_T$	.58	.59	.63	.62	.66	.65	.66	.68	.68	.68	.66	.63
	T_a C	22.0	22.0	22.0	23.0	24.0	25.0	26.0	26.0	26.0	25.0	24.0	23.0
	DD C-DAY	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Location \ Month		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
HOUSTON	TX (LAT. 29.6)												
	$\bar{H}$ MJ/m^2	10.05	12.64	16.37	18.97	23.11	25.08	24.53	21.69	19.09	16.58	11.55	9.50
	$\bar{K}_T$	.47	.49	.52	.52	.58	.62	.61	.58	.58	.60	.52	.48
	T_a C	11.0	13.0	16.0	21.0	24.0	27.0	28.0	29.0	26.0	22.0	16.0	13.0
	DD C-DAY	231.	163.	105.	13.	0.	0.	0.	0.	0.	13.	86.	185.
INDIANAPOLIS	IN (LAT. 39.4)												
	$\bar{H}$ MJ/m^2	6.15	8.95	13.05	16.43	20.53	22.87	22.67	20.32	16.94	12.25	7.36	5.44
	$\bar{K}_T$	.40	.43	.48	.48	.52	.55	.56	.56	.57	.54	.44	.39
	T_a C	-1.0	.0	4.0	11.0	17.0	22.0	24.0	23.0	19.0	13.0	5.0	.0
	DD C-DAY	639.	533.	436.	215.	88.	6.	0.	3.	35.	168.	388.	587.
INYOKERN	CA (LAT. 35.4)												
	$\bar{H}$ MJ/m^2	13.05	17.32	24.17	29.32	32.99	34.96	32.79	30.86	27.10	20.24	15.31	12.34
	$\bar{K}_T$	.73	.77	.83	.83	.83	.85	.81	.84	.86	.82	.80	.75
	T_a C	7.0	11.0	14.0	18.0	23.0	27.0	32.0	31.0	27.0	20.0	13.0	8.0
	DD C-DAY	341.	218.	148.	71.	6.	0.	0.	0.	0.	24.	176.	334.
ITHACA	NY (LAT. 42.3)												
	$\bar{H}$ MJ/m^2	5.10	8.49	11.79	14.55	19.61	22.54	22.37	19.24	14.89	10.37	5.23	4.14
	$\bar{K}_T$	.37	.45	.45	.43	.50	.54	.56	.54	.52	.49	.35	.34
	T_a C	-5.0	-4.0	.0	7.0	12.0	18.0	20.0	19.0	15.0	10.0	4.0	-2.0
	DD C-DAY	723.	646.	562.	332.	176.	39.	11.	22.	87.	243.	423.	654.
JACKSON	MS (LAT. 32.2)												
	$\bar{H}$ MJ/m^2	8.88	11.72	15.83	20.18	22.94	23.53	22.78	21.39	17.96	15.11	10.42	8.46
	$\bar{K}_T$	.45	.48	.52	.56	.58	.57	.57	.57	.55	.58	.50	.46
	T_a C	8.0	10.0	13.0	19.0	23.0	26.0	28.0	27.0	24.0	19.0	13.0	9.0
	DD C-DAY	316.	246.	174.	41.	3.	0.	0.	0.	0.	51.	167.	280.
JACKSONVILLE	FL (LAT. 30.2)												
	$\bar{H}$ MJ/m^2	11.18	14.49	17.71	21.52	23.28	21.98	21.86	19.93	16.03	13.86	11.47	9.63
	$\bar{K}_T$	.53	.57	.57	.59	.59	.54	.55	.53	.49	.51	.52	.49
	T_a C	12.0	13.0	16.0	20.0	23.0	26.0	27.0	27.0	25.0	21.0	16.0	12.0
	DD C-DAY	193.	157.	98.	13.	0.	0.	0.	0.	0.	11.	89.	176.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
KANSAS CITY, MO (LAT. 39.2)												
$\bar{H}$ MJ/m²	7.62	10.55	14.28	18.46	21.81	24.70	24.24	22.02	17.79	13.40	9.00	6.87
$\bar{K}_T$	.49	.51	.52	.54	.55	.60	.60	.61	.59	.59	.54	.49
$\bar{T}_a$ C	-2.0	1.0	5.0	13.0	18.0	23.0	26.0	25.0	20.0	15.0	6.0	.0
DD C-DAY	641.	496.	414.	174.	62.	7.	0.	0.	23.	131.	357.	563.
KEY WEST, FL (LAT. 24.3)												
$\bar{H}$ MJ/m²	13.69	17.16	20.51	23.95	24.24	22.73	22.36	20.97	18.63	16.49	13.90	12.23
$\bar{K}_T$	.56	.60	.62	.64	.62	.57	.57	.55	.54	.55	.55	.53
$\bar{T}_a$ C	21.0	21.0	23.0	25.0	27.0	28.0	29.0	29.0	28.0	26.0	23.0	21.0
DD C-DAY	9.	14.	3.	0.	0.	0.	0.	0.	0.	0.	0.	10.
LAKE CHARLES, LA (LAT. 30.1)												
$\bar{H}$ MJ/m²	10.00	12.71	16.56	20.20	23.17	24.34	21.79	21.08	18.73	16.81	12.38	9.70
$\bar{K}_T$	.48	.50	.53	.55	.58	.60	.54	.56	.57	.62	.56	.49
$\bar{T}_a$ C	11.0	12.0	15.0	20.0	23.0	27.0	28.0	27.0	25.0	21.0	15.0	12.0
DD C-DAY	212.	152.	108.	22.	0.	0.	0.	0.	0.	11.	117.	189.
LANDER, WY (LAT. 42.5)												
$\bar{H}$ MJ/m²	9.62	13.42	18.86	23.13	24.46	28.23	27.10	24.25	19.40	14.89	9.91	8.24
$\bar{K}_T$	.71	.71	.72	.69	.63	.68	.67	.68	.68	.71	.67	.68
$\bar{T}_a$ C	-6.0	-3.0	.0	6.0	12.0	16.0	21.0	21.0	15.0	8.0	.0	-4.0
DD C-DAY	787.	636.	565.	363.	212.	85.	3.	11.	113.	308.	567.	722.
LANSING, MI (LAT. 42.5)												
$\bar{H}$ MJ/m²	5.65	8.92	12.89	14.99	20.89	23.15	22.78	20.14	15.78	10.80	5.86	4.69
$\bar{K}_T$	.42	.47	.50	.45	.53	.56	.57	.56	.55	.51	.40	.39
$\bar{T}_a$ C	-5.0	-4.0	1.0	8.0	14.0	19.0	22.0	21.0	16.0	11.0	4.0	-3.0
DD C-DAY	730.	638.	553.	308.	156.	27.	5.	15.	74.	234.	443.	653.
LARAMIE, WY (LAT. 41.2)												
$\bar{H}$ MJ/m²	9.37	12.46	17.73	20.83	22.92	26.22	24.80	22.00	17.56	13.34	9.49	7.65
$\bar{K}_T$	.65	.63	.67	.61	.58	.63	.62	.61	.60	.62	.61	.59
$\bar{T}_a$ C	-5.0	-4.0	-2.0	3.0	9.0	14.0	18.0	17.0	12.0	6.0	.0	-4.0
DD C-DAY	763.	650.	653.	453.	296.	143.	39.	56.	192.	374.	577.	715.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
LAS VEGAS, NV (LAT. 36.0)												
$\bar{H}$ MJ/m²	11.67	16.14	21.12	26.01	29.36	31.20	28.27	26.22	23.29	17.94	13.30	10.87
$\bar{K}_T$	.67	.72	.73	.74	.74	.76	.70	.71	.75	.74	.71	.68
$\bar{T}_a$ C	6.0	9.0	12.0	17.0	23.0	28.0	31.0	30.0	26.0	19.0	11.0	7.0
DD C-DAY	382.	271.	186.	62.	3.	0.	0.	0.	0.	43.	215.	343.
LEMONT, IL (LAT. 41.4)												
$\bar{H}$ MJ/m²	7.15	9.70	13.63	16.31	20.78	23.13	22.04	20.32	16.06	11.08	6.57	5.48
$\bar{K}_T$	.50	.50	.51	.48	.53	.56	.55	.57	.55	.51	.43	.43
$\bar{T}_a$ C	-3.0	-2.0	3.0	10.0	16.0	21.0	24.0	23.0	19.0	13.0	5.0	-1.0
DD C-DAY	701.	585.	486.	252.	116.	14.	0.	4.	32.	176.	410.	629.
LEXINGTON, KY (LAT. 38.0)												
$\bar{H}$ MJ/m²	7.15	10.79	15.22	19.91	24.09	25.97	25.76	23.34	20.53	15.10	9.83	7.15
$\bar{K}_T$	.44	.50	.54	.57	.61	.63	.64	.64	.67	.65	.56	.48
$\bar{T}_a$ C	.0	2.0	6.0	13.0	18.0	23.0	25.0	24.0	20.0	14.0	7.0	2.0
DD C-DAY	553.	462.	374.	168.	59.	4.	0.	0.	22.	137.	340.	508.
LINCOLN, NE (LAT. 40.5)												
$\bar{H}$ MJ/m²	7.95	10.66	14.51	17.73	20.74	22.79	22.46	21.24	17.23	13.59	8.66	7.19
$\bar{K}_T$	.54	.53	.54	.52	.53	.55	.56	.59	.58	.62	.54	.54
$\bar{T}_a$ C	-4.0	-2.0	3.0	11.0	16.0	22.0	25.0	24.0	19.0	12.0	4.0	-1.0
DD C-DAY	687.	564.	463.	223.	95.	17.	0.	3.	42.	167.	405.	592.
LITTLE ROCK, AR (LAT. 34.4)												
$\bar{H}$ MJ/m²	8.28	10.96	14.97	19.03	22.08	23.50	23.34	21.58	18.48	14.47	10.20	7.82
$\bar{K}_T$	.45	.47	.51	.53	.56	.57	.58	.58	.58	.57	.52	.46
$\bar{T}_a$ C	4.0	6.0	10.0	16.0	21.0	26.0	27.0	27.0	23.0	17.0	10.0	5.0
DD C-DAY	420.	321.	241.	70.	5.	0.	0.	0.	5.	71.	258.	398.
LOS ANGELES, CA (LAT. 33.6)												
$\bar{H}$ MJ/m²	10.75	14.39	19.19	21.66	24.09	25.80	27.14	24.63	21.08	15.39	12.25	10.29
$\bar{K}_T$	.57	.60	.64	.61	.61	.63	.67	.66	.66	.60	.61	.59
$\bar{T}_a$ C	12.0	13.0	13.0	15.0	16.0	18.0	20.0	20.0	20.0	18.0	15.0	13.0
DD C-DAY	184.	150.	148.	108.	63.	39.	11.	8.	13.	43.	88.	155.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
LOUISVILLE KY (LAT. 38.1)	H MJ/m²	6.87	9.67	13.61	17.58	21.56	23.45	23.03	20.85	17.08	12.69	7.95	6.28
	K_T	.42	.45	.49	.51	.55	.57	.57	.57	.56	.54	.46	.42
	T_a C	.0	2.0	6.0	13.0	18.0	22.0	24.0	24.0	20.0	14.0	7.0	1.0
	DD C-DAY	546.	454.	367.	159.	58.	0.	0.	0.	19.	134.	333.	506.
LYNN MA (LAT. 42.3)	H MJ/m²	4.94	8.74	12.55	16.48	18.99	22.50	22.54	17.65	14.22	9.66	5.56	4.18
	K_T	.36	.46	.48	.49	.49	.54	.56	.49	.49	.46	.37	.34
	T_a C	-1.0	.0	3.0	9.0	15.0	20.0	23.0	22.0	18.0	13.0	7.0	1.0
	DD C-DAY	604.	540.	470.	285.	116.	20.	0.	5.	33.	176.	335.	546.
MACON GA (LAT. 32.4)	H MJ/m²	10.38	12.98	16.41	21.39	23.70	23.95	23.07	21.81	18.13	15.41	11.14	9.08
	K_T	.53	.53	.54	.59	.60	.58	.57	.58	.56	.59	.54	.50
	T_a C	9.0	10.0	14.0	19.0	23.0	26.0	27.0	27.0	24.0	19.0	13.0	9.0
	DD C-DAY	302.	235.	166.	37.	3.	0.	0.	0.	0.	46.	169.	288.
MADISON WI (LAT. 43.1)	H MJ/m²	6.41	9.22	13.99	16.53	19.82	23.07	23.24	19.76	16.40	11.28	6.31	5.63
	K_T	.49	.50	.54	.49	.51	.56	.58	.56	.58	.55	.44	.48
	T_a C	-7.0	-6.0	.0	7.0	13.0	19.0	21.0	20.0	15.0	10.0	1.0	-5.0
	DD C-DAY	830.	696.	599.	328.	165.	40.	8.	22.	96.	263.	505.	742.
MANHATTAN KA (LAT. 39.1)	H MJ/m²	8.04	11.05	14.44	18.13	22.06	23.07	22.23	22.02	17.17	12.23	9.50	6.53
	K_T	.52	.53	.52	.53	.56	.56	.55	.61	.57	.54	.57	.46
	T_a C	-1.0	1.0	5.0	13.0	18.0	23.0	26.0	25.0	20.0	14.0	6.0	.0
	DD C-DAY	623.	496.	401.	183.	69.	7.	0.	0.	32.	150.	373.	544.
MATANUSKA AK (LAT. 61.3)	H MJ/m²	1.34	3.85	10.13	14.90	18.25	19.34	17.12	13.15	8.29	4.18	1.59	.63
	K_T	.49	.50	.64	.56	.51	.48	.45	.43	.42	.42	.42	.37
	T_a C	-11.0	-7.0	-3.0	2.0	8.0	12.0	14.0	12.0	8.0	1.0	-6.0	-10.0
	DD C-DAY	914.	714.	689.	477.	310.	168.	129.	169.	288.	526.	738.	904.

Location		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
MEDFORD OR (LAT. 42.2)	H MJ/m²	4.94	8.87	13.88	20.24	24.63	27.31	29.23	25.17	18.78	11.63	6.36	3.85
	K_T	.36	.46	.53	.60	.63	.66	.73	.70	.65	.55	.43	.31
	T_a C	3.0	5.0	7.0	10.0	14.0	18.0	22.0	21.0	18.0	12.0	6.0	3.0
	DD C-DAY	489.	369.	348.	247.	139.	52.	6.	12.	49.	200.	358.	470.
MEMPHIS TN (LAT. 35.0)	H MJ/m²	8.04	11.18	15.03	19.68	23.19	24.66	24.41	22.40	18.50	14.82	9.96	7.70
	K_T	.44	.48	.51	.55	.59	.60	.61	.61	.59	.60	.52	.46
	T_a C	5.0	7.0	11.0	17.0	22.0	26.0	28.0	27.0	23.0	17.0	10.0	6.0
	DD C-DAY	422.	330.	254.	73.	12.	0.	0.	0.	4.	79.	235.	384.
MIAMI FL (LAT. 25.5)	H MJ/m²	14.34	17.40	20.53	22.75	23.08	22.21	22.46	21.24	18.69	16.27	14.80	13.34
	K_T	.61	.62	.63	.61	.59	.55	.57	.56	.55	.56	.60	.60
	T_a C	19.0	19.0	21.0	23.0	25.0	27.0	27.0	28.0	27.0	25.0	22.0	20.0
	DD C-DAY	41.	31.	11.	0.	0.	0.	0.	0.	0.	0.	0.	36.
MIDLAND TX (LAT. 31.6)	H MJ/m²	11.75	15.05	19.95	23.04	25.80	25.72	25.68	24.55	21.37	16.69	13.47	11.37
	K_T	.58	.60	.65	.64	.65	.63	.64	.66	.66	.63	.63	.61
	T_a C	6.0	8.0	12.0	17.0	22.0	26.0	27.0	27.0	23.0	18.0	11.0	7.0
	DD C-DAY	362.	260.	179.	50.	0.	0.	0.	0.	0.	42.	212.	329.
MILWAUKEE WI (LAT. 42.6)	H MJ/m²	6.24	8.79	13.10	16.83	21.27	23.65	23.57	20.31	16.41	11.18	6.74	5.02
	K_T	.46	.47	.50	.50	.54	.57	.59	.57	.57	.53	.46	.42
	T_a C	-7.0	-5.0	.0	7.0	12.0	18.0	21.0	21.0	16.0	11.0	2.0	-4.0
	DD C-DAY	786.	661.	579.	338.	193.	50.	8.	20.	78.	244.	475.	703.
MINN-ST. PAUL MN (LAT. 44.5)	H MJ/m²	5.99	9.21	12.81	16.54	20.18	22.44	22.82	19.51	14.99	10.80	6.03	4.69
	K_T	.49	.52	.51	.50	.52	.54	.57	.55	.54	.54	.44	.43
	T_a C	-11.0	-9.0	-2.0	7.0	14.0	19.0	22.0	21.0	16.0	10.0	.0	-7.0
	DD C-DAY	909.	754.	632.	332.	151.	36.	6.	12.	96.	262.	543.	799.

Location \ Month		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
MT WEATHER	VA (LAT. 39.0)												
H	MJ/m2	7.20	11.47	14.15	17.33	21.27	21.98	21.35	18.00	15.70	11.76	8.46	7.03
K_T		.46	.55	.51	.50	.54	.53	.53	.50	.52	.52	.50	.49
T_a	C	-1.0	.0	3.0	10.0	15.0	20.0	22.0	21.0	18.0	12.0	5.0	.0
DD	C-DAY	615.	535.	453.	251.	102.	13.	0.	3.	44.	189.	370.	573.
NASHVILLE	TN (LAT. 36.1)												
H	MJ/m2	6.82	10.04	13.76	18.82	21.62	23.71	23.13	20.66	17.90	13.67	9.07	6.73
K_T		.39	.45	.48	.53	.55	.58	.57	.56	.57	.56	.49	.42
T_a	C	3.0	5.0	9.0	15.0	20.0	24.0	26.0	25.0	22.0	16.0	9.0	5.0
DD	C-DAY	460.	373.	291.	98.	25.	0.	0.	0.	6.	100.	277.	424.
NATICK	MA (LAT. 42.2)												
H	MJ/m2	6.36	9.70	13.63	16.35	20.91	17.10	21.45	19.11	15.01	10.91	6.15	5.60
K_T		.46	.51	.52	.49	.53	.41	.53	.53	.52	.52	.41	.46
T_a	C	-2.0	-2.0	3.0	9.0	15.0	20.0	23.0	22.0	17.0	12.0	6.0	.0
DD	C-DAY	672.	585.	487.	282.	123.	17.	0.	6.	56.	203.	375.	608.
NEW ORLEANS	LA (LAT. 29.6)												
H	MJ/m2	8.96	10.84	14.03	17.25	18.80	18.55	17.46	17.42	16.03	14.95	11.64	8.29
K_T		.42	.42	.45	.47	.47	.46	.44	.46	.48	.54	.52	.42
T_a	C	11.0	13.0	15.0	20.0	23.0	26.0	27.0	27.0	25.0	20.0	15.0	12.0
DD	C-DAY	202.	143.	107.	22.	0.	0.	0.	0.	0.	11.	107.	179.
NEWPORT	RI (LAT. 41.3)												
H	MJ/m2	6.48	9.66	13.80	16.52	20.45	22.50	21.62	18.78	15.89	11.42	7.32	5.90
K_T		.45	.49	.52	.49	.52	.54	.54	.52	.54	.53	.47	.46
T_a	C	.0	.0	3.0	7.0	12.0	17.0	21.0	21.0	18.0	13.0	8.0	2.0
DD	C-DAY	567.	531.	487.	340.	191.	55.	0.	9.	43.	171.	330.	501.
NEW YORK	NY (LAT. 40.5)												
H	MJ/m2	5.44	8.33	12.14	15.45	18.09	19.68	19.22	16.29	13.86	10.13	6.15	4.81
K_T		.37	.41	.45	.45	.46	.48	.48	.45	.47	.46	.38	.36
T_a	C	.0	1.0	3.0	11.0	17.0	22.0	25.0	24.0	20.0	15.0	9.0	2.0
		[illegible]	[illegible]	[illegible]	730.	69.	3.	0.	0.	15.	124.	293.	493.

Location \ Month		JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
NORFOLK	VA (LAT. 36.5)												
H	MJ/m2	8.71	11.30	15.57	19.97	22.61	23.95	23.03	20.14	16.66	12.98	9.34	7.70
K_T		.51	.51	.54	.57	.57	.58	.57	.55	.54	.54	.51	.49
T_a	C	4.0	5.0	8.0	14.0	19.0	23.0	25.0	24.0	22.0	16.0	10.0	5.0
DD	C-DAY	422.	367.	296.	126.	29.	0.	0.	0.	5.	78.	223.	391.
NORTH OMAHA	NE (LAT. 41.2)												
H	MJ/m2	8.55	11.60	14.90	19.38	21.48	23.57	23.78	21.81	16.58	12.31	8.29	6.95
K_T		.60	.59	.56	.57	.55	.57	.59	.61	.57	.57	.53	.54
T_a	C	-5.0	-3.0	3.0	10.0	17.0	22.0	25.0	23.0	19.0	12.0	4.0	-2.0
DD	C-DAY	753.	626.	522.	258.	116.	23.	0.	7.	58.	198.	460.	653.
OAK RIDGE	TN (LAT. 36.0)												
H	MJ/m2	6.94	9.95	13.63	18.69	21.54	22.79	21.79	19.91	17.44	13.34	8.82	6.73
K_T		.40	.44	.47	.53	.54	.55	.54	.54	.56	.55	.47	.42
T_a	C	3.0	5.0	9.0	15.0	19.0	23.0	25.0	24.0	21.0	15.0	8.0	4.0
DD	C-DAY	463.	383.	306.	122.	43.	0.	0.	0.	11.	120.	298.	444.
OKLAHOMA CITY	OK (LAT. 35.2)												
H	MJ/m2	10.66	13.26	17.02	20.83	22.58	26.35	25.51	24.59	20.24	15.85	11.88	9.91
K_T		.59	.58	.58	.59	.57	.64	.63	.67	.64	.64	.62	.60
T_a	C	2.0	4.0	9.0	15.0	20.0	25.0	27.0	27.0	23.0	16.0	9.0	4.0
DD	C-DAY	486.	369.	296.	100.	20.	0.	0.	0.	7.	82.	263.	431.
PAGE	AZ (LAT. 36.4)												
H	MJ/m2	12.56	15.99	22.02	25.87	29.10	29.60	28.47	24.95	21.60	16.83	12.98	10.17
K_T		.73	.72	.77	.74	.74	.72	.71	.68	.70	.70	.70	.64
T_a	C	.0	2.0	5.0	10.0	15.0	20.0	24.0	22.0	18.0	12.0	5.0	.0
DD	C-DAY	591.	447.	396.	240.	107.	21.	0.	6.	41.	189.	390.	562.
PARKERSBURG	WV (LAT. 39.2)												
H	MJ/m2	5.99	8.46	12.64	15.87	20.39	22.65	22.02	20.26	16.50	11.89	6.99	5.53
K_T		.38	.41	.46	.46	.52	.55	.55	.56	.55	.52	.42	.39
T_a	C	1.0	1.0	6.0	13.0	18.0	22.0	24.0	23.0	20.0	14.0	7.0	2.0
DD	C-DAY	553.	471.	381.	178.	67.	4.	0.	0.	26.	149.	333.	515.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
PASADENA CA (LAT. 34.1)												
$\bar{H}$ MJ/m^2	10.51	13.94	18.38	21.31	23.82	24.28	26.54	25.08	20.18	15.32	11.35	9.88
$\bar{K}_T$	.56	.59	.62	.60	.60	.59	.66	.68	.63	.60	.57	.57
$\bar{T}_a$ C	12.0	13.0	13.0	15.0	17.0	19.0	23.0	23.0	22.0	19.0	15.0	13.0
DD C-DAY	191.	151.	141.	94.	47.	26.	0.	0.	6.	29.	91.	166.
PENSACOLA FL (LAT. 30.3)												
$\bar{H}$ MJ/m^2	10.47	13.44	16.96	21.31	23.53	23.78	22.48	21.31	18.00	16.49	11.64	9.38
$\bar{K}_T$	.50	.53	.54	.59	.59	.58	.56	.57	.55	.61	.53	.48
$\bar{T}_a$ C	11.0	12.0	15.0	20.0	23.0	26.0	27.0	27.0	25.0	21.0	15.0	12.0
DD C-DAY	237.	179.	117.	21.	0.	0.	0.	0.	0.	18.	105.	199.
PEORIA IL (LAT. 40.4)												
$\bar{H}$ MJ/m^2	6.82	9.54	13.48	17.67	21.31	23.99	23.57	21.02	17.04	12.52	7.75	5.82
$\bar{K}_T$	.46	.47	.50	.52	.54	.58	.59	.58	.58	.57	.48	.43
$\bar{T}_a$ C	-5.0	-2.0	3.0	11.0	16.0	22.0	24.0	23.0	19.0	13.0	4.0	-2.0
DD C-DAY	709.	580.	477.	231.	100.	9.	0.	4.	39.	182.	418.	637.
PHOENIX AZ (LAT. 33.3)												
$\bar{H}$ MJ/m^2	12.42	17.06	21.79	26.89	30.28	30.95	27.27	25.59	23.75	18.90	14.18	11.71
$\bar{K}_T$	.65	.71	.73	.75	.76	.75	.68	.69	.74	.73	.70	.66
$\bar{T}_a$ C	10.0	13.0	15.0	19.0	24.0	29.0	32.0	31.0	28.0	22.0	15.0	11.0
DD C-DAY	238.	162.	103.	33.	0.	0.	0.	0.	6.	9.	101.	216.
PHILADELPHIA PA (LAT. 39.5)												
$\bar{H}$ MJ/m^2	7.33	10.13	14.53	17.79	20.64	23.19	22.52	19.47	16.24	12.27	8.00	6.36
$\bar{K}_T$	.48	.49	.53	.52	.52	.56	.56	.54	.54	.54	.48	.46
$\bar{T}_a$ C	.0	1.0	5.0	11.0	17.0	22.0	24.0	23.0	20.0	14.0	8.0	2.0
DD C-DAY	563.	484.	398.	204.	68.	0.	0.	0.	21.	138.	313.	513.
PITTSBURGH PA (LAT. 40.3)												
$\bar{H}$ MJ/m^2	6.62	8.92	13.48	16.75	20.39	23.40	22.90	20.18	17.00	12.31	7.70	5.94
$\bar{K}_T$	.44	.44	.50	.49	.52	.57	.57	.56	.57	.56	.48	.44
$\bar{T}_a$ C	.0	.0	5.0	11.0	17.0	22.0	24.0	23.0	19.0	13.0	7.0	1.0
DD C-DAY	592.	513.	424.	212.	89.	6.	0.	3.	32.	166.	348.	546.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
POCATELLO ID (LAT. 42.5)												
$\bar{H}$ MJ/m^2	6.91	10.47	15.28	21.77	24.28	27.42	28.26	24.70	19.89	13.82	8.58	6.49
$\bar{K}_T$	.51	.55	.59	.65	.62	.66	.70	.69	.69	.66	.58	.54
$\bar{T}_a$ C	-4.0	.0	2.0	7.0	12.0	17.0	22.0	21.0	15.0	9.0	2.0	-2.0
DD C-DAY	720.	554.	510.	328.	187.	77.	0.	11.	107.	286.	488.	656.
PORT ARTHUR TX (LAT. 29.6)												
$\bar{H}$ MJ/m^2	9.59	12.35	16.08	18.21	22.44	23.86	22.11	20.47	18.09	15.99	10.76	8.92
$\bar{K}_T$	.45	.48	.51	.50	.57	.59	.55	.54	.55	.58	.48	.45
$\bar{T}_a$ C	11.0	13.0	16.0	20.0	24.0	27.0	28.0	28.0	26.0	21.0	16.0	12.0
DD C-DAY	233.	168.	112.	18.	0.	0.	0.	0.	0.	19.	102.	190.
PORTLAND ME (LAT. 43.4)												
$\bar{H}$ MJ/m^2	6.57	9.91	15.01	16.98	21.45	22.62	23.46	20.16	16.02	11.42	6.57	5.77
$\bar{K}_T$	.51	.54	.59	.51	.55	.55	.58	.57	.56	.56	.46	.50
$\bar{T}_a$ C	-5.0	-4.0	.0	6.0	11.0	17.0	20.0	19.0	15.0	9.0	4.0	-3.0
DD C-DAY	744.	657.	579.	375.	207.	62.	7.	29.	108.	282.	448.	564.
PORTLAND OR (LAT. 45.4)												
$\bar{H}$ MJ/m^2	4.02	6.57	10.05	14.78	17.71	19.80	23.15	18.59	14.36	8.41	4.86	3.47
$\bar{K}_T$	.34	.38	.41	.45	.46	.48	.58	.53	.52	.43	.37	.34
$\bar{T}_a$ C	3.0	6.0	8.0	10.0	14.0	17.0	19.0	19.0	17.0	12.0	7.0	5.0
DD C-DAY	463.	346.	332.	240.	147.	71.	27.	31.	66.	193.	328.	418.
PROSSER WA (LAT. 46.1)												
$\bar{H}$ MJ/m^2	4.90	9.29	14.70	21.81	25.79	28.47	29.60	25.29	19.18	11.47	5.69	4.19
$\bar{K}_T$	.43	.55	.61	.67	.67	.69	.74	.73	.71	.61	.45	.42
$\bar{T}_a$ C	-1.0	4.0	6.0	10.0	14.0	18.0	21.0	20.0	16.0	10.0	4.0	.0
DD C-DAY	624.	428.	376.	240.	127.	47.	7.	16.	66.	231.	413.	543.
PUEBLO CO (LAT. 38.2)												
$\bar{H}$ MJ/m^2	11.39	14.74	18.67	22.78	25.20	28.05	27.13	25.08	21.10	16.50	12.31	10.01
$\bar{K}_T$	.70	.69	.67	.66	.64	.68	.67	.69	.69	.71	.71	.68
$\bar{T}_a$ C	-1.0	1.0	4.0	11.0	16.0	21.0	25.0	24.0	19.0	12.0	5.0	1.0
DD C-DAY	601.	471.	431.	225.	82.	16.	0.	0.	31.	186.	403.	551.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
PULLMAN WA (LAT. 46.4)												
H MJ/m^2	5.14	7.61	12.42	19.07	22.67	28.69	29.52	23.08	17.90	10.71	6.15	4.01
K_T	.46	.46	.52	.59	.59	.69	.74	.66	.66	.57	.50	.41
T_a C	-2.0	1.0	3.0	7.0	11.0	15.0	19.0	18.0	15.0	9.0	3.0	.0
DD C-DAY	637.	481.	460.	317.	204.	105.	26.	42.	114.	271.	452.	572.
PUT-IN-BAY OH (LAT. 41.4)												
H MJ/m^2	5.02	8.32	12.21	15.43	20.66	22.67	23.71	21.58	16.69	12.34	6.57	4.64
K_T	.35	.43	.46	.46	.53	.55	.59	.60	.57	.57	.43	.36
T_a C	-2.0	-1.0	2.0	9.0	15.0	21.0	24.0	23.0	19.0	14.0	6.0	.0
DD C-DAY	661.	576.	501.	283.	122.	13.	0.	0.	22.	154.	367.	589.
RALEIGH NC (LAT. 35.5)												
H MJ/m^2	9.95	12.75	16.81	19.78	20.87	23.84	22.71	20.20	16.14	13.05	10.00	8.45
K_T	.56	.56	.58	.56	.53	.58	.56	.55	.52	.53	.53	.52
T_a C	5.0	6.0	10.0	15.0	20.0	24.0	25.0	25.0	22.0	16.0	10.0	5.0
DD C-DAY	422.	354.	279.	100.	27.	0.	0.	0.	7.	103.	250.	410.
RALEIGH-DURHAM NC (LAT. 35.5)												
H MJ/m^2	9.00	11.85	15.66	20.22	21.64	22.44	23.15	20.14	16.62	13.23	10.05	8.16
K_T	.51	.52	.54	.57	.55	.54	.57	.55	.53	.54	.53	.50
T_a C	5.0	6.0	10.0	15.0	20.0	24.0	25.0	25.0	21.0	16.0	10.0	5.0
DD C-DAY	422.	354.	279.	100.	27.	0.	0.	0.	7.	103.	250.	410.
RAPID CITY SD (LAT. 44.1)												
H MJ/m^2	7.78	11.63	16.69	20.28	22.41	24.76	24.88	22.62	17.98	13.13	8.57	6.61
K_T	.62	.65	.66	.61	.58	.60	.62	.64	.64	.65	.62	.59
T_a C	-5.0	-2.0	.0	7.0	13.0	18.0	23.0	22.0	16.0	10.0	2.0	-2.0
DD C-DAY	741.	636.	584.	342.	181.	70.	12.	7.	92.	267.	498.	651.
RENO NV (LAT. 39.3)												
H MJ/m^2	9.80	13.56	18.80	24.79	27.80	29.89	29.60	27.05	22.27	16.54	11.60	8.75
K_T	.63	.65	.68	.72	.71	.72	.73	.74	.74	.73	.69	.62
T_a C	.0	2.0	4.0	8.0	12.0	16.0	20.0	19.0	15.0	10.0	4.0	.0
DD C-DAY	570.	434.	426.	303.	182.	81.	9.	28.	93.	253.	415.	551.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
RICHLAND WA (LAT. 46.2)												
H MJ/m^2	3.60	8.41	13.93	19.53	21.58	27.06	24.09	25.13	16.23	9.58	5.19	4.14
K_T	.32	.50	.57	.60	.56	.65	.60	.72	.60	.51	.41	.42
T_a C	.0	4.0	8.0	12.0	17.0	20.0	24.0	22.0	18.0	12.0	6.0	2.0
DD C-DAY	571.	395.	327.	183.	72.	17.	7.	16.	43.	202.	383.	503.
RICHMOND VA (LAT. 37.5)												
H MJ/m^2	7.91	10.72	15.07	19.34	21.86	23.49	23.40	20.14	16.54	12.64	8.67	7.12
K_T	.48	.49	.53	.55	.55	.57	.58	.55	.54	.54	.49	.47
T_a C	3.0	4.0	8.0	14.0	19.0	23.0	25.0	25.0	21.0	15.0	9.0	4.0
DD C-DAY	474.	398.	316.	126.	36.	0.	0.	0.	12.	113.	267.	448.
RIVERSIDE CA (LAT. 33.6)												
H MJ/m^2	11.51	15.37	20.01	22.65	26.08	28.47	28.18	25.87	22.40	17.06	13.36	11.30
K_T	.61	.64	.67	.63	.66	.69	.70	.70	.70	.67	.67	.64
T_a C	11.0	12.0	13.0	15.0	18.0	20.0	24.0	24.0	22.0	18.0	14.0	11.0
DD C-DAY	226.	173.	157.	93.	41.	12.	0.	0.	3.	34.	118.	208.
ROCHESTER NY (LAT. 43.1)												
H MJ/m^2	5.65	8.41	12.64	16.66	21.52	23.95	24.03	20.51	15.53	10.55	6.03	4.77
K_T	.43	.45	.49	.50	.55	.58	.60	.58	.55	.51	.42	.41
T_a C	-4.0	-4.0	1.0	8.0	14.0	19.0	22.0	21.0	17.0	11.0	5.0	-2.0
DD C-DAY	706.	626.	551.	315.	158.	26.	5.	14.	70.	221.	408.	632.
SACRAMENTO CA (LAT. 38.3)												
H MJ/m^2	6.82	11.10	16.62	22.23	28.39	28.68	28.47	24.37	20.43	15.28	9.42	6.36
K_T	.42	.52	.60	.64	.72	.69	.71	.67	.67	.66	.54	.43
T_a C	7.0	10.0	12.0	15.0	18.0	21.0	24.0	23.0	22.0	17.0	12.0	8.0
DD C-DAY	343.	237.	207.	126.	67.	11.	0.	0.	3.	56.	200.	331.
ST. CLOUD MN (LAT. 45.3)												
H MJ/m^2	7.11	10.50	15.31	17.69	20.87	22.62	23.21	20.53	15.05	10.08	6.11	5.14
K_T	.60	.61	.62	.54	.54	.55	.58	.59	.55	.52	.47	.50
T_a C	-12.0	-9.0	-2.0	6.0	13.0	18.0	21.0	20.0	14.0	9.0	.0	-8.0
DD C-DAY	966.	804.	673.	368.	180.	47.	10.	21.	127.	299.	583.	847.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
ST. LOUIS	MO (LAT. 38.4)											
H MJ/m2	7.37	10.30	14.49	18.00	22.15	23.95	23.78	20.93	17.50	12.89	8.71	6.45
K_T	.46	.49	.52	.52	.56	.58	.59	.57	.58	.56	.51	.44
T_a C	.0	2.0	6.0	14.0	19.0	24.0	26.0	25.0	21.0	15.0	7.0	1.0
DD C-DAY	581.	465.	379.	151.	57.	6.	0.	0.	19.	124.	333.	523.
SALT LAKE CITY	UT (LAT. 40.5)											
H MJ/m2	6.82	10.72	14.82	20.06	23.87	26.00	25.96	23.07	18.67	13.23	8.54	6.11
K_T	.46	.53	.55	.59	.61	.63	.64	.64	.63	.60	.53	.46
T_a C	-1.0	1.0	4.0	10.0	15.0	19.0	25.0	24.0	18.0	11.0	4.0	.0
DD C-DAY	637.	492.	437.	263.	132.	49.	0.	3.	58.	223.	432.	598.
SAN ANTONIO	TX (LAT. 29.3)											
H MJ/m2	11.58	14.51	17.52	18.82	22.54	25.26	26.14	24.34	20.49	16.52	12.17	10.54
K_T	.54	.56	.56	.51	.57	.62	.65	.65	.62	.60	.54	.52
T_a C	11.0	12.0	16.0	20.0	24.0	27.0	28.0	28.0	26.0	21.0	15.0	12.0
DD C-DAY	238.	159.	108.	22.	0.	0.	0.	0.	0.	17.	113.	202.
SAN DIEGO	CA (LAT. 32.4)											
H MJ/m2	11.10	14.36	17.92	19.43	20.64	21.35	22.90	20.89	18.67	15.11	11.89	10.26
K_T	.57	.59	.59	.54	.52	.52	.57	.58	.58	.58	.57	.56
T_a C	12.0	13.0	14.0	15.0	17.0	18.0	20.0	21.0	21.0	18.0	15.0	13.0
DD C-DAY	174.	132.	122.	80.	44.	29.	3.	0.	9.	24.	78.	143.
SAN FRANCISCO	CA (LAT. 37.5)											
H MJ/m2	8.16	11.85	17.08	21.44	24.20	24.99	22.61	20.01	17.75	13.90	9.63	7.33
K_T	.49	.54	.60	.61	.61	.61	.56	.55	.58	.59	.54	.48
T_a C	10.0	12.0	12.0	13.0	14.0	15.0	15.0	15.0	17.0	16.0	14.0	11.0
DD C-DAY	243.	181.	184.	162.	143.	108.	112.	98.	57.	71.	129.	224.
SANTA MARIA	CA (LAT. 34.5)											
H MJ/m2	11.08	14.64	20.32	23.42	26.64	29.11	28.48	25.59	21.91	17.48	13.01	10.58
K_T	.60	.63	.69	.66	.67	.71	.71	.69	.69	.70	.67	.62
T_a C	10.0	11.0	11.0	12.0	13.0	15.0	16.0	16.0	17.0	15.0	13.0	10.0
DD C-DAY	235.	206.	202.	157.	129.	92.	55.	52.	53.	81.	150.	217.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
SAVANNAH	GA (LAT. 32.1)											
H MJ/m2	10.30	13.15	16.87	21.64	23.57	23.19	22.44	20.97	16.87	14.57	11.10	8.96
K_T	.52	.53	.55	.60	.59	.57	.56	.56	.52	.55	.53	.49
T_a C	10.0	11.0	14.0	19.0	23.0	26.0	27.0	27.0	25.0	20.0	14.0	10.0
DD C-DAY	268.	211.	142.	35.	0.	0.	0.	0.	0.	33.	141.	254.
SAULT ST. MARIE	MI (LAT. 46.3)											
H MJ/m2	5.56	9.45	14.89	17.52	22.00	23.00	23.96	19.95	13.47	9.03	4.39	3.97
K_T	.49	.57	.62	.54	.57	.56	.60	.57	.50	.48	.35	.41
T_a C	-9.0	-10.0	-4.0	3.0	9.0	14.0	17.0	17.0	13.0	7.0	.0	-6.0
DD C-DAY	847.	767.	709.	450.	265.	112.	53.	58.	155.	322.	528.	759.
SCHENECTADY	NY (LAT. 42.5)											
H MJ/m2	5.44	8.41	11.46	14.22	17.31	18.78	18.57	16.69	12.55	9.16	5.39	4.35
K_T	.40	.44	.44	.42	.44	.45	.46	.47	.44	.44	.36	.36
T_a C	-5.0	-4.0	1.0	8.0	15.0	20.0	23.0	21.0	17.0	11.0	4.0	-2.0
DD C-DAY	744.	641.	563.	307.	136.	20.	4.	11.	76.	234.	420.	656.
SEATTLE	WA (LAT. 47.3)											
H MJ/m2	3.26	5.69	11.04	16.56	20.95	21.79	23.71	19.86	13.72	7.90	4.43	2.68
K_T	.31	.35	.47	.52	.54	.53	.59	.57	.51	.43	.37	.29
T_a C	5.0	7.0	7.0	10.0	13.0	16.0	18.0	18.0	16.0	12.0	8.0	6.0
DD C-DAY	410.	333.	321.	220.	134.	65.	28.	26.	72.	183.	302.	365.
SHREVEPORT	LA (LAT. 32.2)											
H MJ/m2	9.45	11.67	15.81	19.53	22.92	22.75	23.50	21.75	17.36	14.47	10.16	8.28
K_T	.48	.48	.52	.54	.58	.56	.58	.58	.54	.55	.49	.45
T_a C	8.0	10.0	14.0	18.0	22.0	26.0	28.0	28.0	25.0	19.0	13.0	9.0
DD C-DAY	307.	237.	169.	45.	0.	0.	0.	0.	0.	26.	165.	265.
SILVER HILL	MD (LAT. 38.5)											
H MJ/m2	7.61	10.20	14.22	18.32	21.45	23.21	21.58	19.19	16.60	12.34	8.45	6.82
K_T	.48	.48	.51	.53	.54	.56	.54	.53	.55	.53	.49	.47
T_a C	2.0	3.0	7.0	13.0	18.0	23.0	25.0	24.0	21.0	15.0	9.0	3.0
DD C-DAY	506.	431.	343.	147.	40.	0.	0.	0.	8.	106.	283.	476.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
SPOKANE	WA (LAT. 47.4)											
$\bar{H}$ MJ/m^2	4.94	8.91	13.26	19.53	23.25	25.30	27.73	23.17	17.02	8.62	5.48	3.18
$\bar{K}_T$	.47	.56	.56	.61	.60	.61	.70	.67	.64	.47	.46	.35
$\bar{T}_a$ C	-3.0	.0	3.0	8.0	13.0	16.0	21.0	20.0	15.0	9.0	2.0	-1.0
DD C-DAY	682.	510.	474.	315.	182.	80.	12.	26.	109.	296.	492.	620.
SPRINGFIELD	MO (LAT. 37.1)											
$\bar{H}$ MJ/m^2	8.33	11.39	15.41	18.59	22.11	23.91	23.61	22.15	19.01	13.94	99.22	7.54
$\bar{K}_T$	.50	.52	.54	.53	.56	.58	.59	.60	.62	.59	5.52	.49
$\bar{T}_a$ C	1.0	3.0	7.0	14.0	18.0	23.0	25.0	25.0	21.0	15.0	7.0	2.0
DD C-DAY	553.	436.	367.	153.	52.	6.	0.	3.	19.	126.	325.	499.
STATE COLLEGE	PA (LAT. 40.5)											
$\bar{H}$ MJ/m^2	5.81	8.45	12.42	15.60	19.53	22.75	22.08	18.99	15.10	11.50	6.48	5.02
$\bar{K}_T$	.39	.42	.46	.46	.50	.55	.55	.53	.51	.52	.41	.38
$\bar{T}_a$ C	-2.0	-2.0	2.0	9.0	15.0	20.0	22.0	21.0	17.0	11.0	5.0	-1.0
DD C-DAY	654.	572.	489.	267.	115.	13.	3.	8.	61.	214.	400.	609.
STILLWATER	OK (LAT. 36.1)											
$\bar{H}$ MJ/m^2	8.66	11.96	16.23	19.07	20.99	24.80	24.80	22.67	19.03	14.72	10.75	8.53
$\bar{K}_T$	.50	.53	.56	.54	.53	.60	.62	.62	.61	.60	.58	.53
$\bar{T}_a$ C	2.0	5.0	9.0	16.0	20.0	25.0	27.0	27.0	22.0	17.0	9.0	4.0
DD C-DAY	481.	358.	287.	97.	21.	0.	0.	0.	6.	81.	258.	429.
SUMMIT	MT (LAT. 48.2)											
$\bar{H}$ MJ/m^2	5.11	6.78	11.22	17.33	19.34	20.64	23.45	21.35	14.82	9.04	4.27	3.18
$\bar{K}_T$	.51	.44	.48	.55	.50	.50	.59	.62	.56	.51	.38	.37
$\bar{T}_a$ C	-8.0	-5.0	-4.0	1.0	6.0	10.0	14.0	13.0	8.0	4.0	-2.0	-6.0
DD C-DAY	854.	691.	715.	518.	377.	253.	143.	171.	302.	457.	647.	777.
SYRACUSE	NY (LAT. 43.1)											
$\bar{H}$ MJ/m^2	5.40	8.08	12.14	15.66	20.26	23.11	23.36	19.72	14.99	10.09	5.19	4.31
$\bar{K}_T$	.41	.43	.47	.47	.52	.56	.58	.55	.53	.49	.36	.37
$\bar{T}_a$ C	-5.0	-4.0	1.0	8.0	14.0	19.0	22.0	21.0	17.0	11.0	5.0	-2.0
DD C-DAY	713.	628.	548.	308.	151.	26.	6.	10.	67.	218.	400.	436.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
TALLAHASSEE	FL (LAT. 30.3)											
$\bar{H}$ MJ/m^2	10.33	13.01	17.69	20.20	22.92	19.91	22.75	22.46	17.73	14.76	15.22	13.01
$\bar{K}_T$	.49	.51	.57	.55	.58	.49	.57	.60	.54	.54	.69	.67
$\bar{T}_a$ C	11.0	12.0	16.0	19.0	23.0	26.0	27.0	27.0	25.0	20.0	15.0	12.0
DD C-DAY	227.	179.	104.	19.	0.	0.	0.	0.	0.	17.	113.	209.
TAMPA	FL (LAT. 27.6)											
$\bar{H}$ MJ/m^2	13.67	16.35	19.95	22.79	24.88	23.96	22.29	20.70	18.99	16.94	14.93	12.63
$\bar{K}_T$	.61	.61	.62	.62	.63	.59	.56	.55	.56	.60	.64	.60
$\bar{T}_a$ C	16.0	16.0	19.0	21.0	24.0	26.0	27.0	27.0	26.0	23.0	19.0	16.0
DD C-DAY	113.	98.	50.	5.	0.	0.	0.	0.	0.	0.	39.	94.
TRENTON	NJ (LAT. 40.1)											
$\bar{H}$ MJ/m^2	7.24	10.22	14.36	17.75	20.56	22.86	22.61	19.64	16.29	12.31	8.16	6.49
$\bar{K}_T$	.48	.50	.53	.52	.52	.55	.56	.54	.55	.55	.50	.48
$\bar{T}_a$ C	.0	.0	5.0	11.0	16.0	21.0	24.0	23.0	19.0	13.0	7.0	1.0
DD C-DAY	567.	492.	410.	213.	75.	0.	0.	0.	22.	140.	312.	518.
TUCSON	AZ (LAT. 32.1)											
$\bar{H}$ MJ/m^2	13.09	16.81	22.83	27.85	30.95	29.65	26.26	24.67	24.30	18.69	14.85	12.42
$\bar{K}_T$	.66	.68	.75	.77	.78	.72	.65	.66	.75	.71	.71	.67
$\bar{T}_a$ C	10.0	11.0	14.0	18.0	22.0	27.0	30.0	28.0	26.0	20.0	14.0	10.0
DD C-DAY	262.	191.	134.	42.	3.	0.	0.	0.	0.	14.	128.	226.
TULSA	OK (LAT. 36.1)											
$\bar{H}$ MJ/m^2	8.67	11.43	15.45	18.30	21.56	24.41	23.86	22.23	18.34	13.77	9.80	8.16
$\bar{K}_T$	.50	.51	.54	.52	.55	.59	.59	.60	.59	.57	.53	.51
$\bar{T}_a$ C	3.0	5.0	9.0	16.0	20.0	25.0	28.0	27.0	23.0	17.0	10.0	4.0
DD C-DAY	489.	370.	293.	98.	16.	0.	0.	0.	6.	79.	260.	434.
TWIN FALLS	ID (LAT. 40.3)											
$\bar{H}$ MJ/m^2	6.82	10.05	14.86	19.34	23.11	24.79	25.20	22.61	18.09	11.97	7.37	5.49
$\bar{K}_T$	.46	.50	.55	.57	.59	.60	.63	.63	.61	.54	.46	.41
$\bar{T}_a$ C	-1.0	1.0	4.0	9.0	13.0	17.0	22.0	21.0	16.0	10.0	4.0	.0
DD C-DAY	644.	490.	454.	290.	161.	73.	0.	12.	99.	260.	442.	589.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
WASHINGTON DC (LAT. 38.5)												
H MJ/m2	6.65	9.62	13.38	16.85	18.69	23.34	22.12	19.32	15.35	11.75	8.82	6.15
K_T	.42	.45	.48	.49	.47	.56	.55	.53	.51	.51	.51	.42
T_a C	2.0	3.0	7.0	13.0	18.0	23.0	25.0	24.0	21.0	15.0	9.0	3.0
DD C-DAY	484.	423.	348.	160.	41.	0.	0.	0.	18.	121.	288.	463.
WICHITA KS (LAT. 37.4)												
H MJ/m2	[illegible].29	11.97	15.99	19.76	22.78	25.20	24.41	22.57	18.71	14.40	10.26	8.29
K_T	.56	.55	.56	.57	.58	.61	.61	.62	.61	.61	.58	.54
T_a C	.0	2.0	6.0	14.0	19.0	24.0	27.0	26.0	21.0	15.0	7.0	1.0
DD C-DAY	581.	447.	373.	153.	50.	4.	0.	0.	18.	117.	337.	526.
YUMA AZ (LAT. 32.4)												
H MJ/m2	12.77	16.79	21.64	26.50	29.43	29.52	27.30	24.58	22.19	18.50	13.82	11.35
K_T	.65	.69	.71	.74	.74	.72	.68	.66	.69	.71	.67	.62
T_a C	12.0	15.0	17.0	21.0	25.0	29.0	34.0	33.0	30.0	24.0	17.0	13.0
DD C-DAY	171.	107.	54.	13.	0.	0.	0.	0.	0.	0.	60.	153.
AKLAVIK NW (LAT. 68.1)												
H MJ/m2	.21	2.09	8.45	16.23	21.54	22.08	18.65	12.42	6.52	2.59	.46	.04
K_T	1.61	.56	.72	.69	.62	.54	.49	.44	.41	.44	.65	.00
T_a C	-28.0	-27.0	-22.0	-12.0	.0	9.0	13.0	10.0	3.0	-7.0	-19.0	-26.0
DD C-DAY	1462.	1298.	1268.	930.	591.	268.	152.	255.	448.	78[illegible].	1147.	1406.
CHURCHILL MA (LAT. 58.4)												
H MJ/m2	2.72	6.27	12.75	18.61	21.33	22.16	21.12	15.89	9.41	4.81	2.51	1.46
K_T	.65	.67	.73	.67	.58	.54	.55	.51	.44	.41	.47	.49
T_a C	-27.0	-26.0	-19.0	-10.0	-2.0	5.0	11.0	11.0	5.0	-1.0	-11.0	-21.0
DD C-DAY	1421.	1265.	1183.	872.	641.	375.	200.	208.	378.	601.	900.	1249.
EDMONTON AT (LAT. 53.3)												
H MJ/m2	3.72	7.36	13.05	17.27	21.29	21.45	22.00	17.10	12.46	7.86	4.64	2.76
K_T	.53	.59	.64	.58	.57	.52	.56	.52	.52	.53	.56	.48
T_a C	-14.0	-11.0	-5.0	4.0	11.0	14.0	16.0	15.0	10.0	5.0	-4.0	-10.0
DD C-DAY	1006.	844.	739.	425.	222.	123.	41.	100.	288.	410.	675.	891.

Location \ Month	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
KAPUSKASING OT (LAT. 49.2)												
H MJ/m2	4.60	7.95	12.96	15.47	17.15	20.07	20.07	16.73	11.29	6.69	3.35	3.35
K_T	.49	.53	.57	.49	.45	.49	.51	.49	.44	.39	.31	.42
T_a C	-18.0	-16.0	-9.0	[illegible]	7.0	14.0	16.0	15.0	10.0	4.0	-4.0	-14.0
DD C-DAY	1132.	964.	868.	543.	322.	123.	41.	95.	225.	420.	692.	1004.
LETHBRIDGE AT (LAT. 49.4)												
H MJ/m2	5.02	8.78	14.22	17.56	21.75	24.25	25.51	21.75	15.47	10.04	5.86	3.76
K_T	.54	.59	.63	.58	.57	.59	.64	.64	.60	.59	.55	.47
T_a C	-8.0	-7.0	-2.0	5.0	11.0	14.0	17.0	16.0	12.0	7.0	.0	-4.0
DD C-DAY	832.	717.	644.	387.	224.	118.	31.	62.	177.	339.	562.	709.
MONCTON NB (LAT. 46.1)												
H MJ/m2	4.18	7.53	12.13	15.89	18.40	18.82	19.65	17.15	12.96	8.78	4.60	3.76
K_T	.37	.45	.50	.49	.48	.46	.49	.49	.48	.46	.36	.38
T_a C	-8.0	-8.0	-3.0	3.0	9.0	15.0	17.0	16.0	13.0	7.0	1.0	-5.0
DD C-DAY	823.	742.	663.	438.	260.	95.	34.	58.	153.	339.	495.	746.
MONTREAL QU (LAT. 45.3)												
H MJ/m2	4.60	8.36	13.38	16.73	19.65	20.49	21.33	18.40	12.96	8.36	4.18	3.35
K_T	.39	.48	.54	.51	.51	.50	.53	.52	.47	.43	.32	.32
T_a C	-9.0	-7.0	-2.0	5.0	12.0	17.0	18.0	17.0	15.0	8.0	1.0	-6.0
DD C-DAY	870.	767.	653.	380.	176.	38.	5.	24.	92.	289.	490.	773.
OTTAWA OT (LAT. 45.3)												
H MJ/m2	6.02	9.53	14.01	16.85	20.78	23.34	22.87	19.61	14.85	9.24	5.14	4.56
K_T	.51	.55	.57	.51	.54	.56	.57	.56	.54	.48	.39	.44
T_a C	-10.0	-10.0	-3.0	5.0	12.0	16.0	17.0	16.0	14.0	8.0	.0	-8.0
DD C-DAY	902.	801.	684.	393.	189.	50.	14.	45.	123.	315.	520.	816.
ST. JOHNS NF (LAT. 47.3)												
H MJ/m2	3.35	6.27	10.04	13.38	16.73	17.98	18.40	14.22	11.71	7.11	3.35	2.93
K_T	.32	.39	.42	.42	.43	.44	.46	.41	.44	.39	.28	.32
T_a C	-4.0	-4.0	-2.0	1.0	5.0	10.0	15.0	15.0	11.0	6.0	2.0	-1.0
DD C-DAY	701.	650.	659.	515.	394.	240.	103.	100.	190.	362.	462.	618.

For greatest accuracy, a month-by-month computation must be made of system performance; exhibit 8.15 shows the monthly values. Exhibit 8.16 is an example of the use of exhibit 8.15. Albany, N.Y., in January has a $\bar{K}_T$ of 0.38 (see exhibit 8.16). The average ambient temperature is -5.0°C (22°F). The insolation is 11.47 MJ/m^2 on a horizontal surface, and 367°C days are normally accumulated.

Albany, N.Y. in January:

$\bar{K}_T$ = **0.38**

$\bar{T}_A$ = **5.0° C**

$\bar{H}$ = **11.47 MJ/m²**

DD = **367/month**

Exhibit 8.16 Example of Use of Exhibit 8.15

For most PV systems, one must design not only for average power, but for days in which there is no sunshine. One must know how much energy storage is needed to carry through to the next day or so without sunshine. The insolation on one day is poorly correlated with the insolation on the next. If today is clear, tomorrow has an equal chance of being clear or cloudy. The lack of correlation eases the problem of estimating the number of sequential days the insolation will fall below any specified value. Exhibits 8.17 and 8.18 present the correlation devised by Liu and Jordan that shows the frequency of occurrence of each value of $\bar{K}_T$, given the average value, $\bar{K}_T$. The curves show the cumulative probability. For example (exhibit 8.19), if $\bar{K}_T$ were 0.5, the probability that $\bar{K}_T$ would be equal to or less than 0.40 would be 0.323 (from exhibit 8.18). The probability that $\bar{K}_T$ would be less than 0.4 for n days in a row would be given by exhibit 8.20. Cumulative probability gives the probability that a value <u>or</u> those less than the value will occur. The frequency distribution gives the probability.

$$P_n = p^n$$

or, for two days in a row,

$$P_2 = (0.323)^2 = 0.104$$

The probability that $\bar{K}_T$ would be less than 0.4 for four days in a row would be $(0.323)^4$, or 0.01, once out of every 100 days.

K_T	VALUE OF f FOR $\bar{K}_T$ =				
	.3	.4	.5	.6	.7
.04	.073	.015	.001	.000	.000
.08	.162	.070	.023	.008	.000
.12	.245	.129	.045	.021	.007
.16	.299	.190	.082	.039	.007
.20	.395	.249	.121	.053	.007
.24	.496	.298	.160	.076	.007
.28	.513	.346	.194	.101	.013
.32	.579	.379	.234	.126	.013
.36	.628	.438	.277	.152	.027
.40	.687	.493	.323	.191	.034
.44	.748	.545	.358	.235	.047
.48	.793	.601	.400	.269	.054
.52	.824	.664	.460	.310	.081
.56	.861	.719	.509	.360	.128
.60	.904	.760	.614	.410	.161
.64	.936	.827	.703	.467	.228
.68	.953	.888	.792	.538	.295
.72	.967	.931	.873	.648	.517
.76	.979	.967	.945	.758	.678
.80	.986	.981	.980	.884	.859
.84	.993	.997	.993	.945	.940
.88	.995	.999	1.000	.985	.980
.92	.998	.999		.996	1.000
.96	.998	1.000		.999	
1.00	1.000			1.000	

Exhibit 8.17 Generalized K_T Distribution Curves.

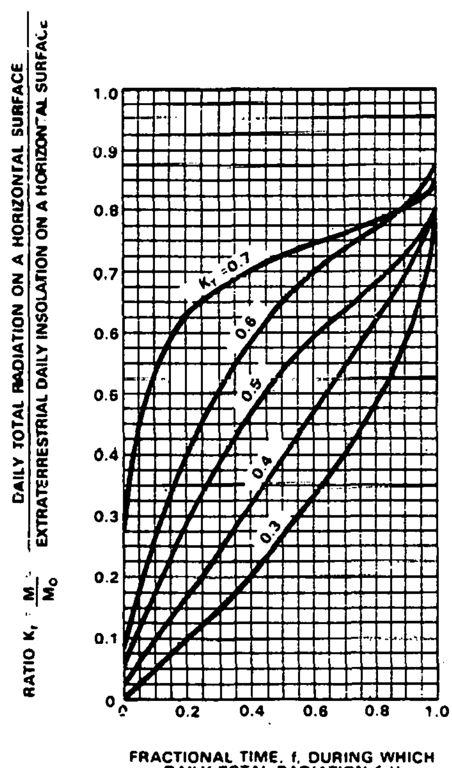


Exhibit 8.18 The Generalized K_T Distribution Curves.

Given: $K_T = 0.5$ What is probability $K_T \leq 0.40$?
a. Enter exhibit 8.13 or exhibit 8.14 at $K_T = 0.5$ b. Read to $K_T = 0.40$ c. Read probability = 0.323

Exhibit 8.19 Use of Frequency Charts.

Probability = P^M			
M:	1	2	4
Probability:	0.323	0.104	0.010

Exhibit 8.20 Consecutive Days of $K_T < 0.4$.

8.3.5 INSOLATION ON TILTED SURFACES

The insolation computed and the probabilities of experiencing this insolation pertain to insolation on a flat, horizontal surface. Most solar cells will be tilted toward the sun to take advantage of the higher incident flux. The method of Liu and Jordan can also be used to devise a way of computing the flux on the tilted surface.

First, the flux must be broken into the direct and diffuse components. The diffuse component is due to the scattering of sunlight in the atmosphere by dust, clouds, water vapor, etc. One assumes that the diffuse flux is isotropic, coming uniformly from every sector of the sky (isotropic refers to the same value regardless of direction of measurement). If the diffuse flux is known for the horizontal surface, which "sees" the entire sky, the diffuse flux for the tilted surface can be computed by correcting for the amount of sky "seen" by the tilted surface. The ratio of views is given by the formula shown in exhibit 8.21, where A is the tilt of the surface (A is zero for a horizontal suface; 90° for a vertical surface). If the direct sunlight onto the horizontal surface is known, the flux can be divided by the cosine of the angle of incidence (solar-altitude angle) to determine the intensity of the beam flux. This intensity can be multiplied by the cosine of the angle of incidence (with respect to the tilted surface) to determine the direct flux on the tilted surface. Summing the direct and diffuse fluxes gives the total insolation on the tilted surface, except for the flux reflected from the surroundings. A typical value for the ground reflectance is 0.1; for snow, it is 0.46 to 0.86. The flux received by the tilted surface due to ground reflectance is given by the last formula in exhibit 8.21, where S_H is the insolation on the horizontal surface. Exhibit 8.22 gives the relationship between K_T and the diffuse flux, as obtained by

Liu and Jordan. The computation of the flux on a tilted surface is complicated. Most of the computation effort lies in determining the angle of incidence to the horizontal and to the tilted area. Fortunately, Duffie and Beckman have performed the computations and have tabulated the results (see exhibit 8.23). The following computational procedure is based on the use of their tables.

Direct Sunlight: By cosine of angle with solar rays

Diffuse Sunlight: By view of sky, $F = (1 + \cos A)/2$

Ground-Reflected Sunlight: By view of earth, $(1\text{-}F)\ R_G\ S_H$

$R_G \simeq 10\%$

Exhibit 8.21 Conversion to Flux on Tilted Surfaces

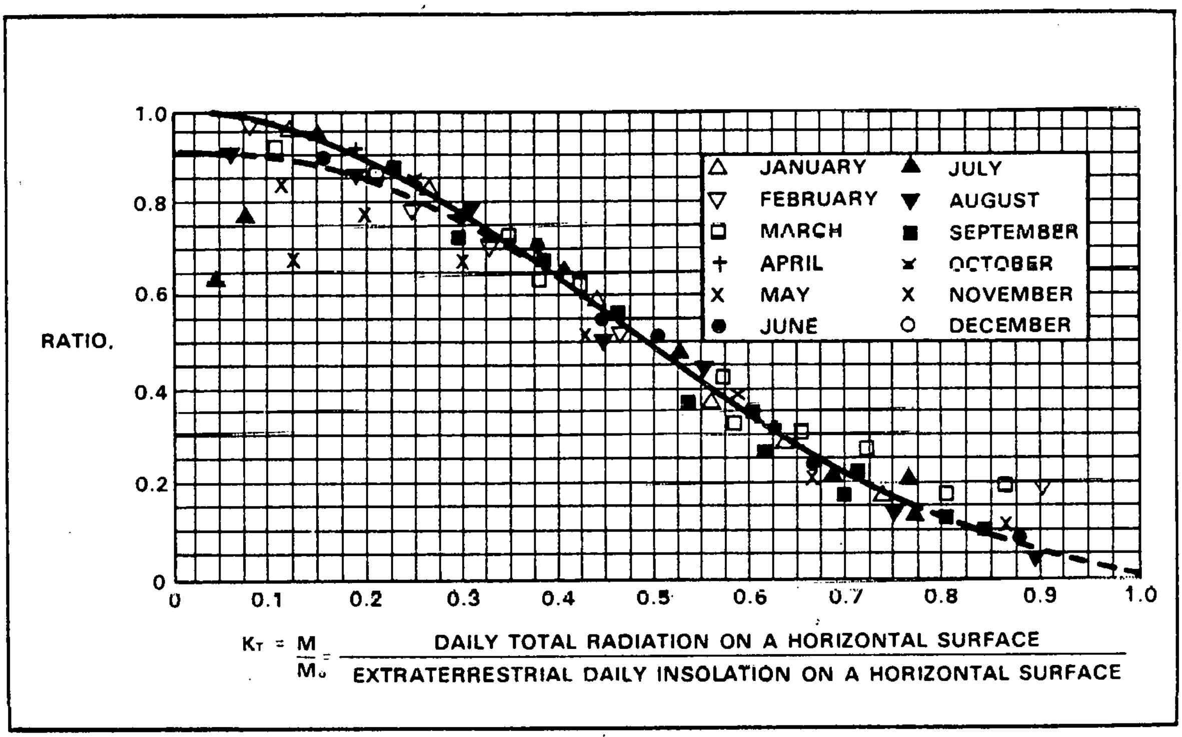


Exhibit 8.22 Ratio of Daily Diffuse Radiation on a Horizontal Surface to the Daily Total Radiation on a Horizontal Surface as a Function of the Cloudiness Index K_T.

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(LATITUDE-TILT)= 15.0											
25	1.09	1.06	1.03	1.00	.98	.98	.98	.99	1.02	1.05	1.08	1.09
30	1.15	1.10	1.05	1.01	.98	.97	.97	.99	1.03	1.08	1.13	1.16
35	1.23	1.15	1.07	1.01	.97	.96	.96	1.00	1.05	1.12	1.20	1.25
40	1.34	1.22	1.11	1.02	.97	.95	.96	1.00	1.07	1.18	1.30	1.38
45	1.51	1.31	1.15	1.03	.97	.94	.95	1.00	1.10	1.25	1.45	1.58
50	1.77	1.44	1.21	1.05	.97	.93	.95	1.01	1.14	1.35	1.67	1.91
55	2.26	1.65	1.29	1.07	.96	.93	.94	1.02	1.19	1.50	2.04	2.53
	(LATITUDE-TILT)= .0											
25	1.17	1.12	1.04	.97	.93	.91	.92	.95	1.01	1.08	1.16	1.19
30	1.24	1.15	1.05	.97	.92	.90	.91	.95	1.02	1.11	1.21	1.27
35	1.33	1.20	1.08	.97	.91	.89	.90	.95	1.03	1.16	1.29	1.38
40	1.46	1.27	1.11	.98	.90	.87	.89	.94	1.05	1.21	1.41	1.53
45	1.65	1.37	1.15	.99	.90	.86	.88	.94	1.08	1.29	1.57	1.76
50	1.96	1.52	1.21	1.00	.89	.85	.87	.95	1.11	1.40	1.82	2.14
55	2.51	1.75	1.29	1.01	.89	.84	.86	.95	1.16	1.56	2.25	2.88
	(LATITUDE-TILT)=-15.0											
25	1.21	1.11	1.00	.91	.84	.82	.83	.88	.96	1.07	1.18	1.26
30	1.28	1.15	1.01	.90	.83	.80	.81	.87	.97	1.10	1.24	1.32
35	1.37	1.20	1.03	.90	.82	.79	.80	.86	.97	1.14	1.32	1.43
40	1.51	1.27	1.06	.90	.81	.77	.79	.86	.99	1.19	1.44	1.60
45	1.71	1.37	1.10	.90	.80	.76	.77	.85	1.01	1.27	1.61	1.86
50	2.04	1.52	1.15	.91	.79	.74	.76	.85	1.04	1.38	1.88	2.26
55	2.63	1.76	1.23	.92	.78	.73	.75	.85	1.08	1.54	2.33	3.05
	VERTICAL											
25	.94	.78	.62	.48	.42	.40	.41	.45	.56	.73	.90	.99
30	1.04	.85	.67	.52	.44	.42	.43	.48	.60	.79	.99	1.10
35	1.17	.94	.72	.55	.47	.44	.45	.51	.65	.86	1.10	1.24
40	1.33	1.04	.78	.59	.50	.47	.48	.55	.70	.95	1.25	1.44
45	1.57	1.18	.86	.64	.53	.49	.51	.59	.76	1.06	1.45	1.72
50	1.93	1.36	.95	.68	.56	.52	.54	.63	.82	1.20	1.75	2.17
55	2.55	1.62	1.06	.74	.60	.55	.57	.67	.91	1.40	2.24	3.00

$\bar{K}_T = 0.30$

Exhibit 8.23 Values of $\bar{R}$ for $\bar{K}_T$.

VALUES OF $\bar{R}$ FOR $\bar{K}_T = 0.40$

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					(LATITUDE-TILT)= 15.0							
25	1.11	1.08	1.04	1.01	.98	.97	.98	1.00	1.03	1.07	1.10	1.13
30	1.20	1.13	1.07	1.01	.98	.96	.97	1.00	1.05	1.11	1.18	1.22
35	1.31	1.20	1.11	1.03	.97	.95	.96	1.00	1.07	1.17	1.28	1.34
40	1.46	1.30	1.15	1.04	.97	.94	.96	1.01	1.10	1.25	1.41	1.52
45	1.69	1.43	1.21	1.06	.97	.94	.95	1.02	1.15	1.35	1.61	1.79
50	2.04	1.61	1.30	1.09	.98	.94	.95	1.04	1.20	1.49	1.90	2.22
55	2.68	1.89	1.41	1.12	.98	.93	.95	1.06	1.28	1.70	2.41	3.06
					(LATITUDE-TILT)= .0							
25	1.24	1.15	1.06	.98	.92	.90	.91	.95	1.03	1.12	1.22	1.27
30	1.34	1.21	1.09	.98	.91	.88	.90	.95	1.04	1.17	1.30	1.38
35	1.46	1.29	1.13	.99	.91	.87	.89	.95	1.07	1.23	1.41	1.52
40	1.64	1.39	1.17	1.00	.90	.86	.88	.96	1.10	1.31	1.57	1.73
45	1.90	1.53	1.23	1.02	.90	.86	.88	.96	1.14	1.42	1.79	2.04
50	2.32	1.74	1.32	1.04	.90	.85	.87	.98	1.19	1.58	2.13	2.56
55	3.05	2.04	1.43	1.07	.90	.84	.87	.99	1.27	1.80	2.71	3.54
					(LATITUDE-TILT)=-15.0							
25	1.31	1.17	1.02	.91	.82	.79	.80	.87	.98	1.12	1.27	1.35
30	1.41	1.23	1.06	.91	.81	.77	.79	.86	.99	1.17	1.36	1.46
35	1.54	1.31	1.09	.91	.80	.76	.78	.86	1.01	1.23	1.47	1.62
40	1.73	1.41	1.13	.92	.80	.75	.77	.86	1.04	1.31	1.64	1.84
45	2.01	1.56	1.19	.93	.79	.74	.76	.87	1.08	1.42	1.87	2.18
50	2.45	1.77	1.27	.95	.79	.73	.76	.88	1.13	1.58	2.24	2.74
55	3.24	2.09	1.39	.98	.79	.72	.75	.89	1.19	1.81	2.85	3.80
					VERTICAL							
25	1.05	.84	.63	.44	.36	.34	.35	.40	.54	.77	.99	1.12
30	1.18	.94	.69	.49	.39	.36	.37	.44	.60	.85	1.11	1.26
35	1.35	1.05	.76	.54	.43	.39	.41	.49	.66	.95	1.26	1.43
40	1.57	1.18	.84	.59	.47	.42	.44	.53	.73	1.06	1.46	1.71
45	1.88	1.36	.94	.65	.51	.46	.48	.58	.81	1.21	1.73	2.08
50	2.36	1.60	1.06	.71	.55	.50	.52	.63	.90	1.40	2.12	2.68
55	3.18	1.95	1.21	.78	.60	.54	.56	.69	1.00	1.66	2.76	3.78

VALUES OF $\bar{R}$ FOR $\bar{K}_T = 0.50$

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					(LATITUDE-TILT)= 15.0							
25	1.14	1.09	1.05	1.01	.98	.97	.97	1.00	1.03	1.04	1.12	1.15
30	1.23	1.16	1.08	1.02	.97	.96	.96	1.00	1.06	1.13	1.21	1.26
35	1.37	1.24	1.13	1.03	.97	.95	.96	1.01	1.09	1.20	1.33	1.41
40	1.55	1.36	1.19	1.05	.97	.94	.96	1.02	1.13	1.30	1.49	1.62
45	1.82	1.51	1.26	1.08	.98	.94	.96	1.03	1.18	1.42	1.72	1.93
50	2.24	1.73	1.36	1.12	.99	.94	.96	1.06	1.25	1.59	2.08	2.45
55	2.99	2.06	1.50	1.16	1.00	.94	.96	1.08	1.34	1.83	2.67	3.44
					(LATITUDE-TILT)= .0							
25	1.29	1.19	1.08	.98	.91	.88	.90	.95	1.04	1.15	1.26	1.32
30	1.40	1.26	1.11	.99	.91	.87	.89	.95	1.06	1.21	1.36	1.45
35	1.36	1.35	1.16	1.00	.90	.86	.88	.96	1.09	1.28	1.50	1.63
40	1.77	1.48	1.22	1.02	.90	.86	.88	.97	1.13	1.38	1.68	1.87
45	2.08	1.65	1.30	1.04	.90	.85	.87	.98	1.18	1.52	1.95	2.25
50	2.57	1.89	1.40	1.08	.91	.85	.87	1.00	1.25	1.70	2.36	2.86
55	3.44	2.26	1.34	1.12	.92	.85	.88	1.02	1.34	1.97	3.04	4.02
					(LATITUDE-TILT)=-15.0							
25	1.38	1.22	1.05	.91	.81	.77	.79	.86	.99	1.16	1.33	1.43
30	1.50	1.29	1.09	.91	.80	.76	.78	.86	1.01	1.22	1.44	1.57
35	1.66	1.39	1.13	.92	.80	.75	.77	.86	1.04	1.30	1.58	1.75
40	1.89	1.52	1.19	.94	.79	.74	.76	.87	1.08	1.40	1.78	2.02
45	2.22	1.69	1.26	.96	.79	.73	.76	.88	1.12	1.53	2.06	2.43
50	2.75	1.94	1.36	.98	.79	.73	.76	.89	1.19	1.72	2.49	3.09
55	3.68	2.32	1.50	1.02	.80	.72	.75	.91	1.27	1.99	3.22	4.34
					VERTICAL							
25	1.13	.89	.63	.42	.32	.29	.30	.37	.53	.80	1.06	1.21
30	1.29	1.00	.71	.47	.35	.32	.33	.41	.60	.89	1.20	1.38
35	1.48	1.13	.79	.53	.40	.35	.37	.47	.67	1.01	1.38	1.60
40	1.74	1.29	.89	.59	.44	.39	.41	.52	.75	1.14	1.61	1.91

VALUES OF $\bar{R}$ FOR $\bar{K}_T = 0.60$

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					(LATITUDE-TILT)= 15.0							
25	1.15	1.11	1.06	1.01	.98	.96	.97	1.00	1.04	1.09	1.14	1.17
30	1.27	1.18	1.10	1.02	.97	.95	.96	1.00	1.07	1.15	1.24	1.29
35	1.41	1.28	1.15	1.04	.97	.94	.96	1.01	1.10	1.23	1.38	1.46
40	1.62	1.41	1.21	1.07	.98	.94	.95	1.07	1.15	1.34	1.56	1.70
45	1.92	1.58	1.30	1.10	.98	.94	.96	1.04	1.21	1.48	1.82	2.05
50	2.40	1.83	1.41	1.14	.99	.94	.96	1.07	1.29	1.67	2.22	2.66
55	3.24	2.20	1.57	1.19	1.01	.94	.97	1.10	1.39	1.95	2.89	3.75
					(LATITUDE-TILT)= .0							
25	1.33	1.21	1.09	.98	.91	.87	.89	.95	1.05	1.17	1.30	1.37
30	1.46	1.30	1.13	.99	.90	.86	.88	.95	1.08	1.24	1.42	1.51
35	1.63	1.40	1.19	1.01	.90	.85	.87	.96	1.11	1.33	1.57	1.71
40	1.88	1.55	1.26	1.03	.90	.85	.87	.97	1.16	1.44	1.78	1.99
45	2.23	1.74	1.35	1.06	.91	.85	.87	.99	1.22	1.59	2.08	2.41
50	2.78	2.02	1.47	1.10	.92	.85	.88	1.02	1.30	1.81	2.56	3.10
55	3.76	2.43	1.63	1.15	.93	.85	.88	1.05	1.41	2.11	3.31	4.41
					(LATITUDE-TILT)=-15.0							
25	1.43	1.26	1.07	.91	.80	.75	.77	.86	1.00	1.19	1.39	1.49
30	1.57	1.34	1.11	.92	.79	.74	.76	.86	1.03	1.26	1.51	1.65
35	1.76	1.45	1.16	.93	.79	.73	.76	.86	1.06	1.35	1.67	1.86
40	2.02	1.60	1.23	.95	.79	.73	.75	.87	1.11	1.47	1.90	2.17
45	2.40	1.80	1.32	.98	.79	.72	.75	.89	1.16	1.62	2.22	2.63
50	2.99	2.09	1.44	1.01	.80	.72	.75	.91	1.24	1.84	2.71	3.37
55	4.06	2.52	1.59	1.05	.81	.72	.76	.93	1.34	2.15	3.52	4.78
					VERTICAL							
25	1.20	.92	.63	.39	.28	.25	.26	.34	.53	.82	1.12	1.28
30	1.37	1.04	.72	.46	.32	.28	.30	.39	.60	.93	1.28	1.48
35	1.59	1.19	.81	.52	.37	.32	.34	.43	.68	1.06	1.48	1.73
40	1.88	1.37	.92	.59	.42	.37	.39	.51	.77	1.21	1.73	2.07
45	2.30	1.61	1.05	.66	.48	.42	.44	.58	.87	1.40	2.09	2.56
50	2.93	1.93	1.21	.75	.54	.47	.50	.65	.99	1.65	2.61	3.34
55	4.01	2.39	1.41	.84	.60	.52	.55	.72	1.13	2.00	3.46	4.80

VALUES OF $\bar{R}$ FOR $\bar{K}_T = 0.70$

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					(LATITUDE-TILT)= 15.0							
25	1.17	1.12	1.06	1.01	.98	.96	.97	1.00	1.04	1.10	1.16	1.19
30	1.30	1.20	1.11	1.03	.97	.95	.96	1.00	1.07	1.17	1.27	1.33
35	1.46	1.31	1.17	1.05	.97	.94	.95	1.01	1.12	1.26	1.42	1.51
40	1.69	1.45	1.24	1.08	.98	.94	.95	1.03	1.17	1.38	1.62	1.78
45	2.03	1.65	1.34	1.12	.99	.94	.96	1.06	1.24	1.53	1.92	2.18
50	2.56	1.93	1.47	1.16	1.00	.94	.97	1.09	1.33	1.75	2.36	2.83
55	3.50	2.34	1.64	1.22	1.02	.94	.98	1.13	1.45	2.06	3.11	4.07
					(LATITUDE-TILT)= .0							
25	1.37	1.24	1.11	.98	.90	.86	.88	.95	1.06	1.20	1.34	1.41
30	1.52	1.34	1.16	1.00	.90	.85	.87	.95	1.09	1.27	1.47	1.58
35	1.71	1.46	1.22	1.02	.90	.85	.87	.96	1.13	1.37	1.64	1.80
40	1.98	1.62	1.30	1.05	.90	.84	.87	.98	1.19	1.50	1.88	2.11
45	2.38	1.84	1.40	1.08	.91	.84	.87	1.00	1.26	1.67	2.21	2.58
50	3.00	2.15	1.53	1.13	.92	.85	.88	1.03	1.35	1.91	2.73	3.35
55	4.09	2.61	1.72	1.19	.94	.85	.89	1.07	1.47	2.25	3.59	4.81
					(LATITUDE-TILT)=-15.0							
25	1.49	1.30	1.09	.91	.78	.73	.76	.85	1.01	1.23	1.44	1.56
30	1.65	1.39	1.14	.92	.78	.72	.75	.86	1.04	1.30	1.58	1.73
35	1.86	1.52	1.20	.94	.78	.72	.75	.87	1.09	1.41	1.76	1.98
40	2.15	1.69	1.28	.96	.78	.72	.74	.88	1.14	1.54	2.02	2.32
45	2.58	1.91	1.38	.99	.79	.71	.75	.90	1.20	1.71	2.37	2.83
50	3.24	2.23	1.51	1.04	.80	.72	.75	.92	1.29	1.96	2.92	3.66
55	4.41	2.72	1.69	1.09	.81	.72	.76	.96	1.40	2.31	3.83	5.23
					VERTICAL							
25	1.26	.96	.64	.37	.25	.21	.23	.31	.52	.85	1.18	1.36
30	1.46	1.09	.73	.44	.29	.25	.27	.37	.60	.97	1.35	1.57
35	1.70	1.26	.84	.51	.35	.29	.32	.43	.69	1.11	1.57	1.85
40	2.03	1.46	.96	.59	.40	.34	.37	.50	.79	1.28	1.86	2.23
45	2.49	1.72	1.10	.67	.47	.40	.43	.57	.90	1.49	2.25	2.78
50	3.19	2.07	1.28	.76	.53	.45	.48	.65	1.03	1.77	2.83	3.65
55	4.39	2.59	1.30	.87	.60	.51	.55	.74	1.19	2.15	3.78	5.27

8.3.6 COMPUTATIONAL PROCEDURE

The flux on a tilted surface on any day with clearness $\bar{K}_T$ can be computed as follows (see exhibit 8.24).

STEP 1.	**For month, location, use exhibit 8.16 to obtain $\bar{K}_T$ (or choose K_T per Exhibit 8.14).**
STEP 2.	**Read $\bar{R}$ from exhibit 8.24.**
STEP 3.	**Read E the extraterrestrial flux, from exhibit 8.26.**
STEP 4.	**Compute the flux on the tilted surface from $Q = K_T \bar{R} E$.**

Memphis 50° tilt June

1. $\bar{K}_T = 0.60$
2. $\bar{R} = 0.73$
3. $E = 41.2$
4. $Q = 0.60 \times 0.73 \times 41.2 = 18.05$ MJ/m² - Day

   $= 18.05/3.6 = 5.01$ kWh/m² Day

Exhibit 8.24 Computational Procedure.

Step One

For the month and location, determine $\bar{K}_T$ from exhibit 8.15 (using part A for the United States and several cities in Canada and part B for other cities throughout the world) if average conditions are desired ($K_T = \bar{K}_T$). If nonaverage conditions are being analyzed, refer to exhibit 8.17 or 8.18. If the world data on insolation are used, the flux must be converted to $\bar{K}_T$ by multiplying the tabular values by 0.0481 to convert to MJ/m^2-day and then by dividing by the appropriate extraterrestrial flux as listed in exhibit 8.25.

LATITUDE \ MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
25	23.9	28.2	33.0	37.1	39.4	40.1	39.6	37.9	34.4	29.5	24.9	22.7
30	21.1	25.7	31.3	36.5	39.6	40.7	40.1	37.6	33.1	27.3	22.1	19.7
35	18.1	23.1	29.3	35.5	39.6	41.2	40.3	37.0	31.5	24.9	19.2	16.7
40	15.1	20.3	27.2	34.3	39.3	41.4	40.3	36.2	29.7	22.3	16.3	13.6
45	12.0	17.5	24.8	32.8	38.8	41.3	40.0	35.1	27.7	19.6	13.3	10.0
50	9.0	14.5	22.3	31.2	38.1	41.2	39.6	33.8	25.4	16.7	10.3	7.0
55	6.1	11.5	19.5	29.3	37.2	40.9	39.1	32.4	23.0	13.8	7.3	4.0

$$1 \text{ MJ/m}^2 = \frac{1}{3600} \frac{\text{Wh}}{\text{M}^2} = 88.08 \text{ Btu/ft}^2$$

Exhibit 8.25 Monthly Average Daily Extraterrestrial Radiation MJ/m²-Day.

Step Two
Obtain the value of $\bar{R}$, the ratio of flux on the tilted surface to the flux on the horizontal, from exhibit 8.23.

Step Three
Determine the extraterrestrial flux on a horizontal surface from exhibit 8.25.

Step Four
Determine the flux on the tilted surface from the equation on exhibit 8.24, $Q = K_T\bar{R}E$, where E is the insolation outside the atmosphere (extraterrestrial).

The flux so computed is the daily flux, MJ/m^2 per day. If K_T were chosen randomly, then the frequency plot (exhibit 8.17 or 8.18) could be used to determine the frequency of the value of K_T and thence, the frequency of the value of the corresponding insolation, Q. A plot of frequency versus flux will give sufficient statistical data to compute the average-day performance and the frequency of non-average occurrences.

8.3.7 COMPUTATION OF INSOLATION ON THE AVERAGE DAY

The use of the computational procedure to obtain the insolation on an array tilted at latitude plus 15° for an average day in June in Memphis, Tennessee, will be illustrated. From exhibit 8.15 the value of $\bar{K}_T$ is 0.60 for June. From exhibit 8.23, for June, at the latitude of Memphis (35°), with the array tilted at 50°, $\bar{R}$ is equal to 0.73. Latitude is the angular distance, measured in degrees, north or south from the equator. Also for June at this latitude, the extraterrestrial insolation, E, is found on exhibit 8.25 to be 41.2 MJ/m^2-day. Therefore the daily insolation on the array is

$$\begin{aligned} Q &= \bar{K}_T \bar{R} E, \\ &= 0.60 \times 0.73 \times 41.2, \\ &= 18.05\ MJ/m^2 - day, \end{aligned}$$

or in more useful units of kWh/m^2 - day,

$$\begin{aligned} Q &= 18.05 \times 10^6/3{,}600{,}000. \\ &= 5.01\ kWh/m^2 - day. \end{aligned}$$

8.3.8 COMPUTATION OF AVERAGE INSOLATION

Exhibit 8.24 illustrates the use of the insolation-computation procedure when the average insolation is needed, rather than the insolation on the average day, as illustrated above.

The computational procedure will be illustrated for Fresno, California (latitude = 36.5°) in December. We wish to determine the frequency distribution for the flux on a solar array tilted at the latitude angle above the horizontal and facing south.

For K_T = 0.1, the insolation is 97-percent diffuse, as indicated in exhibit 8.22, so R is equal to F.

For convenience, one estimates the values of R by interpolation/extrapolation to be 1.17 at K_T = 0.2 and 1.97 at K_T = 0.8. To improve on this estimate, an hour-by-hour computation would be necessary.

From exhibit 8.25 (step C), the extraterrestrial flux is calculated by interpolation, with the result shown in exhibit 8.28.

$$E = 16.7 + \frac{36.5 - 35}{40 - 35} (13.6 - 16.7)$$
$$= 17.6 \text{ MJ/m}^2\text{-day}$$

Exhibit 8.28 Extraterrestrial Insolation Calculation.

Step D now can be used to compute the insolation versus frequency, as shown in exhibit 8.29.

K_T	CP	$Q = K_T \bar{R} E$
0.1	0.08	1.6 MJ/m²-day
0.2	0.22	4.1
0.3	0.34	7.6
0.4	0.47	11.1
0.5	0.60	15.0
0.6	0.73	18.9
0.7	0.89	23.3
0.8	1.00	27.7
	average	11.9

Exhibit 8.29 Flux (Q) on the Tilted Surface.

The median day (CP = 0.50) gives Q = 12.0 MJ/m²-day. The average day ($\bar{K}_T$ = 0.42) gives Q = 11. MJ/m2-day. If the system was designed for the average day ($\bar{K}_T$ = 0.42, CP = 0.4 6), the probability of falling short of solar power for m days consecutively would be 0.496^m, or

m:	1	2	3	4	5	6	10
Probability:	0.496	0.246	0.122	0.060	0.030	0.015	0.001

Exhibit 8.30 Probability of Having m Consecutive Days with K_T Less Than 0.42.

This table does not indicate the number of days of battery storage required, because no indication is given regarding how much above 0.42 K_T the insolation will be on the clearer days. The storage requirements must be computed from an analysis of insolation under extreme conditions. The next section contains the data for designing the storage system.

8.3.9 CONCLUSION

The computation of insolation is unavoidable. Although it must be performed only once for each site, it must be performed for three or four tilt angles so the optimum tilt can be determined, as described next. The step-by-step procedure of section 6 above should at least reduce the time required for the computations.

8.4 MONTHLY PERFORMANCE COMPUTATION

The apparent digression concerning insolation was necessary so the system input could be computed. The electrical-system performance can be calculated. In accordance with the simplified computation of the section on "Quick Sizing of Components," a first estimate of the required array size was obtained. In the example, 14.67 m^2 of array was needed to feed the 6.17 percent efficient system. Although the previous section presents only typical insolation computations, it is assumed that the insolation had been computed in detail and the results were as illustrated in exhibit 8.31, column A, (a computation sheet that makes the work of the preliminary system-performance analysis easier). It is also assumed that the load had been computed as tabulated in column C.

1. Array size (kWp) = 1.1
2. Array area (m^2) = 14.67
3. System efficiency (.): 0.06175
4. Product (line 2) x (line 3): 0.91

Column:	A	B	C	D
Item:	Average Day Insolation on a Tilted Array	Electrical Output of Array	Electrical Demand	Energy From Backup
Units:	(kWh/m^2-Day)	(kWh/Day)	(kWh/Day)	(kWh)
Instructions: / Month	From Insolation Analysis	Line 4 x Col.A	From Load Analysis	Col.C-Col.B x No. of Days in Month (Enter 0.0 if Col. B=Col.C)
JAN	3.6	3.28	3.6	9.92
FEB	4.0	3.64	3.6	0
MAR	4.5	4.05	3.6	0
APR	4.8	4.37	3.6	0
MAY	5.0	4.55	3.6	0
JUN	5.0	4.55	3.6	0
JUL	4.9	4.46	3.6	0
AUG	4.8	4.37	3.6	0
SEP	4.8	4.37	3.6	0
OCT	4.6	4.19	3.6	0
NOV	4.7	4.19	3.6	0
DEC	3.8	3.46	3.6	4.34
5. Total				14.26 kWh

6. Total storage = (line 5) + (Short term storage from map on exhibit 8.33) + overnight storage x (Maximum value in Col. C) = 14.26 + (4.33 x 3.6) + 2.4 = 32.26

Exhibit 8.31 Computation of System Performance.

The computation sheet is to be used to determine the performance of a system with given array size. The calculated array size is entered on the first and second lines and the estimated system efficiency on the third. The product of system efficiency and collector area is entered on line 4. The monthly insolation on the tilted surface, as computed by the procedures described in the previous section, is entered in column A of the table. The electrical demand, as computed by the procedures in section 6 of this seminar manual, is entered in column C. The output of the PV system is computed in column B by multiplying the insolation by the system efficiency and the collector area (line 4). (The difference between column B and column C represents the amount of energy that must be supplied by the batteries, or by an auxiliary power source.) If column B exceeds column C, zero is entered in column D for that month; otherwise, column C minus column B times the number of days in the month is entered in column D.

As indicated on line 5 of exhibit 8.31, the amount of long-term storage required, either in terms of fuel or batteries, is the sum of the values in column D. The long-term storage is required to overcome seasonal differences in insolation and system demands. In addition to the long-term storage, some allowance must be made for the short-term storage requirements to compensate for consecutive days without sunshine. Exhibit 8.32 has been prepared to indicate the short-term storage needs. The short-term needs have been computed based both on direct weather (insolation) data and on weather simulations. As indicated on line 6, the total storage requirement is the sum of the long-term and short-term needs. The short-term need will almost always be supplied by the batteries; the long-term, by either batteries or a backup system.

(BASED ON AN ARRAY TILT OF LATITUDE +15° AND AN ARRAY SIZE BASED ON THE THREE LOWEST MONTHLY INSOLATION VALUES.)

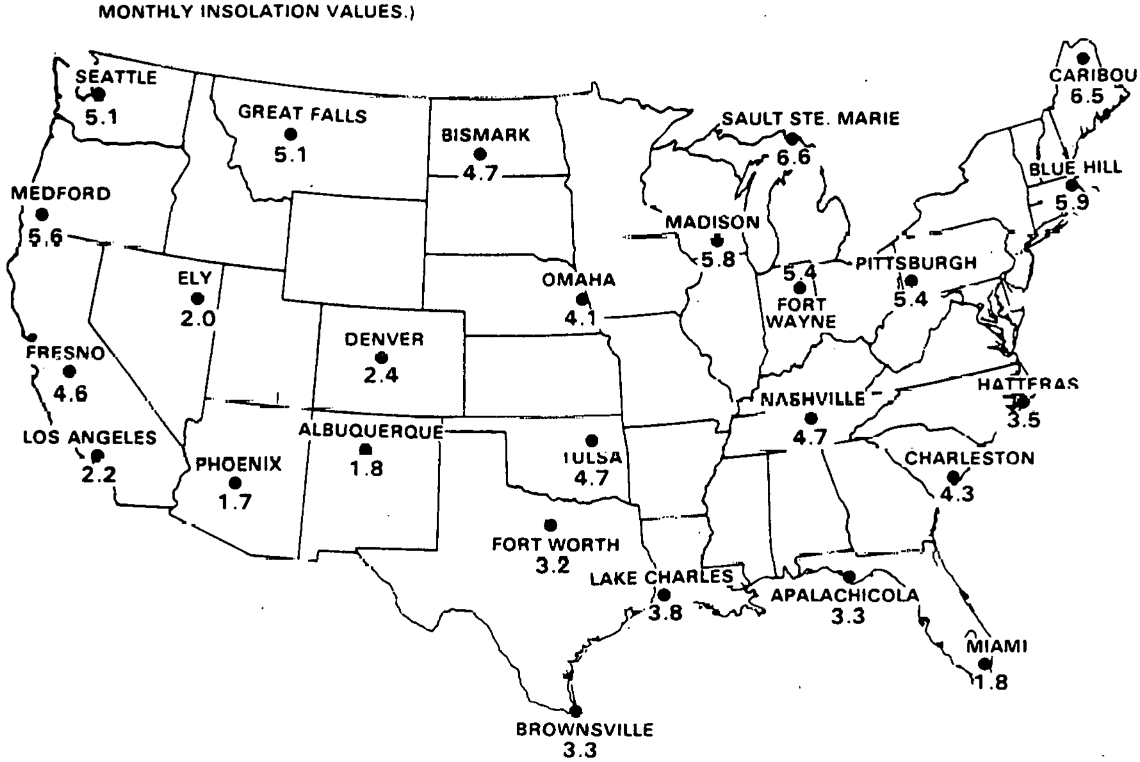


Exhibit 8.32 Short Term Storage Requirements for Selected Cities.

The sample case, in which a collector area of 14.67 m^2 was required, has been continued in the example illustrated on figure 8.31. On line 6 for this collector area and tilt angle, the batteries must be sized to deliver 32.26 kWh. Since the collector area and the battery size are both based on useful capacities, some adjustment is required to allow for system degradation, allowable depth of discharge, etc., as described in the next section and tabulated in exhibit 8.33.

COMPONENT	Nominal Size	Adjustment Factor	Size
Array:	1.10 kWp	÷ 0.8 for degradation	1.38 kWp
Battery:	32.26 kWh	÷ 0.6 for depth of discharge	53.77 kWh
Regulator:	12V, 92 A	÷ 0.8 for array degradation	12V, 115 A
Transmission Lines:	12V, 92 A	÷ 0.8 for array degradation	12V, 115 A

Exhibit 8.33 Component Sizes.

8.5 COMPONENT SIZES

Once the operating sizes of the array and storage system have been computed, all the components of the PV system can be sized. The necessary array size has already been calculated, but must be adjusted to allow for degradation with time (see exhibit 8.33). The sizing of the battery system for charge will equal the storage energy required (kWh), divided by the system voltage (V), divided by the allowed percent discharge level of the batteries. Energy divided by voltage equals charge, where one coulomb of charge equals one joule of energy divided by one volt. Kwh can be converted to joules and Ah can be converted to coulombs.The allowed discharge of the battery depends on the type of batteries to be used. For example, lead-acid-cadmium grid batteries should be discharged only 40 percent of their rated capacity, so the amount of battery storage required is equal to the calculated requirement divided by 0.4.

If 20-percent degradation is allowed for the solar array over its lifetime, the array output initially will be 1/0.8 = 1.25 times its required output.

The regulator should be sized to handle the maximum power from the array under noon insolation on a clear day. The sea-level insolation under such conditions is approximately 1 kW/m^2, down from the 1.35 kW/m^2 in outer space due to the atmospheric attenuation. Therefore, in the installation year, when the efficiencies are highest, the power transmitted through the regulator could be as high as the product: 1 Kw/m^2 x 1.25 x array efficiency x array area with the product having the units of kW. Therefore, the regulator in the example problem should be sized for 1 x 1.25 x 0.075 x 14.67 = 1.38 kW of power.

The transmission lines should be sized also to handle the noon load on a clear day (1.38 kW/12 V = 115 A), where P/V = I, and one kW equals 1000 x one volt x one amp.

A DC/AC inverter, if used, must supply the peak load, so the maximum power through the inverter would be dictated by the peak power demand of the load. If the peak power input to the inverter could be the same as the peak power output of the array, the inverter size would be determined in the same way as the size of the regulator, as discussed above (115 A).

8.6 DESIGN OPTIMIZATION

What has been calculated, for a given array tilt angle, are the necessary array size and storage requirements to meet the load demands. An optimization methodology must include the costs of these components, as well as the other system components, to determine the minimum-cost system.

Exhibit 8.34 presents a form for the computation of life cycle cost. The cost of the various devices must be determined from the vendors. Typical prices and the names of several vendors are provided in section 9 of this manual. The engineering estimates of installation costs must be based on the site conditions. The factors for estimating the maintenance and operating costs are indicated in exhibit 8.34 and represent the best estimates available to date for long-term annual costs. The bottom line (line 20) is the life cycle cost of a PV system with the calculated collector area and collector tilt.

One can now alter the angle of the array by $\pm 5^{\circ}$ from the previous tilt angle used. This will result in different insolation values, a new array size, and a different battery storage requirement. The life cycle cost should be computed for each iteration and compared with the previous results. Enough tilt angles and array sizes must be evaluated so that the combination yielding the minimum life cycle cost will be established.

A full consideration of life cycle costing and design optimization is beyond the scope of this seminar and will be considered in subsequent seminars.

	Component Sizes		
1.	PV array: nominal area ÷ degradation factor		18.34 m²
2.	Power conditioner from array:		1.38 kWp
3.	Battery size:		80.7 kWh
4.	Power conditioner to load:		— kWp
	Component Costs	Basic System	Spares
5.	PV Panels	15,525	775
6.	Structure	320	—
7.	Power conditioner for array	800	800
8.	Battery	8,100	810
9.	Power conditioner to load	—	—
10.	Monitoring system (telemetry)	400	
11.	Total components	25,245	2,386
12.	Engineering	2,500	
13.	Installation	1,000	
14.	Project Management	500	
15.	Total First Costs (sum Lines 11a, 11b, 12, 13, 14, 15)	31,631	
	Annual Costs		
16.	Maintenance = 1.78 x (0.01 x Line 5 + 0.02 x (Line 7 x Line 8 + Line 9 + Line 10)) = 590		
	Replacements (based on 7 percent inflation and 10 percent return on investment)		
17.	Battery	5,670	
18.	Power conditioners	—	
19.	Total	5,670	
20.	Life cycle cost = Line 15 + Line 19 + 8.514 x Line 16 =	42,324	

Exhibit 8.34 Life Cycle Cost Computation.

References:

1. Shellard, H.C., communication to the authors.

2. Dubief, J., "Le Climat Du Sahara," 43, 44 Alger (1959).

3. Lewis, B.M., communication to the authors.

4. Dubief, J., "Le Climat Du Sahara," 55, Alger (1959).

5. WMO Records of Solar Radiation for IGY and IGC.

6. Soares de Azeudeo, M., communication to the authors.

7. Boletim Actinometrico de Portugal, Ano I-V, Lisboa.

8. Morse, R.N., communication with authors.

9. Director of Meterology, Australian Dept. of the Interior, communication with authors.

10. Simmer, R.G., Acting Director, New Zealand Meterological Service, communication to authors.

11. Fritz, S., "Solar Radiation Measurements in the Artic Ocean," Polar Atmosphere Symposium, Oslo, 159 (New York 1958).

12. Reed, W.W., Supplement No. 32, Monthly Weather Review, Washington, 1929.

13. Bonython, C.W., communication to the authors.

14. W.B. Rimmer and C.W. Allen, "Solar Radiation Observations on Mount Stromlo 1927-1939, "Memoirs of the Commonwealth Observatory, Mt. Stromlo, No. 11, 1950.

15. Collmann, W., "Diagramme zum Strahlungsklima Europas," Berichte des Deutschen Wetterdienstes, Band 6, No. 42 (1958).

16. Reed, W.W., Monthly Weather Review, Band 6, Supplement No. 31, Washington 1928.

17. Teixeira, T.R., communication to the authors.

18. Bahli, F., communication with authors.

19. United States Department of Commerce Weather Bureau, 1950-1961, Climatological Data, National Summary.

20. Duffie and Beckman, Solar Design by the F-Chart Method, Wiley 1978.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

SECTION 9
PV SYSTEM COMPONENTS

9.1 INTRODUCTION

In this section, the characteristics of typical available components and subsystems are presented in terms of efficiency, control, price, and availability. The data have been taken from manufacturers' or suppliers' literature. The specifications of several designs are compared in each case, so the reader can recognize the correlation between price and performance and determine the reasonableness of various performance requirements.

9.2 AVAILABLE COMPONENTS

A brief survey of manufacturers' and standard catalogs reveals the availability and costs of the major components for solar PV power systems. The results of a survey conducted in preparation for this seminar are presented in exhibits 9.1 to 9.8. For typical systems under 1.5 kWp array sizes, there are components available off the shelf (within approximately 16 weeks). The price range is high because many of the components, designed to service laboratory instruments or computers, have more stringent requirements than would normally prevail for solar PV power systems. (A discussion of the requirements for various potential loads can be found in section 6, Load Analysis.) Therefore, selection of components must be related to the system design. For example, some of the less expensive power conditioners are more efficient because they do less power conditioning; however, the higher efficiency is accompanied by a less regulated output, resulting in less efficient operation of the load. The combined efficiency of the power conditioner and the load, therefore, must be considered in performing the subsystem tradeoffs.

An individual discussion will be provided for each of the components. The data are arranged in the order that the components appear in the system, starting with the solar array.

9.3 SOLAR PANELS

V-I Data were obtained from representative solar panel manufacturers listed by GSA. The data are summarized in exhibits 9.1 and 9.2. Exhibit 9.1 illustrates the combinations of currents and voltages available in modules that can be ordered from the GSA list. Exhibit 9.2 summarizes typical specifications. Note from exhibit 9.2 that the costs are all approximately $16.5/W of peak power. Panel sizes have not been standardized; however, most manufacturers supply their own structures, so standardization is not important.

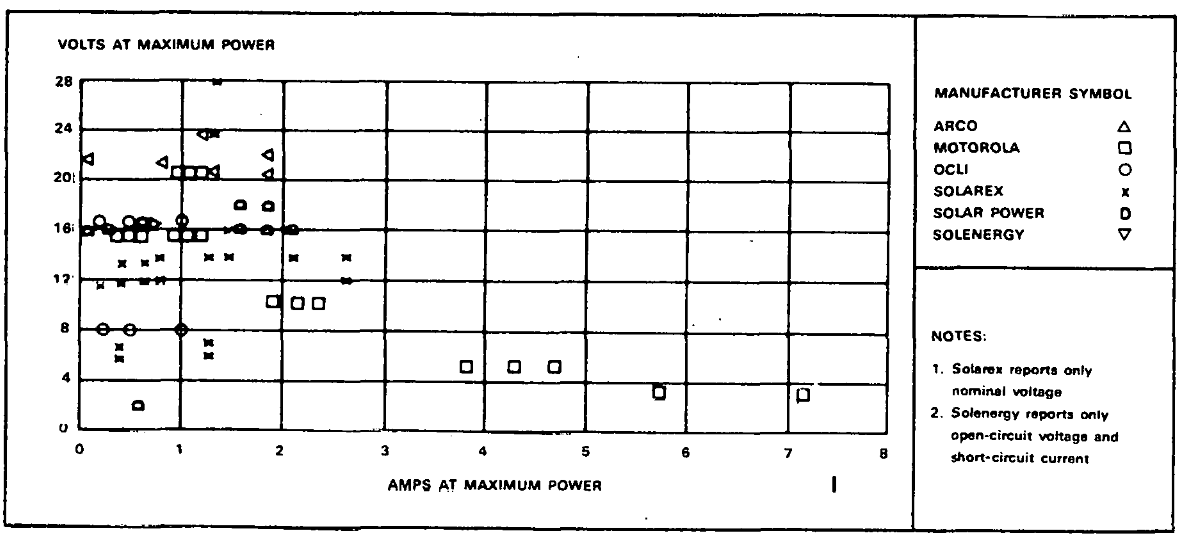


Exhibit 9.1 GSA-Listed PV Modules as of 11/1/78.

Spec / MANUFACTURER	MOTOROLA	MOTOROLA	ARCO	SOLAR POWER	SOLAR POWER	SOLAREX	SOLAREX
Model	MSP01E30	MSP01A30	ASI16-1200	P-1012	M12-361	435	HB-506
Price[1]	\$414-555	\$414-555	\$225-268	\$54-60	\$390-485	\$95-179	\$494-936
Delivery	30 days	30 days	30-60 days	30-60 days	30-60 days	90 days	90 days
Efficiency[2]	7.4%	7.4%	7.8%	5.3%	6.8%	7.9%	11.2%
Output[3]							
W	25.3	25.3	19.4	1.4	33.5	6.6	35.0
V	3.62	21.10	16.2	16.5	16.5	16.0	28
Protection	No	No	No	Diode	Diode	Optional	Optional
T_c-T_a	20° C	20° C					
Power Temp. Coefficient	- 0.5%/° C	- 0.5%/° C					
Array Characteristics							
Voc	4.50	27.0	20.9		21.0	20.0	36
Temp. Coefficient	- 0.4%/° C	- 0.4%/° C	- 0.4%		- 0.4%	- 0.4%	- 0.4%
Isc	7.8	1.3	1.3		2.05	0.45	1.42
Temp. Coefficient	+ 0.08%/° C	+ 0.08%/° C	0.0%			+ 0.1%	+ 0.4%
$R_{series/cell}$	0.047 ohm	0.047 ohm	0.054 ohm		0.032 ohm	0.115 ohm	0.056 ohm
Temp. Coefficient							
Fill Factor	0.72	0.72	0.71		0.72	0.73	0.68
MTBF							
Physical							
No. of Cells	6P × 8S O	1P × 48S O	1P × 36S O	O	1P × 36S O	1P × 36S	1P × 64S
Dimensions	23" × 23" × 2"	23" × 23" × 2"	9" × 43" × 1.4"	13.6" × 3" × 0.3"	46" × 15.3" × 2"	10.4" × 12.5"	21" × 24"
Cover	Glass	Glass	Glass	Polycarbonate	Silicon	Silicon	Glass
Weight	12 lb	12 lb	7.3 lb	0.6 lb	13 lb.		12 lb
Ambient Temp. Limit	- 40° C to + 80° C	- 40° C to + 80° C	- 40° C to + 90° C		- 55° C to + 60° C	- 70° C to + 70° C	- 40° C to + 100° C
Insulation	600 vdc	600 vdc					1,500 vdc
Max. Snow Load	60 lb/ft²	60 lb/ft²					
Max. Wind Load	100 mph	100 mph		175 mph	175 mph	175 mph	280 mph
Dual Leads	Yes	Yes	Yes	Yes	Yes		Yes
Intermediate Tap							
GSA Listed	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Passed DPL Test							
\$/W[1,3]	\$16.4-\$21.9	\$16.4-\$21.9	\$11.6-\$13.7	\$38.6-\$42.9	\$12.6-\$15.2		\$14.3-\$26.7

[1] Range on GSA List
[2] Based on gross frontal area
[3] At 1 kW/m², 25° C ambient

Exhibit 9.2 Comparison of Typical Specifications for PV Modules

The open-circuit voltage (Voc), short-circuit current (Isc), and series resistance (Rseries) are important in combining arrays (see sections 1 and 2 for a discussion on solar-panel theory). For the same reason, the temperature coefficients are important. Arrays matched at one temperature may not be matched at another. As indicated in exhibit 9.2, the reported temperature coefficients are all approximately 0.4 percent per °C. The temperature coefficient gives the change in electric power at a particular temperature.

Some arrays come with dual leads from each cell, module, panel and subarray. If one should fail, the other will suffice. None of the GSA-listed arrays come with an intermediate tap that would permit the use of a partial shunt regulator. The partial-shunt regulator is described in Section 5, Power Conditioning.

The NASA Jet Propulsion Laboratory (JPL), California Institute of Technology has purchased models from many manufacturers and has subjected them to extensive life and performance testing. The specifications in the second part of this section are based on, but are less severe than, the JPL specifications and test conditions. Although many manufacturers have submitted panels for JPL testing, few of the production models have been evaluated. In total, there are approximately 11 manufacturers from whom modules can be bought off-the-shelf.

9.4 DC REGULATORS

Data were obtained from solar cell manufacturers on the DC regulators offered with the panels. The data that should be specified are listed in exhibit 9.3. Costs will be on the order of $1/W. The use of regulators is shown in Sections 1.2 and 5.

Manufacturer
Model
Price
Delivery
Efficiency
Input
- **Volts**
- **Amps**
- **Protection**

Output
- **Waveform**
- **Volts**
- **Amps**
- **Protection**

MTBF*
Physical
- **Dimensions**
- **Weight (lb)**
- **Temp. Limits**
- **Cooling**

***NOTE — MTBF is the mean time between failures for failures occurring after the break in period and before wear out. It is the reciprocal of the failure rate. For example, if the failure rate is 1 percent per year due to random failures, the MTBF would be 100 years.**

Exhibit 9.3 Specification Items for DC Regulators.

Normally, DC regulators for PV applications are designed and configured by the array nanufacturer, and are the key components in successful stand-alone systems.

9.5 BATTERIES

Both nickel-cadmium and lead-acid battery specifications are tabled in exhibit 9.4. The prime contenders for use with PV systems are the nickel-cadmium, the CD, and the DD33 batteries. The cost per kWh delivered over the life of the battery is lowest for the CD; the cost per product of kWh and the life in years is lowest for nickel-cadmium and DD33. The actual battery size usually is not important, because batteries can be grouped to obtain the desired voltage and current. For very small applications, automotive batteries, sized to prevent more than a 10-percent discharge, might be the most cost effective. Cost per kWh is the energy cost and discharge refers to either kWhe or AH (amp-hours), where kWhe is electric energy and AH is charge. The amp-sec is a coulomb of charge, and the kWe is 1000 watts of electric power. The product of kWhe and the life in years is used for the cost per energy per year.

9.6 DC/AC INVERTERS

Exhibits 9.5 and 9.6 list the characteristics of typical DC inverters. If the solar PV system were to supply AC voltage to the load, the inverter would be used. An inverter is approximately 90 percent efficient. Its cost is approximately $2/W if a sine wave is needed, but only $0.60/W if a square wave is acceptable. The use of inverters is shown in Sections 1.2 and 5.

Spec \ Manufacturer	Nickel Cadmium				Lead-Acid			
	G	ME	ME	ME	EL	CD	WI	WI
Model		CED	CED-79	CED-43	Motive	Calcium	Motive	Motive
Price total	$249	$1,260	$360	$248	$191	$1,110	$934	$469
$/rated kWh	1,383	273	312	448	36	192	156	235
Delivery								
Efficiency				0 715				
Input (at 5 hr rate)								
a. Charging								
Max. volts/cell					2.4			
Max rate	10 hr	10 hr	10 hr	10 hr				
b. Overcharging								
Max volts								
Max. current								
Output (at 8 hr rate)								
kWh	0.17	4.8	1.2	0.56	5.4 (20 hr)	5 4	5 4 (6 hr)	1 8 (6 hr)
V								
Max. current								
Life								
10% depth								
50% depth								
80% depth	2,000	2,000	2,000	2,000	250 cyc	1,750	1,250	1,250
Shelf		20 yr	20 yr	20 yr				
Self Discharge	← 1%/day typical →							
Physical								
Dimensions		22" · 12" · 18.5"	15" · 10" · 11"	11" · 9" · 13"	21" · 15" 11"	9" · 11" · 18"	31" · 8" · 23"	
Weight	11.5 lb	400 lb	100 lb	63 lb		708 lb	546 lb	228 lb
Temp. Limits								
0% charge								
50% charge								
100% charge	- 40° F	- 40° F	- 40° F	- 60° F	- 60° F	- 60° F	- 60 F	- 60 F
$/usable kWh[1]	1,537[2]	303[2]	347[2]	498[2]	44	258	194	293

[1] Based on 80% discharge except as noted.
[2] Based on 90% discharge.

Spec \ Manufacturer	Lead-Acid								
	G	SGB	GD	OD	WI	EL	EL	EL	EL
Model	Gel cell	Motive	Calcium	Calcium	DD33	Auto SLI	Diesel	Motive	Motive
Price: total	$47	$510	$235	$318	$151	$38	$117	$1,231	$460
$/rated kWh	140	269	244	231	126	34	48	188	246
Delivery									
Efficiency			0 85	0.85					
Input (at 5 hr rate)									
a Charging									
Max volts									
Max current									
b Overcharging									
Max volts									
Max current									
Output (at 8 hr rate)									
kWh	0 34 (20 hr)	2 04 (6 hr)	0 96 (20 hr)	1 28 (20 hr)	1 2	1 14	2 46	6 55	1 87
V						12	12	12	12
Max current									
Life									
10% depth						1,800 (5 yr)			
50% depth					80 (1 yr)				
80% depth	250	1,300	1,750 (7 yr)	1,750 (7 yr)	10 (1 yr)	5 cycles			
Shelf			1 yr	1 yr					
Self Discharge						← 30% day typical →			
Physical									
Dimensions	8" · 6" · 8"	13" · 7" · 23"		7" · 9" 11					
Weight	21 lb	380 lb	96 lb	204 lb		54 lb	149 lb	829 lb	253 lb
Temp Limits									
0% charge			20 F	- 20 F					
50% charge									
100% charge	- 60 F								
$/usable kWh	175	336	305	289	630[2]	340[3]	480[3]	235	308

[1] Based on 80% discharge except as noted
[2] Based on 20% discharge
[3] Based on 10% discharge

Exhibit 9.4 Specification for Batteries.

● Some manufacturers of self-commutated and line-commutated inverters are (SEIA):

Abacus Controls, Inc., Summerville, N.J. Abacus is finalizing the development of a 10 kw, single phase self-commutated inverter under contract to NASA-Lewis. This system was developed for use with photovoltaic arrays but is capable of being used with other sources as well.

The inverter is capable of operating in parallel with a utility line or as a stand-alone system. A digitally controlled transistor bridge provides a very high quality power output with less than 5% total current harmonic content when interfaced and with less than 4% total voltage harmonic distortion when operating in a stand-alone mode. The phase angle of the output can be controlled (± 90°) to give either a leading or lagging power factor. Efficiency is approximately 90% for outputs over 25% with a no-load draw of 250 watts. Input voltage range is 160-240 volts DC.

The equipment is presently available in small quantitites at a cost of approximately $1600/kw capacity including the photovoltaic interface and an isolation transformer. Projected costs for a moderate production level are $700/kw.

Delta Electronic Control Corp., Irvine, Calif. Delta produces a line of self-commutated, line-feeding or stand-alone inverters with rated capacities up to 300 KVA. Single and three-phase inverters up to 30 KVA use transistors for the switching element. Higher capacity equipment uses a pulse width modulated control concept with silicon controlled rectifiers.

The total voltage harmonic distortion for the transistor models is less than 3% when operating in the stand-alone mode. The total current harmonic distortion when inter-connected to the utility is also held to less than 3%. Efficiency is typically 90% for loads in excess of 10%.

Inverter costs, including an isolation transformer and photovoltaic input filter, range from approximately $1,000/KVA capacity at the 10 KVA level and $200/KVA at the 300 KVA level.

Exide-Power Systems Division, Raleigh, N.C. Exide manufactures a line of Uninterruptable Power Supplies (UPS) ranging in capacity from 30 to 400 KVA. Under contract to TEAM, Inc., and the Department of Energy, Exide is adapting two 180 KVA self-commutated inverters (which are normally part of a UPS package) for use with a photovoltaic array and battery bank. These systems will be synchonized with the utility line but will not be able to feed energy into it.

These systems typically have a total voltage harmonic distortion of 5% with no single harmonic in excess of 3%. Efficiencies range from 70-75% at 25% load to 80-92% at full load. Costs, including an isolation transformer, range from approximately $1,000/KVA at the 30 KVA level to approximately $200/KVA at the 400 KVA level.

Windworks, Inc., Mukwonago, Wisc. Windworks manufactures and distributes line-commutated, line feeding inverters known as Gemini Synchronous Inverters. Units are available up to 15 kw, single phase and up to 1500 kw, three phase. Applications of this equipment include wind systems, photovoltaic arrays, small hydroelectric installations, solar thermal electric systems, and industrial waste energy recovery.

These systems can only be used in the presence of a lower impedance AC source such as the utility grid or a remote diesel/generator set. Total voltage harmonic distortion for this type of equipment is a function of the relative impedances of the two sources but is typically less than 1% for utility applications. Total current harmonic distortion can be as high as 30% for a single phase system. Power factor is essentially proportional to voltage and reaches a maximum of 0.7 for single phase equipment and 0.85 for three phase units. Efficiency of the basic inverter, exclusive of input filters and isolation transformers is approximately 90% at 10% load and 96-98% at full load.

Costs for the basic inverter range from $180/kw to $200/kw for single phase systems and from $250/kw (20 kw capacity) to $50/kw (1000 kw capacity) for three phase equipment.

Spec \ Manufacturer	CML-M	CML-M	EICO	POWERMAKER
Model	MNS-50	DRS-50	1080	2124
Price			$86	$139
Deliver				
Efficiency	72%	67%		67%
Input				
V	22-30	22-30	12	11-15
Wires	2	2		
Protection	Lead Rev. Fuse	Lead Rev. Fuse		Lead Rev.
Output				
Wave form	Sine	Sine		Square
V	105/115/125 ± 6%	115 ± 0.5%	117	120
Temp. Stab.	0.03%/° C	0.01%/° C		
V.A (W)	50	50	220	300
Phases	1	1	1	
Freq.	60 ± 0.5%	400 ± 0.5%		60
Temp. Stab.	0.05%/° C	0.05%/° C		
Harmonic Dist.	3%	1%		
Wires	2	2		
Protection	Fuse	Fuse		Yes
MTBF				
Physical				
Dimensions	5" × 11" × 11"	5" × 11" × 8"	4" × 6" × 6"	6" × 7" × 6"
Weight	28 lb	25 lb	7 lb	13 lb
Temp. Limits	- 20° C to + 50° C	- 20° C to + 50° C		0° C to 40° C
Cooling	Passive	Passive		

Exhibit 9.5 DC/AC Inverters (0.05 kW Output).

Spec \ Manufacturer	CML-M	CML-M	CML-M	BATP
Model	MNS-500	MRS-500	DRS-500	DA-500S
Price (qty #1)	$1,090			$1,645
Delivery	16 wks			
Efficiency	72%	67%	67%	
Input				
V	22-30	22-30	22-30	22-30
Wires	2	2	2	
Protection	CB overvoltage Lead Rev.	CB overvoltage Lead Rev.	CB overvoltage Lead Rev.	
Output				
Form	Sine	Sine	Sine	Sine
V	105/115/125 ± 6%	115 ± 0.5%	115 ± 0.5%	115/230 ± 1%
Temp. Stab.	0.3%/° C	0.01%/° C	0.01%/° C	
V.A.	500	500	500	500
Phases	1	1	1	1
Hz	60 ± 0.5%	60 ± 0.5%	400 ± 0.5%	60 ± 0.015%
Temp. Stab.	0.05%/° C			
Harmonic Dist.	3%	3%	1%	3%
Wires	2	2	2	
Protection	CB	CB	CB	
MTBF				
Physical				
Dimensions	0" × 14" × 14"	12" × 14" × 14"	8" × 14" × 16"	11" × 15" × 19"
Weight	80 lb	150 lb	70 lb	130 lb
Temp. Limits	- 20° C to + 50° C	- 20° C to + 50° C	- 20° C to + 50° C	0° C to 50° C
Cooling	Fan	Fan	Fan	
Date	8/74	8/74	8/74	

Spec \ Manufacturer	T	T	POWERVERTER	POWERVERTER
Model	5212-26	5006W	PV-550	PV-500FC
Price (qty#1)	$1,416	$1,195	$139	$278
Delivery		3 wks		
Efficiency	70%	70%		
Input				
V	11-15/22-30	11-15/22-30	12	12
Wires				
Protection	CB Lead Rev.			
Output				
Form	Sine	Sine		
V	115 ± 1%	115 ± 5%	117	117
Temp. Stab.				
V.A.	500	500	550	500
Phases	1	1	1	1
Hz	60 ± 0.5%	60 ± 0.5%	60	60 ± 2%
Temp. Stab.				
Harmonic Dist.				
Wires				
Protection				
MTBF				
Physical				
Dimensions	7" × 19" × 13"		5" × 10" × 9"	5" × 10" × 9"
Weight	65		19	19
Temp. Limits	- 10 to + 55° C			
Cooling				
Date		8/74		

Exhibit 9.6 DC/AC Inverters (0.50 kW Output).

9.7 AC/DC CONVERTERS

For large AC systems, an AC/DC converter might be used to convert the regulated AC to DC for charging a battery. An additional inverter is used to invert the battery current to AC for the load. The losses associated with such a system are tolerable only if there is a gain due to better matching of load demand and array output. The converters for which data are shown are all approximately 65-85 percent efficient and cost approximately $1/W (see exhibit 9.7). A converter is useful for AC loads if the demand requirements are drastically reduced when stored energy is used. The use of converters is shown in Section 1.2 for supplying AC with battery storage for low night demands.

Spec \ Manufacturer		SOLA	SOLA	SOLA
Model	APS-24-2.2	83-12-250-1	28-28-243	281561-2
Price	$70	$81	$151	$306
Delivery				
Efficiency	65%			75%
Input				
Wave Form	Sine			
V	115/230 ± 10%	108 to 132	100 to 300	100 to 130
A				
Frequency	47-63	50-400	60	60
Phases	1			
Output				
VA	53	60	120	480
V	24 ± 0.2%	11.5 to 125 ± 0.05%	28 ± 1%	48 ± 1%
Temp. Stab.		0.03%/° C	0.03%/° C	
Ripple	5 mV	10 mV	300 mV	1%
Protection	overload		isolated current limiting	current limiting
MTBF				
Physical				
Dimensions				5" × 2" × 10"
Weight		7 lb	14 lb	
Temp. Limits	0° to 65° C	0° to 55° C	0° to 50° C	
Cooling		passive		

Source: 1979 Allied Electronics Catalog

Exhibit 9.7 AC/DC Converters (Rectifiers, Power Suppliers) (0.05 kW)

9.8 MONITORING INSTRUMENTATION

Some transducers that might be useful in monitoring the system performance on a continuing basis are listed in exhibit 9.8. Transducers can supply measurements to recording equipment and digital and analog computers. The current transducer is inexpensive, and the power transducer has a high price, especially relative to a system that might only cost $3,000. If the current transducer is used in conjunction with the battery, however, an approximate value of the power can be obtained, since the battery voltage varies only ± 15 percent, and power = voltage x current (DC power = wattage). For a single phase AC circuit, Wattage = Voltage x Current x Power Factor (cosine of phase angle) where power factor is the percentage of total power due to resistance. For a three phase AC circuit, the total wattage (W) = 3 x single phase wattage where the single phase voltage = 1/3 (square root 3) x voltage between phases. The single phase voltage is the voltage between phase and neutral, thus a three phase AC circuit has "four" phases where the neutral is the "fourth phase". The amount of total power in an AC circuit due to excitation and field flux is termed reactive power (VAR). Total AC power = square root (W^2 + VAR^2).

Manufacturer / SPEC	OSI-PC8	OSI-CT-L
	DC W Transducer	Current Transducer
Price	$450	$97
Inst. Voltage	115 VAC	
Input		
V	25 to 600	
A	0 to 650	50 to 2,000
Frequency	DC to 400 Hz	DC to 5,000 to Hz
Resp. Time	50 microsec	50 microsec
Ohms	(into 0 to 10,000 ohms)	4
Output		
V		30 mV
A	1 ma max.	
Ripple	0.01 ma	
Accuracy	± 1%	± 0.5% linearity
Temp Stab	± 1%, 0° to 40° C	- 0.15%/° C, - 40 to 65° C
ohms		3

Exhibit 9.8 Transducers

9.9 COMPONENT MANUFACTURERS

The component manufacturers listed in this section are meant to be representative of what is available. The list is far from exhaustive. For each application, a similar survey will be necessary.

Exhibit 9.9, which is a partial list of manufacturers, follows.

Manufacturer \ Address	Corporate	Wash., D.C. Representative
CMLM	CML-Macara, Inc. 166 National Road Edison, NJ 08817 (201) 287-2810	Gans-Fryling, Inc. 2062 14th Street Arlington, VA 22201 (703) 527-3262
ACDC	ACDC Electronics, Inc. Oceanside Industrial Ctr. Oceanside, CA 92054 (714) 757-1880	Electronics Marketing Associates, Inc. 11501 Huff Court Kensington, MD 20795 (202) 381-5300
BATP	Bulova American Time Products Bulova Water Co., Inc. 61-20 Woodside Avenue Woodside, NY 11377 (212) 335-6000	
T	Topaz Electronics 3855 Ruffin Road San Diego, CA 92123 (714) 279-0111	Bartlett Associates 4405 East-West Highway Bethesda, MD 20014 (301) 656-3061
EICO		
OSI	Ohio Semitronics, Inc. 1205 Chesapeake Avenue Columbus, OH 43212 (614) 486-9561	
ME	McGraw Edison Edison Battery Division 210 Redstone Hill Road Bristol, CT 06010 (203) 582-6321	
EL	Electro Lite 1225 E. 40th Street Chattanooga, TN 37407 (615) 867-4750	
G	Globe-Union Inc. 5757 North Green Bay Ave. Milwaukee, WI 53201 (414) 228-2394	Perrot Engineering Labs 1020 N. Fillmore Arlington, VA 22201 (703) 528-5861

Exhibit 9.9 Partial List of Manufacturers. of System Components

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SECTION 10
MODEL SYSTEMS SPECIFICATIONS

10.1 INTRODUCTION

JPL has developed and published specifications for the PV modules; however, industry work standards have not yet been agreed upon. The Solar Energy Research Institute is the lead agency in this area. Support is provided by the Electric Power Research Institute and the Solar Energy Industry Association.

This section has been prepared to assist those who will be writing specifications for procurement. The following specifications should be used as a model in the development of specifications for any particular installation.

This model specification is designed: (1) to enable the system designer to define the system in sufficient detail for the manufacturers to supply suitable equipment and for the installer to install the system so it will meet the desired functional requirements; (2) to define the quality of the equipment and installation so the maintenance and life of the system will be as anticipated in the design selection and life-cycle cost analyses; and (3) to control the quality of the manufacture and installation of the system. The designer should keep these purposes in mind when applying the model specifications. If the designer deletes an item, he should be willing to accept the corresponding loss of system definition and quality control. If an item is added, it should be done because there is a need for a more complete definition and quality control.

It is expected that, as experience is gained with terrestrial applications of solar PV systems, standards will be developed by the industry. In the absence of widely accepted standards and test procedures, the following model specification represents one effort at documenting requirements for design, manufacture, installation, service life, and the quality control associated with each (See exhibit 10.1). The JPL module specification was the basis for section 10.4, appendices 11.A and 11.B, and section 14.3.

General Photovoltaic Solar System Requirements (see section 10.2)
System Requirements (see section 10.3)
PV Module Specifications (see section 10.4)
Inverter (see appendix B.7)
Battery Voltage Regulator (see appendix B.8)
Converter (see appendix B.9)
Battery (see appendix B.10)
Electrical
Structure
Fence
Foundations
Test and Acceptance (see appendix B.11)
Warranty (see appendix B.12)

Appendices

11A. Performance Measurement Procedures
11B. Test Procedures

Exhibit 10.1 Typical Outline for System Specifications.

10.2 GENERAL PHOTOVOLTAIC (PV) SYSTEM REQUIREMENTS

A. General

1. Drawings:

   a) The drawings diagrammatically illustrate the arrangements of the principal equipment and shall be followed as closely as possible.

   b) The drawings shall be neat and the arrangements well spaced throughout.

   c) The drawings and specifications need not include exact equipment dimensions, locations, nor complete accessory items and control wiring devices required for each manufacturer's equipment.

   d) The drawings shall provide complete and properly functioning systems that comply with the standards and performance requirements specified herein.

2. Changes in Location:

   a) Changes in locations of equipment from the locations indicated on the drawings, to suit the actual conditions of the work, require written approval of the contracting officer.

   b) Changes in location after the equipment has been installed, if directed by the contracting officer, shall be made in accordance with applicable provisions of the general conditions.

B. Materials

1. General:

   a) Materials, when not otherwise definitely specified, shall conform to applicable national specifications and standards, such as Underwriters Laboratories, National Electrical Manufacturers Association Code, National Fire Code, National Electrical Code, and the Uniform Building Code.

   b) All material shall be new and in perfect condition.

C. Items Requiring Submittal

1. Shop Drawings:

   a) Refer to A.1, Drawings.

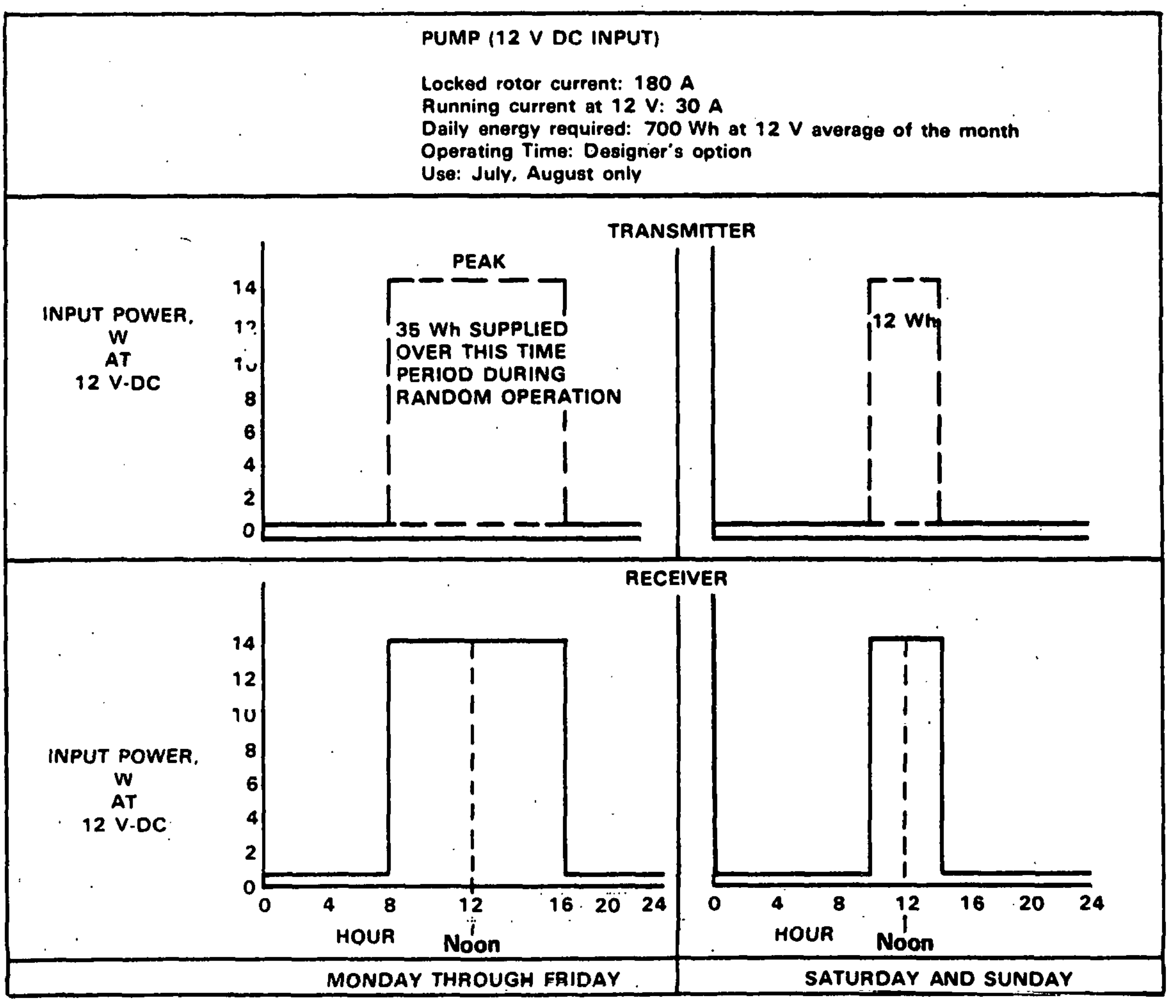
   b) In addition to the above requirements, detailed shop drawings are required for, but not limited to, the following:
      (1) solar cell modules
      (2) power-conditioning equipment
      (3) battery and housing for same.

10.3 SYSTEM REQUIREMENTS

The accompanying engineering drawings, which are part of this specification, describe the system and most of its requirements. The PV system, which is comprised of the PV array, the support structure, the wiring and connectors, the power-conditioning equipment (regulators, inverters, converters, etc.), the batteries, the housings for the equipment, and buses, substations, switchboards, load centers, transmission, distribution, and control shall supply all the energy required to operate: an irrigation pump, a transmitter, a radio receiver, and a telemetry system (See exhibit 10.2). The power and energy requirements of these devices are shown on exhibit 10.3 of these specifications. The area of the power vs. time profile equals energy, where energy equals the summation of power x time duration.

What is included in the PV System: Array, Structures, . . .
What the system powers: Pump, Transmitter, . . .
Where the system will be installed: Billings, Montana
Overview of unusual requirements
- **Insolation: Tabulation of monthly averages, NWS for more data**
- **Load: Graphical representation**
- **Life: 20 years (10 years for battery)**
- **Energy storage required: 10 days without sun**
- **Telemetry/Alarm: 20 miles, signal once per hour based on battery voltage, adds to load**

Exhibit 10.2 General Data Needed to Design a Solar PV System



Energy = Summation of power x time duration, which equals the area of the power profile.

Exhibit 10.3 Power and Energy Requirements.

The equipment and installation are to be suitable for use over a 20-year period in Billings, Montana (example). The system is to be designed for insolation corresponding to that shown on exhibit 10.4. If more insolation detail is required in the design, the insolation data available from the National Weather Service shall be used. The structure shall be designed according to the local codes pertaining to Billings, Montana. Weather data are also available from the National Weather Service for this location.

If storage is required, the battery storage capacity shall be sufficient to supply the energy needs of the devices described above for a period of 10 days without any energy input from the solar array. The batteries shall be designed for a minimum of 10 years' life. A radio-telemetry alarm system shall be provided to transmit a signal proportional to the battery voltage to a receiver 20 miles from the array installation site.

The contractor is to provide both the alarm transmitter and receiver. The signal transmitted will require power in addition to that of the load described on exhibit 10.3. However, the power requirements are to be kept as low as possible by only transmitting the signal approximately once per hour. When the battery voltage falls below that specified in section 10.7, an alarm must light to indicate to the attendant at the receiver that the PV system is not performing within the specifications.

10.4 PV MODULE SPECIFICATIONS

Solar cell modules meeting the requirements of this specification shall be mounted or grouped into an array structure compatible with system design constraints for the PV application described in section 10.3. The module, panel, subarray, and array designs shall satisfy the following general design criteria (See exhibit 10.5).

Exhibit 10.4 Insolation for Billings, Montana (45° Latitude)

MONTH	AVERAGE DAILY INSOLATION ON A HORIZONTAL SURFACE*(MJ/m²/day)
January	6.62
February	9.92
March	15.03
April	19.09
May	22.65
June	25.62
July	26.63
August	23.32
September	17.75
October	10.68
November	7.24
December	5.57

*NOTE:
1. Divide by 3.6 to convert $MJ/m^2/day$ to $kWh/m^2/day$.
2. One MJ equals 1 million joules of energy.
3. One kWh equals 1 thousand watt-hours of energy.
4. One watt equals one joule per second of power.
5. Insolation equals solar flux which equals intensity which equals power density which equals energy per unit time per unit area.
6. The unit of area used is the square meter, the unit of time used is the day, the unit of power used is the watt, and the unit of energy used is the joule or the kilowatt-hour.

Definitions: Based on annual average environment (80 MW/cm² 20° C)

Electrical Design

- 20° C, 100 MW/cm²: 600 VDC
- Grounding: 1F 50 VDC
- String Reliability/Redundance: Not Specified
  - Hot spot does not further degrade
- Regulator connection: Intermediate Tap
- Diodes: External on each module

Mechanical Design

- Dimensions: Less than 4' · 8'
- Framing: Will not retain snow
- Interchangeable
- Optical Surface: Tempered glass or approved equivalent
- Each module labeled

Environmental Design

- Temperature: - 40° C to + 90° C; (50) 6-hr cycle
- Humidity: 0 to 95%; (6) 24-hr cycle
- Loads: Per site; (10,000) cycles pressure and suction; 20 cpm
- Warping: ¼" per foot
- Hail: Per site; (9) impacts with 1.5 × NBS diameters

Optical Design:

- Limit decrease in efficiency with angle of incidence

Exhibit 10.5 PV Module Specifications.

10.4.1 DESIGN REQUIREMENTS

10.4.1.1 PERFORMANCE MEASUREMENT DEFINITIONS

The following standard performance-measurement definitions shall be utilized:

(1) Nominal Power Output - The power output of individual modules shall be determined per appendix 11.A.1 as the product of the module Nominal Operating Voltage (V_{NO}) and the module current measured at V_{NO} under Standard Operating Conditions (SOC) defined as an irradiance level of 100 mW/cm^2 and cell temperature equal to the Nominal Operating Cell Temperature (NOCT).

(2) Nominal Operating Voltage - V_{NO} is the reference voltage level at which the modules are designed to provide maximum power output at standard operating conditions (100 mW/cm^2, NOCT). The V_{NO} level shall be selected by the module manufacturer/system designer.

(3) NOCT - NOCT is the module cell temperature under operating conditions in the Nominal Thermal Environment (NTE)* which is defined as:
Insolation = 80 mW/cm^2.
Air Temperature = 20° C.
Wind Average Velocity = 1 m/s.
Mounting = Tilted, Open Back, Open Circuit.

The NOCT measurement procedure is described in Appendix 11.A.2.

* The NTE approximates the annual average environment.

10.4.1.2 ELECTRICAL DESIGN REQUIREMENTS

The electrical design of the module shall meet the following requirements:

(1) Electrical Voltage Isolation - All module circuitry, including output terminals, shall be insulated from external surfaces. The manufacturer/contractor shall establish the voltage isolation requirement on the basis of the maximum open circuit voltage of the complete system at an ambient temperature of -20° C, with 100 mW/cm² irradiance. The voltage level shall be set at a minimum of 600 V DC.

(2) Electrical Grounding and Safety - To minimize electrical hazard to personnel, all modules shall be provided with an external grounding terminal or stud serving as a common grounding point for all exposed external conductive surfaces not part of the module circuitry. A grounding stud is not required for modules designed for systems with operating voltage levels less than 50 V or for modules without exposed conductive surfaces, unless removal of covers or mounting hardware will expose such surfaces. Lightning protection must be provided for the array.

(3) Cell String Circuit Reliability/Redundancy - Circuit redundancy features shall be incorporated where cost effective to enhance the reliability of completed modules. Any conflict between minimum reliability and cost shall be in favor of minimum reliability, per se. Design features may include, but are not limited to the following:

(a) Redundant interconnections between solar cells, including redundant cell attachment points,

(b) Series/parallel interconnection of cells within the module, and

(c) By-pass diodes with each module.

The decision to incorporate redundancy features shall be based on minimum reliability and the expected percent improvement in lifetime/yield and replacement cost as contrasted with the percent increase in module cost/watt. Series/parallel circuit arrangements, when used, shall be designed so that "hot spot" cell heating does not lead to further module permanent degradation under worst-case-single-cell failure conditions defined as follows:

(a) The module output is short circuited.

(b) A single representative solar cell is open circuited to represent a single cell failure.

(c) The incident irradiance is 100 mW/cm², air-mass equal to 1.5.

(d) The thermal boundary conditions are adjusted so that the equilibrium solar cell temperature outside the hot-spot region is equal to NOCT + 20° C.

(4) Connections for a Shunt Voltage Regulator - If a shunt type voltage regulator will be used, an intermediate lead must be provided on each module. The output voltage to ground of this lead shall be between 10 and 11 V, such that the shunt regulator can be connected between the intermediate lead and the high-voltage terminal of the array, since a shunt connection is a parallel connection.

(5) Diodes - All diodes used to prevent reversed current through the modules must be replaced without damage to the module, when diode performance becomes unacceptable.

10.4.1.3 MECHANICAL DESIGN REQUIREMENTS

The mechanical design of the module shall meet the following requirements:

(1) Module Geometry - To meet the array/system requirements for mounting, each module shall meet the envelope, mechanical, and interface requirements specified by an Interface Control Drawing to be prepared by the manufacturer/contractor, providing as a minimum the following information:

- (a) Maximum envelope dimensions and tolerances,
- (b) Location of output terminals,
- (c) Mounting hole or attachment provisions, dimensions, and tolerance,
- (d) Illuminated (active) surface dimensions and shadowing or view angle constraints for low level concentrators, and
- (e) Nominal electrical performance.

To allow for convenient handling, the maximum module dimensions shall not exceed 48 in. by 96 in. Suggested standard dimensions and hole locations are provided in exhibit 10.6. In this exhibit, the module width may be any dimension up to the 96 in. maximum. The framing for the module shall be designed so snow is not accumulated by the frame such that the cells remain covered.

(2) Interchangeability - All modules shall be physically and functionally interchangeable. Tolerances on all external module dimensions shall be maintained at a level consistent with module interchangeability. Surfaces, mounting holes, and any attachment hardware associated with the attachment interfaces shall be maintained within tolerance specified in the Interface Control Drawing.

(3) Optical Surface Soiling - The illuminated optical surface(s) of the module shall be smooth and generally free of projections that could promote entrapment of dust and other debris. Particular attention shall be given to the selection of materials for the optical surface(s) which will minimize the accumulation of nonremovable contaminants, fungus growth, particulate matter and stains, and will promote self-cleaning by natural processes such as wind and rain. A sheet of tempered glass meets these requirements; however, other materials may also prove suitable, but must be approved by the owner.

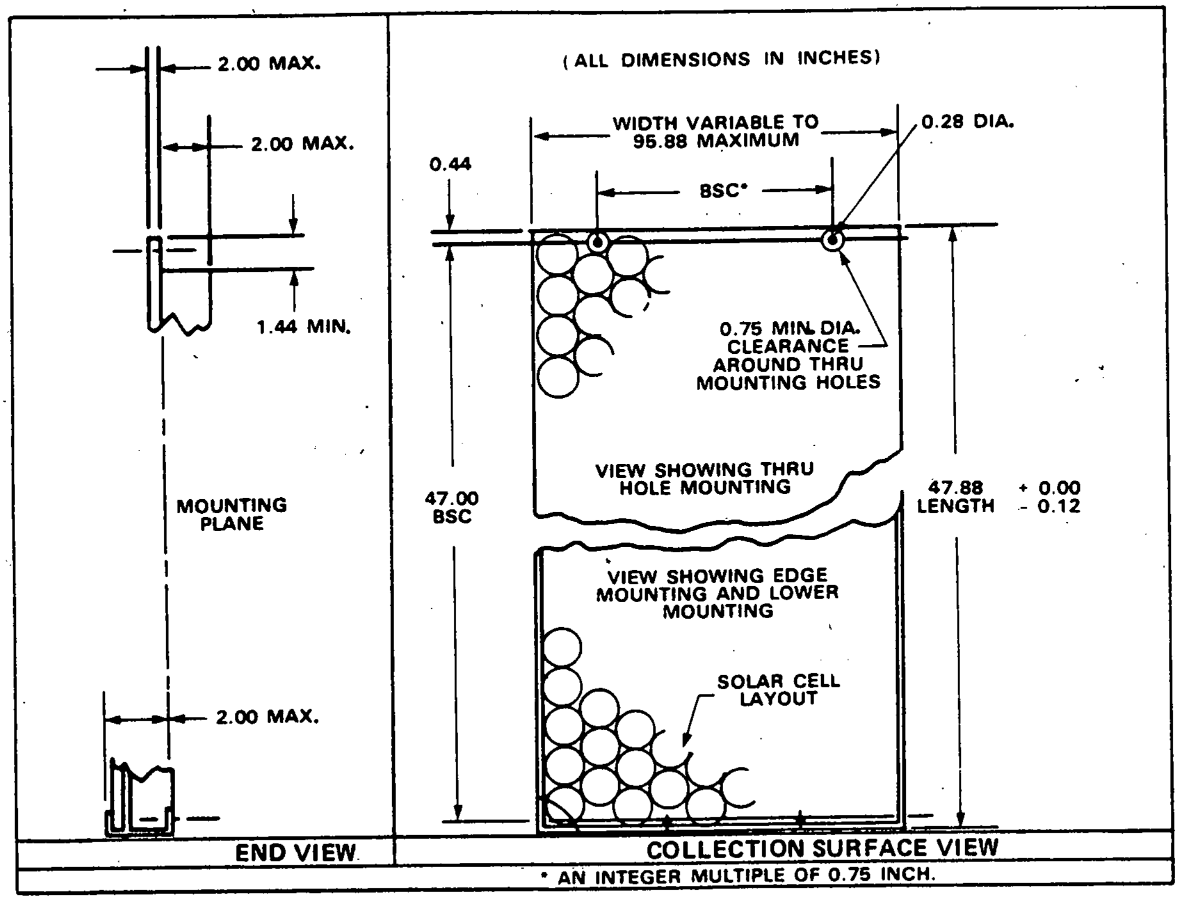


Exhibit 10.6 Suggested Module Standard Dimensions.

(4) Module Labeling and Identification - Each module shall be identified in a permanent and legible manner with suitable labels or markings specifying the manufacturer's module model number (or drawing) and revision, sequential serial number, year and week of manufacture, and maximum system operating voltage for which the module is designed. Additional information may include the V_{NO} and power of the module. The identification shall be installed at a position that is visible from the front (illuminated) side of each module, when installed in the array. The polarity of each electrical terminal shall be marked in a permanent and legible manner in a position that is visible when accessing the electrical terminals in a completed array. Positive, negative, neutral, and ground shall be explicitly indicated.

10.4.1.4 ENVIRONMENTAL DESIGN REQUIREMENTS

Environments to be considered in assessing possible degradation of module electrical performance and physical properties include: solar exposure (particularly ultraviolet-UV); thermal conditions, including freezing and thawing; effects of wind, rain, snow, ice, hail, salt mist, and atmospheric oxidants; dust and debris accumulation, especially nonremovable stains or contamination; and, dynamic loading effects of wind, snow, and hail. As a minimum, the module design shall be capable of withstanding exposure to the following environmental test environments:

(1) Thermal cycling from -40° C to + 90° C per Test Procedure in appendix 11.B.1.

(2) Humidity per Test Procedure appendix 11.B.2.

(3) Mechanical cyclic loading per procedure in appendix 11.B.3. The test load level shall be determined by the manufacturer/contractor on the basis of the anticipated application site maximum wind gust velocity. (A test level pressure of ±50 lb/ft^2 is common practice.)

(4) Warped mounting surface of ¼ in/ft per Test Procedure in appendix 11.B.4.

(5) Hail impact testing per Test Procedure in appendix 11.B.5. The maximum size hailstones that the module can withstand shall be determined by the manufacturer/contractor on the basis of an assessment of the hail risk at the intended application site.

The manufacturer/contractor shall establish additional environmental requirements dictated by special environmental conditions at the intended application site.

10.4.1.5 OPTICAL DESIGN REQUIREMENTS

As the angle of incidence of the insolation to collection area changes, the optical surface coating will result in a decrease in module output for a given insolation. Both reflection and absorption increase with angle of incidence. The tests and ratings resulting from these specifications will be useful in designing the system for year-to-year use. The output of the module shall not be less than that indicated in exhibit 10.7 as the angle of incidence changes, for any azimuth angle of the sun.

	ORDINARY FLOAT	SHEET LIME	CRYSTAL WHITE
IRON OXIDE	0.10-0.13	0.05	0.01
m	1.52	1.51	1.50
THICKNESS	0.125"-0.1875"	0.125"-0.1875"	0.1875"
ρNORMAL	8.2-8.0%	8.1-8.0%	8.0%
αNORMAL	6.8-11.0%	4.9-7.0%	1.5%

Theory—Single Interface ($N = n - nk$)

$$2a^2 = \sqrt{(n^2 - k^2 - \mathrm{Sin}^2 i)^2 + 4n^2K^2} + (n^2 - k^2 - \mathrm{Sin}^2 i)$$

$$2b^2 = \sqrt{(n^2 - k^2 - \mathrm{Sin}^2 i)^2 + 4n^2k^2} - (n^2 - k^2 - \mathrm{Sin}^2 i)$$

$$P_\perp = \frac{a^2 + b^2 - 2a\,\mathrm{Cos}\,i + \mathrm{Cos}^2 i}{a^2 + b^2 + 2a\,\mathrm{Cos}\,i + \mathrm{Cos}^2 i}$$

$$P_{11} = P_\perp \frac{a^2 + b^2 - 2a\,\mathrm{Sin}\,i\,\tan i + \mathrm{Sin}^2 i\,\tan^2 i}{a^2 + b^2 + 2a\,\mathrm{Sin}\,i\,\tan i + \mathrm{Sin}^2 i\,\tan^2 i}$$

$$P = \tfrac{1}{2}(P_\perp + P_{11})$$

For $k = 0$, $a^2 = n^2 - \mathrm{Sin}^2 i$ $b^2 = 0$

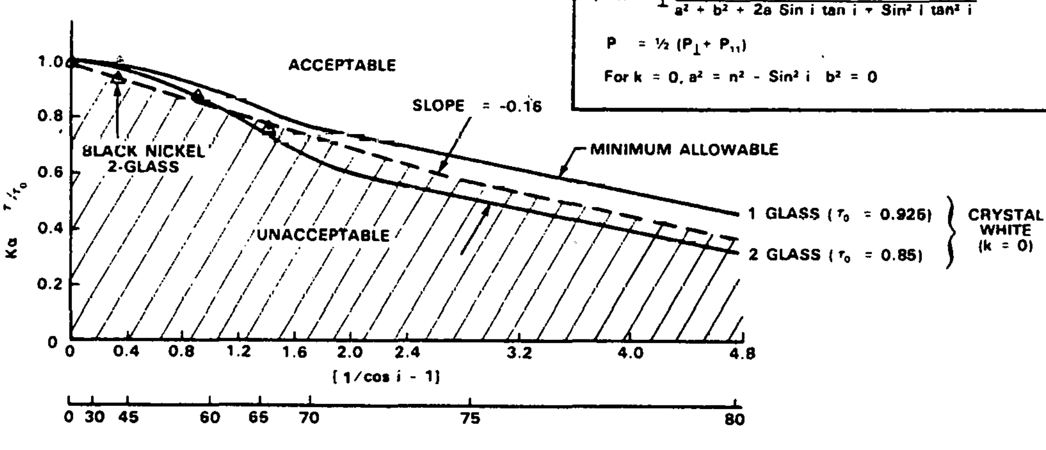


Exhibit 10.7 Transmission Properties of Glass.

10.4.2 QUALIFICATION REQUIREMENTS

10.4.2.1 PERFORMANCE CHARACTERIZATION REQUIREMENTS

The tests included in this section shall be performed to characterize the module performance and to provide a high level of confidence that all modules will function within the specified performance requirements.

(1) Determination of NOCT - For purposes of providing a measurement of module performance that is representative of the anticipated terrestrial application, all module performance measurements are referenced to the NOCT. NOCT is defined as the average cell temperature in the module under operating conditions in the NTE. NTE is characterized by 80 mW/cm^2 insolation, ambient air temperature of 20° C, average wind velocity of 1.0 m/s, with the module mounted in an open back condition (i.e., not insulated on back side). Actual cell temperatures shall be taken at conditions approximating NTE to obtain the solar cell NOCT. The NOCT shall be used for all measurements of module performance at SOC. The approved techniques for performing the NOCT characterization test are included in appendix 11.A.2.

(2) Initial Electrical Measurement - A minimum of five production module samples shall be used to determine module baseline electrical performance.

Measurements shall be conducted at the NOCT determined per paragraph 10.4.2.1 and the V_{NO} specified by the manufacturer/contractor for the intended application. In addition to obtaining a baseline I-V characteristic curve for each module, the average output power (P avg) at V_{NO} shall be calculated from measurements of all prototype samples. Any sample producing less than the nominal average power under SOC shall be replaced by an acceptable module prior to subjecting these modules to the design qualification tests in 10.4.2.2. The Nominal Average Power is defined as the average power at SOC and V_{NO} according to the manufacturer's specification, as used in the system design. The output power determined for each module shall be the calculation base for determining extent of performance degradation during environmental qualification testing.

10.4.2.2 DESIGN QUALIFICATION TEST REQUIREMENTS

This section specifies the minimum tests that shall be performed by the contractor/manufacturer to verify that the modules will satisfy the design requirements of this specification (see exhibit 10.8). Owners may, at their option, in addition to the characterization tests described in 10.4.2.1, perform any or all of these tests on submitted prototype modules prior to approval of the module design. Modules shall be mounted on rigid structural frame simulating the selected mounting interface and configuration for all design qualification testing. As a minimum, the following qualification tests shall be performed in the order listed.

Determine Nominal Operating Temperature and Voltage
Determine Nominal Average Power
Ground Continuity: 50 milliohms
Electrical Isolation: 50 micro amps (Omit test if under 50 V)
Environmental Test:
- **Ground Continuity**
- **Electrical Isolation**
- **Thermal Cycling**
- **Humidity Cycling**
- **Mechanical Cycling**
- **Vibration Test**
- **Warped Mounting**
- **Hail**
- **Electrical Isolation**
- **Final Electrical Performance Test**

Acceptance: Less than 5% Degradation

Exhibit 10.8 Qualification Test for PV Module.

(1) Grounding Continuity Test

Each module having exposed external conductive surfaces (i.e., frame or structural members) shall be tested using a suitable continuity tester to verify that electrical continuity exists between all such surfaces and the module grounding point. The maximum resistance to ground shall be 50 milliohms (50×10^{-3} ohms).

(2) Electrical Isolation Test

Each module shall be subjected to a DC-voltage-withstanding (Hi-Pot) test to assure the capability of the encapsulation system to provide adequate electrical isolation of internal circuitry. This test level shall equal the design level established by the manufacturer per paragraph 10.4.1.2. Leakage current during the test shall not exceed 50 micro A (50×10^{-6} A) and there shall be no evidence of arcs, or flashover indicating insulation failure. Modules for which the maximum system voltage does not exceed $50V_{DC}$ are exempt from this requirement.

(3) Environmental Testing

Each module shall be subjected to the following environmental exposures, plus any additional special environmental tests which the manufacturer/contractor may require for the intended application. These tests shall be conducted in the order indicated:

(a) Ground continuity test

(b) Electrical isolation tests per appendix 11.B.6

(c) Thermal cycling test per appendix 11.B.1

(d) Humidity cycling test per appendix 11.B.2

(e) Mechanical cycling test per appendix 11.B.3

(f) Vibration test - not part of JPL specification

(g) Warped mounting surface test per appendix 11.B.4

(h) Hail impact test per appendix 11.B.5

(i) Electrical isolation tests per appendix 11.B.1

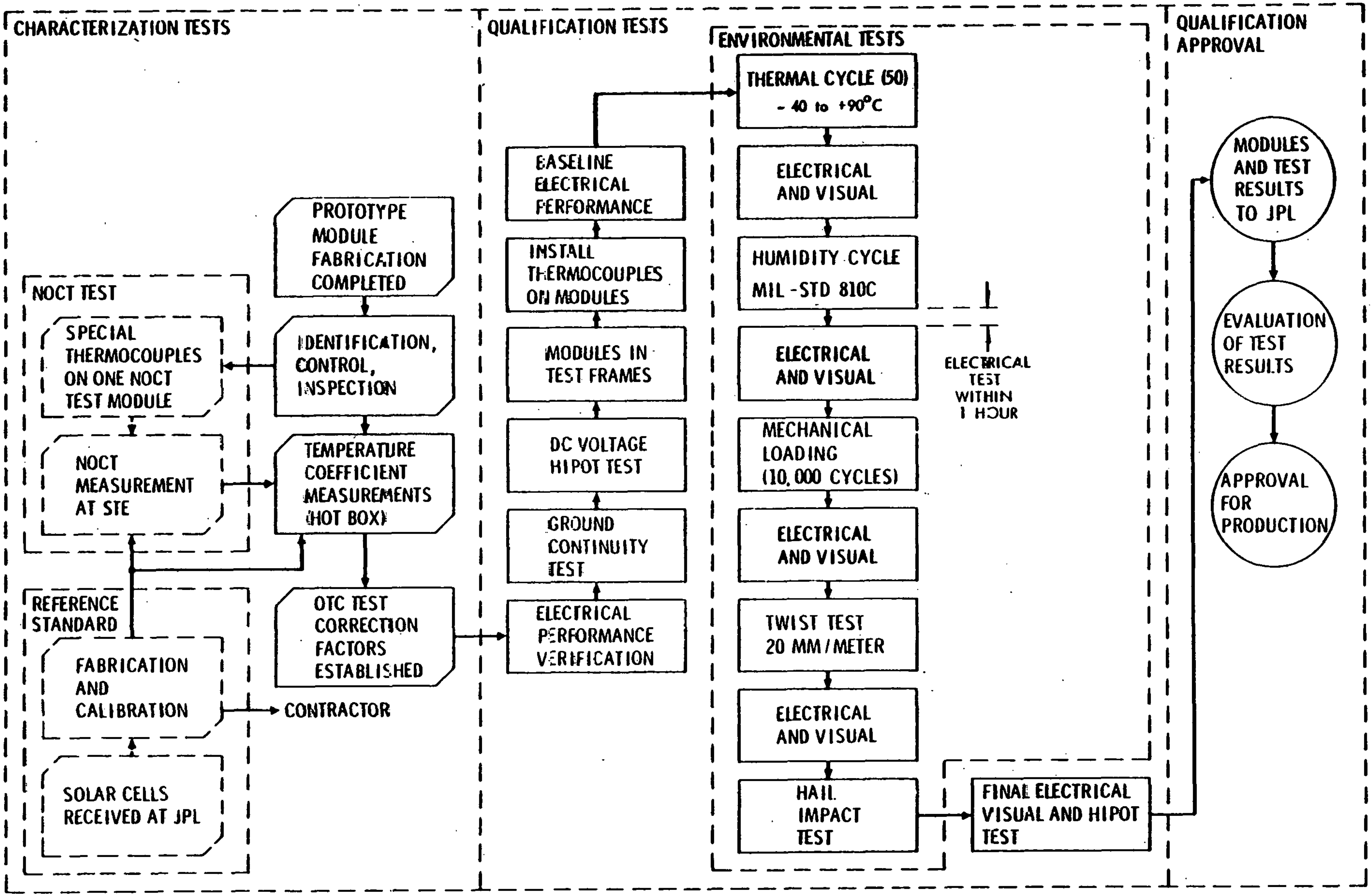
(j) Final electrical performance test per appendix 11.A.1.

(4) Qualification Pass/Fail Criteria--The output power degradation of each tested module, determined after completion of all qualification tests, shall not exceed 5 percent of the initial electrical performance determined per 10.4.2.1. The module shall pass the electrical isolation test (appendix 11.B.6.) when retested at completion of qualification tests. The allowable level of observable cracks or other mechanical degradation (such as delamination of coatings) shall be determined by the manufacturer/contractor. Acceptable performance under the qualification testing requirements is a prerequisite for owner approval of the module design. All test reports showing the results of the qualification tests shall be submitted to the owner.

10.4.2.3 MODULE ACCEPTANCE REQUIREMENTS

(1) Electrical Performance
Each module shall be measured to determine its current-voltage characteristics (I-V curve). Measurements shall be made in accordance with appendix 11.A.1. No module shall be accepted for delivery which produces less than the Nominal Average Power under SOC, where $P = V \times I$.

(2) Electrical Isolation
Each module shall be subjected to a DC 'Hi-Pot' test to assure adequate electrical isolation for safety of operating personnel at system operating voltages. The exposed, external, conducting surfaces shall be electrically isolated from any PV voltage.



Characterization and Qualification Test Flow Plan

SECTION 11.4
MANUFACTURERS SUPPLEMENT

SOLAR POWER CORPORATION

Affiliate of Exxon Enterprises, Inc.

INSTALLATION AND MAINTENANCE MANUAL

SERIES "M" ARRAY
SOLAR ELECTRIC GENERATOR

SECTION 11
INSTALLATION, OPERATION, AND MAINTENANCE

11.1 INTRODUCTION

A PV manufacturer has provided an installation and maintenance manual, with troubleshooting and onsite testing procedures. That manual is included in 11.4.

Solar power system performance is usually monitored onsite, however, remote monitoring via telemetry is possible. Because the choice of monitoring techniques can have a significant impact on life cycle cost, a discussion of the economics of the monitoring procedure is included.

11.2 OPERATION AND MAINTENANCE

Generally, PV power systems are trouble free, requiring only periodic inspections. The conditions of the array should be noted and meticulously recorded after each inspection, as well as information required by DOE in degradation reports, which should be recorded and forwarded.

Foreign matter coming into contact with the array surface will normally fall away due to the mounting angle or be washed away during rain. Some sources of array soiling are dust, pollen, airborne emission particles, and bird droppings.

A sound maintenance practice is to permanently install monitoring meters between subassemblies and ensure isolation capability. It is also desirable to be able to switch the meters into the circuits, as required (see exhibit 11.1). The cost for the meters and switches and the effort to wire them into the circuits will be well worth the work and extra costs involved when routine monitoring or troubleshooting is required.

The specific gravity of battery electrolyte must be inspected, if possible and applicable, to ascertain the charge of the batteries, where specific gravity equals the ratio of electrolyte density to water density. An immersion thermometer and hydrometer are required. The hydrometer reading should be corrected for temperature using the temperature of the electrolyte solution and not the ambient air temperature. The specific gravity in the batteries should not differ from each other by more than 0.020. The state-of-charge of the batteries should be consistent with the season and recent weather conditions. The hydrometer is an instrument for measuring the specific gravity of liquids: it is a graduated, weighted tube that sinks in a liquid up to the point determined by the density of the liquid.

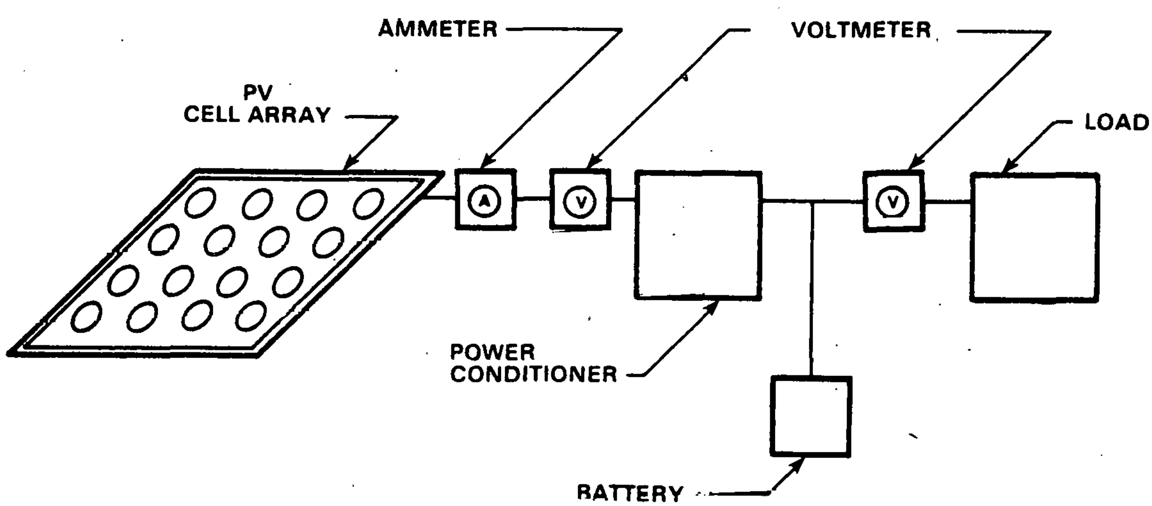


Exhibit 11.1 Proposed Installation for Monitoring/Troubleshooting.

11.3 MAINTENANCE AND REMOTE MONITORING WITH TELEMETRY

Maintenance can be handled through a maintenance contract with the supplier or a local contractor. The cost of such an arrangement is easily determined from quotations. Because high-technology maintenance specialists are not required for most PV systems under most circumstances, the Federal agency will usually handle the maintenance itself.

When the agency performs the maintenance, there is a tradeoff between the frequency of site visits and the use of telemetry systems to radio the condition of the system. For example, if 1 week of power outage is the maximum tolerable in a remote site, then weekly inspections are necessary. However, if a radio telemetry system is used, inspections may not be needed. Only the repair crew will be required to visit the site and, then, only in the event of a failure. The cost of the inspection labor must be weighed against the cost of telemetry systems. A telemeter is any device for measuring temperature, radiation, etc. at some remote point and transmitting values obtained to a distant indicator, recorder, or observer.

Telemetry systems can be obtained that cost approximately $400 for transmission distances under 0.5 mile, with an additional $50 for each mile from the receiver. The telemetry-system cost does not increase much with the amount of data transmitted. The simplest system would transmit a constant signal to a manned, central station. If the PV system should fail, the signal would be discontinued. The maintenance crew would then be dispatched to the site so the system could be repaired within the allowable downtime. If the telemetry system should fail, the signal would again be stopped and the maintenance crew would again be sent out for repair. There would be no difficulty in making the signal proportional to the output current or some similar indicator of system performance.

In some applications, such as forest observation stations and American Indian villages, daily inspection is practical because people are near the systems everyday. In other applications, the PV system is powering a transmitter, so the loss of the transmitted signal would indicate failure. Alternatively, the transmitter could be used to signal that the emergency (backup) battery is being used, so the PV system needs attention. In applications such as these, a separate telemetry system is not required. Periodic inspection of the system may still be desirable to determine if some element of the system not covered by the telemetry system is not functioning properly. Two visits per year would be reasonable, in light of the past, favorable experience with solar PV systems. If the systems prove sufficiently reliable and durable, the semiannual inspections may alleviate the need of the telemetry system.

In the absence of reliability data, the tradeoff must be made between the cost of a telemetry system and the cost of frequent site visits. The cost of the site visit will be approximately $20/hr, when wages and overhead are included. The time on site will be approximately 60 minutes. Additional time will be required for travel. Assuming the travel can be accomplished at 40 mph, the tradeoff between telemetry and site visits is shown on exhibit 11.2. Only if the solar-powered system can be out of commission for more than approximately 100 days should personal inspection be used. (Early in the project, weekly inspections may be desirable to learn of any unforeseen problems. However, over the 20-year life, the frequent visits have little effect on the life cycle cost tradeoff.) For most unattended, remote systems the telemetry system will be cost effective.

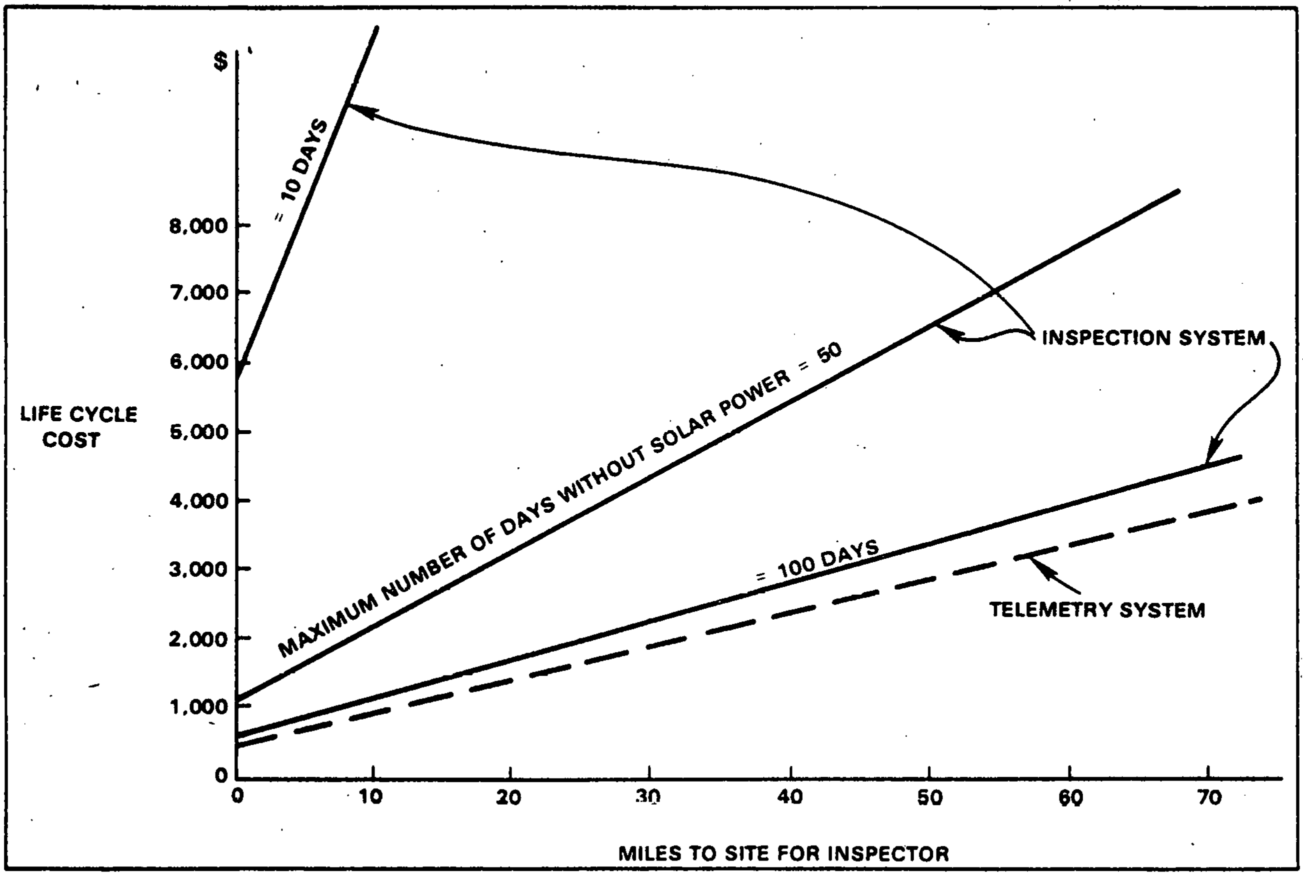


Exhibit 11.2 Comparison of Life Cycle Costs for Telemetry vs. Inspection Systems.

11.4 Installation and Maintenance Manual

TABLE OF CONTENTS

INSTALLATION DATA

Site Location: ______

Tilt Angle: ______ Regulator: BVR______ Design Load: ______ AH/day

Battery: Model ______ connected ______ cells in series by ______ banks in parallel

THE FOLLOWING QA TEST DATA PERTAINS TO YOUR SOLAR ELECTRIC GENERATOR:

Array Performance

Array Model: ______ Serial #: ______

Rated Output* ______ Amps at ______ Volts

Rated Short Circuit Current*: ______ Amps

No. of Series-Connected Solar Cells: ______

No. of Parallel-Connected Solar Cells: ______

Frame Performance

No. of Separate Frames in Array: ______

______ Model M ______ modules on ______ frame(s).

Rated Short Circuit Current* of frame(s): ______ amps ea

______ Model M ______ modules on ______ frame(s).

Rated Short Circuit Current* of frame (s): ______ amps ea.

Module Performance

MODEL M ______ module

Rated Short Circuit Current*: ______ Amps

No. of Series-Connected Solar Cells: ______

No. of Parallel-Connected Solar Cells: ______

MODEL M ______ module

Rated Short Circuit Current*: ______ Amps

No. of Series-Connected Solar Cells: ______

No. of Parallel-Connected Solar Cells: ______

*At 100mW/ cm^2 sunlight intensity and 28°C cell temperature

1.0 GENERAL

1.1 This manual includes the unpacking, assembly, and maintenance instructions for the Solar Power Corporation Solar Electric Generator Series M Arrays. For information relating to the installation and maintenance of the storage battery system, refer to Manufacturer's Instructions.

1.2 Properly installed solar electric generator systems should only require regular maintenance visits once a year. Maintenance recommendations are given in Section 4.1.

1.3 If any trouble does develop, Sections 3.0 and 4.0 give complete test, troubleshooting, and repair procedures. If additional help is required, contact the Technical Service Department at Solar Power Corporation.

2.0 UNPACKING AND ASSEMBLY INSTRUCTIONS

2.0.1 Because the arrays may be anchored to different types of mounting surfaces, the customer is expected to supply mounting hardware.

2.0.2 If the total array consists of more than one frame, repeat all instructions for each frame.

2.1 UNPACKING AND ASSEMBLY - ARRAYS WITH TELESCOPING LEGS

2.1.1 Open the crate. Remove the layer of packing material and any other hardware or items that are on top of the array.

2.1.2 Lift the array out of the crate and hold it nearly vertical or place it on the ground, front module surface facing up. DO NOT PUT THE ARRAY ON THE GROUND FACING DOWN.

2.1.3 Unbolt the mounting feet from the leg sections. Retain this hardware and all other hardware removed in the following steps; it will be needed to assemble the legs and mounting feet to the array frame (reference Figure 1b).

2.1.4 Unbolt the two large leg sections (larger cross sectional area) from the bottom mounting brackets. Attach one mounting foot to one end of each of these leg sections as shown in Figure 1, Point C. It may be necessary to loosen the bolt holding the small leg to the top mounting bracket, thus allowing the leg to swing.

2.1.5 Attach the remaining two mounting feet to the bottom mounting brackets (the ones that do not have leg sections attached to them) as shown in Figure 1, Point D.

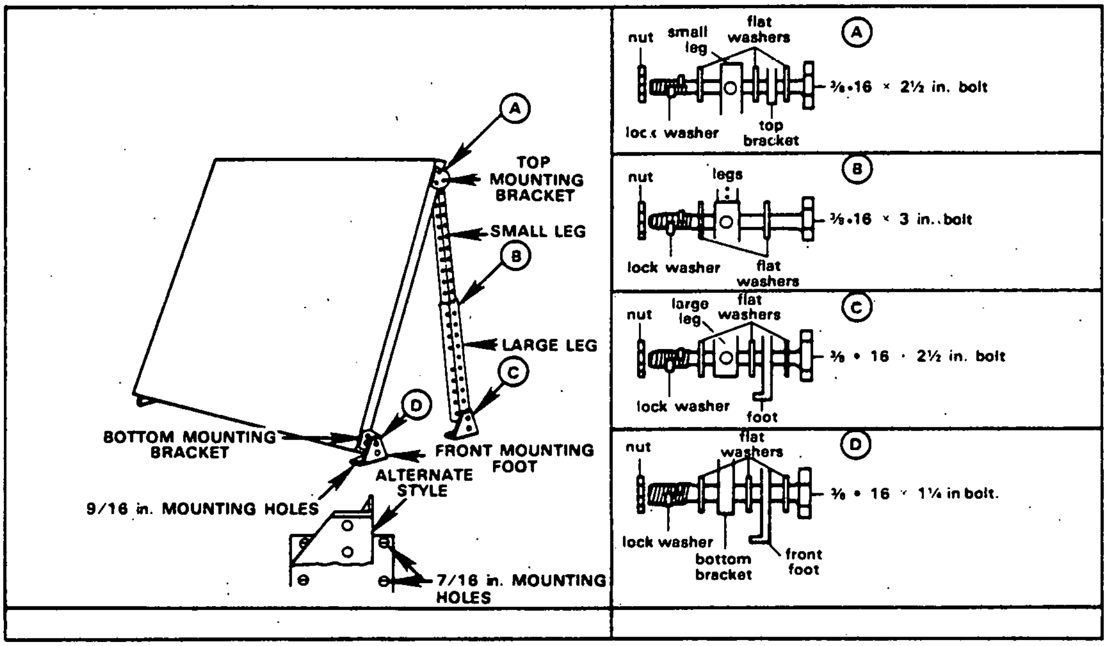
2.1.6 The array is now fully assembled and ready to be moved to its installation location and oriented. If the array must be disassembled or recrated, reverse the above procedure.

2.2 ORIENTING THE ARRAY - ARRAYS WITH TELESCOPING LEGS

2.2.1 When selecting a mounting location, make sure that the bottom of the array will be at least 3 feet (or 1 meter) higher than the maximum snow depth level.

2.2.2 IMPORTANT: THE ARRAY MUST BE ALIGNED SUCH THAT THE FRONT (MODULE) SURFACE DIRECTLY FACES DUE SOUTH (DUE NORTH IN THE SOUTHERN HEMISPHERE). WHEN USING A MAGNETIC COMPASS MAKE SURE TO CORRECT FOR THE LOCAL DIFFERENCE BETWEEN MAGNETIC DIRECTION AND TRUE DIRECTION. Anchor the front mounting feet once the array is aligned.

FIGURE 1

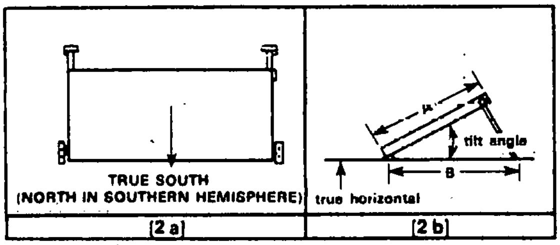


2.2.3 Anchor the legs' mounting feet to the mounting surface. It is best to make support spacing (B) equal to array dimension (A) (reference Figure 2b). Other positions may be used as necessary depending on the angle required and/or terrain considerations.

2.2.4 To set the tilt angle of the array, remove the long bolts anchoring the leg sections together (reference Figure 1, Point B) and adjust the length of the telescoping legs. The tilt angle of the array (the angle the array surface makes with a horizontal surface) should be adjusted to within 2 degrees of the specified angle. An inclinometer (adjustable angle liquid level) is most useful in measuring this angle, although, with care, a protractor and an ordinary bubble level may also be used. Reinsert the bolts and tighten.

2.2.5 Tighten all nuts and bolts.

FIGURE 2



2.3 ATTACHMENT OF CABLES

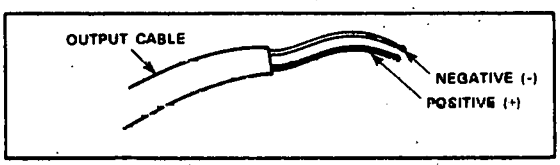
2.3.1 If a battery voltage regulator is included in the system or if one is added to the system, follow the instructions included with the regulator.

2.3.2 **Single Frame Arrays:** The output cable can be attached directly to the battery. Observe the correct polarity; black is positive, white is negative (reference Figure 4). If the polarity is accidentally reversed, no damage will result to either the array or the battery (assuming the battery is of the proper voltage for the array). However, if the polarity is left reversed for more than a few hours, the solar electric generator system will not function and the battery may become discharged.

2.3.3 **Multiframe Arrays:** Each frame is supplied with a separate output cable. Attach the output cable directly to the appropriate battery terminal (observe correct polarity).

2.3.4 After connecting cable(s) to the battery and connecting any required battery intercell connecting wires, protect all battery terminals from corrosion with a layer of grease.

FIGURE 3



3.0 TESTING

There are several tests that can be conducted to check system performance: Test 3-1 (Solar Array Performance), Test 3-2 (Blocking Diode Performance), Test 3-3 (Battery Self-Discharge). These can be performed either independently or in conjunction with the Troubleshooting Guide, Section 4.2.

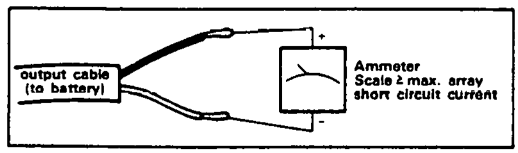
Upon installation, Test 3-1 (Solar Array Performance) should be conducted. Tests 3-2 and 3-3 should be performed if trouble occurs.

The annual maintenance visit can include the following simple check of the solar electric generator system performance. Measure the specific gravity of the battery electrolyte (for lead-acid batteries) with a standard battery hydrometer. Correct the readings to 77°F (25°C) using Table 3-1. Refer to Table 3-2 and relate the percent of battery capacity remaining to the corrected electrolyte specific gravity. If battery electrolyte specific gravity is low, refer to Section 4.2, Conditions 1 and 2.

TEST 3-1: SOLAR ARRAY PERFORMANCE

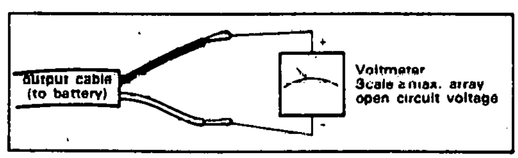
1. This test must be performed during the middle hours of a sunny day. The sun must be clearly visible with no thick haze present.
2. Disconnect array cable(s) or voltage regulator-battery cable from the battery terminals. If the system contains a regulator(s), disconnect regulator(s) following instructions provided with regulator(s) before proceeding to the next step.
3. Connect a suitable ammeter across the two disconnected cable leads (reference Figure 4). The ammeter's resistance should be such that the voltage drop across the ammeter is less than 0.3 volt. Adjust the tilt angle of the array to obtain the maximum current output as indicated by the ammeter.

FIGURE 4



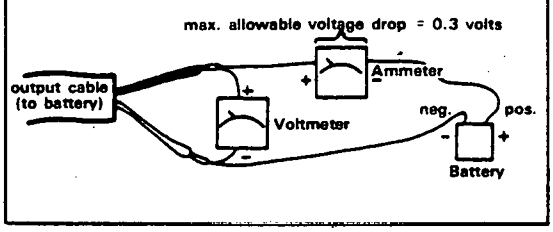
4. The ammeter current reading (short circuit current) should be approximately 70% of the $100mW/cm^2$ short circuit current (listed under "Array Performance" on the front cover).
5. Disconnect the ammeter. Connect across the same cable leads (reference Figure 5) a voltmeter having an impedance of at least 1,000 ohms per volt. The voltmeter reading (open circuit voltage) should be greater than 0.48 volt times the total number of solar cells in series (listed under "Array Performance" on the front cover).

FIGURE 5



6. Disconnect the voltmeter. Reconnect the negative lead to the battery. Connect an ammeter between the positive cable lead and the positive battery terminal (positive ammeter lead to the positive cable lead). Connect the voltmeter to the two cable leads (reference Figure 6). If this voltage is less than 2.2 volts times the number of series-connected lead-acid battery cells, the measured current should be at least 80% of the current measured in Step 4 (assuming sunlight conditions unchanged since Step 3).

FIGURE 6



7. For multiframe arrays this test procedure can be repeated for each individual array section by making these tests at each individual array cable termination. For each individual array section, disconnect the cable leads from the terminal block inside the external junction box and repeat Steps 3 through 6. The corresponding information for each frame is listed on the front cover of this manual (reference "Frame Performance").

8. If an array does not pass this test, refer to the Troubleshooting Guide, Section 4.2.

TABLE 3-1

HYDROMETER READING CORRECTIONS TO 77°F

Electrolyte Temperature [°F]	Correction [add to reading]
140	+0.024
130	+0.020
120	+0.016
110	+0.012
100	+0.008
90	+0.004
80	+0.000
70	-0.004
60	-0.008
50	-0.012
40	-0.016
30	-0.020
20	-0.024
10	-0.028
0	-0.032
-10	-0.036
-20	-0.040
-30	-0.044
-40	-0.048

NOTE: The temperature of the electrolyte solution, not the ambient air temperature, should be measured with an immersion type thermometer. Some hydrometers have a thermometer and temperature correction scale built in.

TABLE 3-2

PERCENT OF 500 HOUR RATE CAPACITY REMAINING
vs.
ELECTROLYTE SPECIFIC GRAVITY (CORRECTED TO 77°F)

	Initial Electrolyte Specific Gravity		
	1.210	1.250	1.300
% Capacity Remaining	Hydrometer Reading [Corrected to 77°F]		
100	1.210	1.250	1.300
90	1.197	1.235	1.283
80	1.185	1.221	1.266
70	1.172	1.206	1.249
60	1.160	1.192	1.232
50	1.147	1.177	1.215
40	1.135	1.163	1.198
30	1.122	1.148	1.181
20	1.110	1.134	1.164
10	1.097	1.119	1.147
0	1.085	1.105	1.130

TEST 3-2: BLOCKING DIODE PERFORMANCE

1. This test must be performed either at night with no artificial light striking the array or with a black opaque cloth covering the entire array (reference Figure 7).

2. Disconnect the positive lead of the array cable(s) or the voltage regulator-battery cable from the battery terminals. Connect a milliammeter between this disconnected lead and the positive battery terminal (positive milliammeter lead to the positive battery terminal) (reference Figure 7). The current measured should be less than 4mA times the number of solar cells connected in parallel (listed under "Array Performance" on the front cover).

3. A current exceeding the above value indicates that the diode(s) has developed excessive reverse leakage current. If the array contains a diode mounted in a junction box, it should be replaced (reference Section 4.3). If the system includes a voltage regulator(s), refer to Regulator Manual for testing procedure. Otherwise, the diode(s) is located inside the module(s) and this test should be repeated for each module on the affected frame. Access to each module's leads may be obtained by removing the attached junction box cover. Disconnect the leads at the terminal block before starting the test. Remember that no light can strike the module's surface. Diodes located in the terminal box attached to the back of each module are sealed and cannot be replaced in the field. Any module that shows excessive reverse leakage current should be replaced (reference Section 4.3).

TEST 3-3: BATTERY SELF-DISCHARGE (LEAD-ACID BATTERIES)

NOTE: THIS TEST WILL REQUIRE REMOVAL OF THE BATTERY SYSTEM FROM THE ARRAY SITE.

1. Disconnect all cables from the battery terminals. Charge the battery or battery cell at a current rate not exceeding the battery's capacity in ampere hours divided by 20 hours (e.g., a 100-ampere hour battery would be charged at a current of 5 amperes or less). A standard battery charger should suffice for this purpose. Discontinue charging when the battery's terminal voltage exceeds 2.3 volts per series-connected battery cell.

2. Take a specific gravity reading of the electrolyte in each battery cell and record the corrected values (use Table 3-1 and an immersion thermometer).

3. Allow the battery to stand idle at room temperature for a week. At the end of the week take a second set of specific gravity readings. Compare with readings taken in Step 2. Corrected readings differing by more than 15 points (0.015) indicate a battery cell with excessively high self-discharge.

4.0 MAINTENANCE

4.1 REGULAR MAINTENANCE

(Yearly intervals recommended.)

4.1.1 Check battery electrolyte level. Replenish with distilled water, if necessary. When checking or adding to the battery electrolyte, the battery manufacturer's recommendations should be followed.

4.1.2 Check the module surface(s) for dirt buildup. Normal rainfall will usually be sufficient to provide for self-cleaning, if the array is tilted at 15° or more from the horizontal. However, if dirt buildup becomes excessive, either plain water or a mild detergent solution followed by a water rinse may be used. DO NOT USE SOLVENTS OR STRONG DETERGENTS.

4.2 TROUBLESHOOTING GUIDE

Most problems can be isolated with the aid of the following guide. If it is impossible to locate the problem, please contact the Technical Service Department at Solar Power Corporation for assistance.

SYMPTOM	Other Symptoms
Battery electrolyte specific gravity low [lead-acid batteries]	Specific gravities of all battery cells differ no more than 20 points (0.020)

Checks and Repairs

1. Check all battery electrical connections for corrosion and mechanical soundness. Clean and/or repair.
2. Check to see if there are any obstructions that shadow any portion of the array during any part of the day. If this condition exists, either the obstruction must be removed or the array must be moved to an unobstructed location.
3. Check the orientation of the array. Make sure it is facing directly due south (north in the southern hemisphere) and the tilt angle is correct (reference Section 2.2 or 2.3).
4. Check the load current. Calculate the equivalent number of amp-hours per day required by the load. Compare this calculation against the design load listed under "Installation Data" on the front cover. If the measured load exceeds the design load, contact the Technical Service Department at Solar Power Corporation. Each solar electric generator system is designed for a specific load. Deviations from that load may result in unsatisfactory operation.
5. Check the solar array output by following the instructions in Test 3-1. Refer to Conditions 3, 4, 5, or 6 (Section 4.2) as necessary.
6. Check the blocking diode(s) by following the instructions in Test 3-2.
7. Check for high battery self-discharge by following the instructions in Test 3-3. If the battery or part of the total battery system fails this test, replace the defective battery cell(s).

SYMPTOM	Other Symptoms
Same as Condition 1	Specific gravity of only one or a few battery cells low

Checks and Repairs

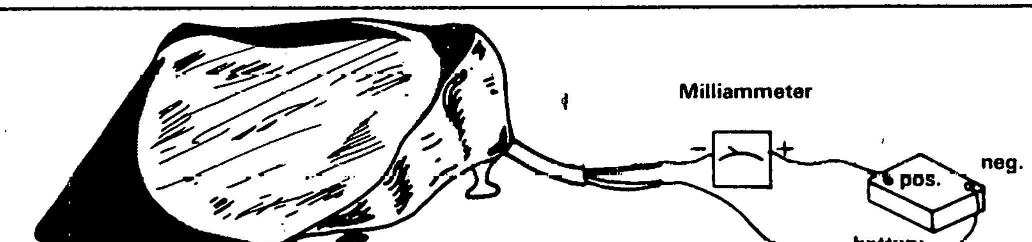
1. Check for excessively high electrolyte level. If so, shelter battery to prevent rain from entering through the vent hole(s).
2. Check the affected cells for high battery self-discharge by following the instructions in Test 3-3. Replace battery cell or battery containing bad cell.

SYMPTOM
Array open circuit voltage equal to zero [from Test 3-1]

Checks and Repairs

1. Single Frame Arrays:
   (a) If the array consists of only one module, that module must be replaced (reference Section 4.3).
   (b) If the array consists of more than one module, remove the cover of the junction box mounted to the back of the array. With the output cable disconnected from the battery terminals, test for voltage at the individual module leads. If voltage is present, there are bad contacts. At the terminal block, or the crimp connectors attached to the output cable are not making contact to the wire, or the output cable's conductors are broken. Clean all connections. Test crimp connectors by pulling on wires. Recrimp or attach wire directly to terminal block if necessary. Test the cable with an ohmmeter or continuity tester. Replace output cable if it is an open circuit.
2. Multiframe Arrays:
   (a) Remove junction box cover. Check for loose connections at the terminal block. Tighten if necessary.

FIGURE 7



Black opaque cloth over entire array or perform at night with no light shining on array.

(b) Test for voltage at the individual array cable terminations. If voltage is present there, proceed to Step 2 (c). If no voltage is present at any of the cable terminations, each array section must be checked individually as described in Step 1(b).

(c) Make sure that at least one lead of the battery cable is disconnected from the battery terminals. Connect a jumper wire between any positive array cable terminal and the positive battery cable terminal. If voltage is now present at the battery cable leads, and there is a blocking diode within an external junction box, either the blocking diode is defective or one of the wires connecting the diode to the terminal block is broken. Detach the plate on which the terminal block is mounted by removing the four corner screws. The blocking diode is located beneath the plate. Inspect for any broken wires and if none are found, replace the diode (reference Section 4.3).

(d) Check the continuity of the battery cable with an ohmmeter or continuity tester. Replace output cable if it is an open circuit.

SYMPTOM

Array open circuit voltage low (from Test 3-1)

Checks and Repairs

1. Check that the voltmeter's resistance is greater than 1,000 ohms per volt, that the sun is clearly visible, that there is no thick haze blocking the sun, and that the array is aimed towards the sun.

2. Single Frame Arrays:

(a) If the array consists of only one module, that module should be replaced (reference Section 4.3).

2. (b) If the array consists of more than one module, remove the cover of the junction box mounted in the back of the array. Disconnect the cable leads from each module. Test each module individually for low open circuit voltage. The voltmeter reading (open circuit voltage) should be greater than 0.48 volt times the number of solar cells in series (listed under "Module Performance" on the front cover). Any module that does not pass this test should be replaced (reference Section 4.3).

3. Multiframe Arrays: Disconnect the array cables from the terminal block in the external junction box or from the battery terminals. Check the open circuit voltage at each individual cable pair of wires to isolate the affected array section. The voltmeter reading (open circuit voltage) should be greater than 0.48 volt times the number of solar cells in series (listed under "Array Performance" on the front cover). To locate the defective module in the array section isolated above, follow the instructions in Step 2(b).

SYMPTOM

Array short circuit current low (from Test 3-1)

Checks and Repairs

1. Check for dirt buildup on any module or portion of a module. Clean according to Section 4.1.2.

2. Check for condensation, snow, or ice on module or any portion of a module. Wipe clean.

3. Check for shading of any module or portion of a module. Retest after removing obstruction.

4. Make sure array is aimed directly at the sun. Retest after correcting tilt.

5. Single frame arrays or when the problem is isolated to a single array frame (reference Step 6): Remove the attached junction box cover. Test each individual module for short circuit current as described in Test 3-1, Steps 3 and 4. Compare these values to the short circuit current values listed on the front cover under "Module Performance". Replace any module (reference Section 4.3) which fails Test 3-1. Make sure all connections in the junction box are tight and clean.

6. Multiframe Arrays: Perform Test 3-1 for each array section (cable) to determine the faulty section. Check for any loose terminals or broken wires within an external junction box. Also check all connectors. If any, for corrosion and tight mating of the male and female contacts. Clean or replace as necessary.

SYMPTOM

Excessive difference between array short circuit and battery charging current (from Test 3-1)

Checks and Repairs

1. Check for corrosion at the battery terminals. Clean terminals and cable leads. Retest.

2. If the array has a junction box(es) (either internal or external), remove the cover(s) and inspect for corrosion on all electrical connections within the box. Clean or replace damaged components. Retest.

3. Test each module individually as described in Steps 3, 4, and 6 of Test 3-1. Compare these values to the short circuit current values as listed on the front cover under "Module Performance". Replace any module(s) that fail Test 3-1 (reference Section 4.3).

4.3 MODULE AND DIODE REPLACEMENT

When it has been determined that a module or a blocking diode needs replacing, proceed as follows:

4.3.1 Replacement of Module

(a) Remove cover of junction box attached to array frame.

(b) Disconnect at the terminal strip the cable leads of the module being replaced.

(c) Loosen the threaded gland of the cable fitting through which the module cable enters the junction box. Pull the end of the cable out of the junction box.

(d) Remove the nuts and bolts holding the module onto the array frame. Lift off the module; save the hardware removed.

(e) Insertion of Replacement Module:
Reverse the removal procedure: (a) through (d) above.

4.3.2. Replacement of Blocking Diode Located in Junction Box

(a) Disconnect battery cable at battery terminals.

(b) Remove the junction box cover and the metal plate on which the terminal block is mounted. Loosen or remove cable leads from the terminal block, if necessary.

(c) The diode will usually be mounted on a heat sink. Make a sketch showing which lead goes to which terminal and how the hardware is assembled. Unsolder the leads to the diode. Remove the diode.

(d) Insert the new diode (exact same number as the diode being replaced). Take care to replace the hardware in the same order as was on the removed diode.

(e) Solder the leads to the new diode. Take care that the leads go to the same terminals as on the removed diode. (Array positive lead to anode: battery positive lead to cathode.)

(f) Replace the metal plate and the junction box cover.

(g) Reconnect the battery cable to the battery terminals.

4.3.3. Replacement of Blocking Diode Located in Module

A blocking diode within the module cannot be replaced in field. The module should be removed from the array frame (reference Section 4.3.1, a-d) and returned to Solar Power Corporation for repair.

5.0 TOOLS AND EQUIPMENT

5.1 INSTALLATION & MAINTENANCE TOOLS

Ratchet Handle (3/8" or 1/2" drive)
6" Extension
1/2" Socket and Wrench
9/16" Socket and Wrench
7/16" Socket and Wrench
3/4" Socket and Wrench
Screw Drivers (1/8" to 1/2" wide)
Slip Joint Pliers (1½" diameter grip)
Locking Pliers
Crimping Tool (VACO 22-10 or equivalent) and assorted crimp terminals
Wire Strippers
Diagonal Cutters (medium)
Compass (magnetic)
Inclinometer

5.2 TESTING EQUIPMENT

Simpson 260 VOM (or equivalent)
Immersion Thermometer
Battery Hydrometer

APPENDIX 11.A
PERFORMANCE MEASUREMENT PROCEDURES

A.1 ELECTRICAL PERFORMANCE

Electrical performance measurements shall be referenced to SOC defined as 100 mW/cm^2 irradiance, air-mass 1.5, NOCT. All procedures, equipment, and standards related to measurements shall conform to the latest revision of date of the contract of NASA TM 73702, Terrestrial PV Measurement Procedures, dated June 1977. Manufacturer's conformance to this procedure is subject to acceptance by the owner. If a reference cell is used, it shall be traceable to NBS and shall be the only irradiance reference used.

To provide for efficient module testing, module performance may be based on module output at either SOC conditions or at Optional Test Conditions (OTC) defined as 100/mW/cm^2 irradiance, and a cell temperature other than NOCT. When measurements are made at OTC the power output (P) at NOCT cell temperature shall be determined as follows:

$$P = V_{NO}(I_{OTC} + \Delta I),$$

where

V_{NO} = Module nominal operating voltage at NOCT.

I_{OTC} = Module current measured at OTC and at a voltage equal to ($V_{NO} + \Delta V$) volts.

ΔI = Current Temperature Correction (delta I).

= I @ (NOCT, V') - I @ (OTC, $V = V' + \Delta V$).

ΔV = Voltage Temperature Correction (delta V).

= V @ (OTC, $I = I' - \Delta I$) - V @ (NOCT, I').

NOCT

OPEN CIRCUIT

CLEAN

$T_{CELL} = T_{AMB} + R * S$ + EXHIBIT A-3 CORRECTION

DETERMINE R EXPERIMENTALLY

CORRECT TO NOMINAL T_{AMB} AND S

GEOMETRY: TILTED, 2 ft ABOVE GROUND, WIND NOT EAST OR WEST

Exhibit A.1 Performance Measurement Procedure.

V' = Voltage = 0.6 V_{oc} @ NOCT.

I' = Current = 0.9 I_{sc} @ NOCT.

Determination of the temperature correction factors, ΔI and ΔV, in the above equation shall be based on actual measurements of a minimum of 5 production modules at both OTC and NOCT $\pm 2^{o}$ cell temperature. The current-voltage (I-V) characteristics of each module shall be measured at both conditions. The corresponding I-V curves for the two temperatures may then be overlayed to determine the correction factors. A simultaneous translation of the curves along both current and voltage axes may be made until an accurate match of the curves is accomplished at two points near the maximum power point. The OTC curve should match the NOCT curve at a point where the NOCT current is approximately 90 percent of I_{sc} (I', above), and at a second point where the NOCT voltage is approximately 60 percent of V_{oc} (V', above). The current and voltage shift required to produce the curve match shall be determined for the exact cell temperature difference between tests. The change per degree C for each factor is then calculated and multiplied by the difference between NOCT and the temperature used for OTC. The resulting ΔI and ΔV shall be averaged for the modules tested to establish temperature correction factors to be used when testing modules at other than SOC. Alternate temperature correction procedures such as that provided by a computer controlled, Large Area Pulsed Solar Simulator (Xenon source) may be used if approved by the owner.

A.2 NOCT

A.2.1 Purpose

The purpose of this test is to acquire sufficient data to make an accurate determination of the NOCT's of a terrestrial module's solar cells. By definition, NOCT is the module cell temperature under operating conditions in the nominal thermal environment (NTE), which is defined as:

Insolation = 80 mW/cm^2
Air temperature = 20^{o} C
Wind average velocity = 1 m/s
Mounting = tilted, open back, open circuit.

The NOCT test procedure is based on gathering actual measured cell temperature data via thermocouples attached directly to the cells of interest, for a range of environmental conditions similar to the NTE. The data are then presented in a way that allows accurate and repeatable interpolation of the NOCT temperature.

A.2.2 Determination of NOCT

The temperature of the solar cell (T_{cell}) is primarily a function of the air temperature (T_{air}), the average wind velocity (V), and the total solar insolation (L) impinging on the active side of the solar array module. The approach for determining NOCT is based on the fact that the temperature difference (T_{cell} - T_{air}) is largely independent of air temperature and is essentially linearly proportional to the insolation level. Analyses indicate that the linear assumption is quite good for insolation levels greater than about 40 mW/cm^2. The procedure calls for plotting (T_{cell} - T_{air}) against the insolation level for a period when wind conditions are favorable. The NOCT is then determined by adding T_{air} = 20^{o} C to the value of (T_{cell} - T_{air}) interpolated for the NTE insolation level of 80 mW/cm^2, i.e., NOCT = $(T_{cell} - T_{air})_{NTE} + 20^{o}$ C.

The plot of (T_{cell} - T_{air}) versus I shall be determined by conducting a minimum of two field tests in which the module being characterized is tested under terrestrial environmental conditions approximating the NTE in accordance with the testing guidelines which follow. Each test shall consist of acquiring a semicontinuous record of (T_{cell} -T_{air}) over a 1- or 2-day period, together with other measurements, as required, to characterize the terrestrial environment during the testing period. Acceptable data shall consist of measurements made when the average wind velocity is 1 m/s $\pm$ 0.75 m/s and with gusts less than 4 m/s for a period of 5 minutes prior to and up to the time of measurement. Local air temperature during the test period shall be 20° C $\pm$ 15° C. Using only acceptable data as so defined, a plot shall be constructed from a set of measurements made either prior to solar noon or after solar noon which defines the relationship between (T_{cell} - T_{air}) and the insolation level (L) for L $\geq$ 40 mW/cm^2.*

When (T_{cell} - T_{air}) is plotted as a function of L for average wind velocities less than 1.75 m/s, results similar to those shown in exhibit A.2 are obtained. For the data shown, the local air temperature was 15.6° C $\pm$ 4.5° C and the wind speed varied from zero to less than 4 m/s with an average of 1 m/s. Using the plot of (T_{cell} - T_{air}) vs. L, the value of (T_{cell} - T_{air}) at NTE is determined by interpolating the average value of (T_{cell} - T_{air}) for L = 80 mW/cm^2. Using the data in exhibit A.2 as an example, (T_{cell} - T_{air}) at NTE is determined to be 20.2° C. The preliminary value of NOCT is thus 20.2° C + 20° C = 40.2° C.

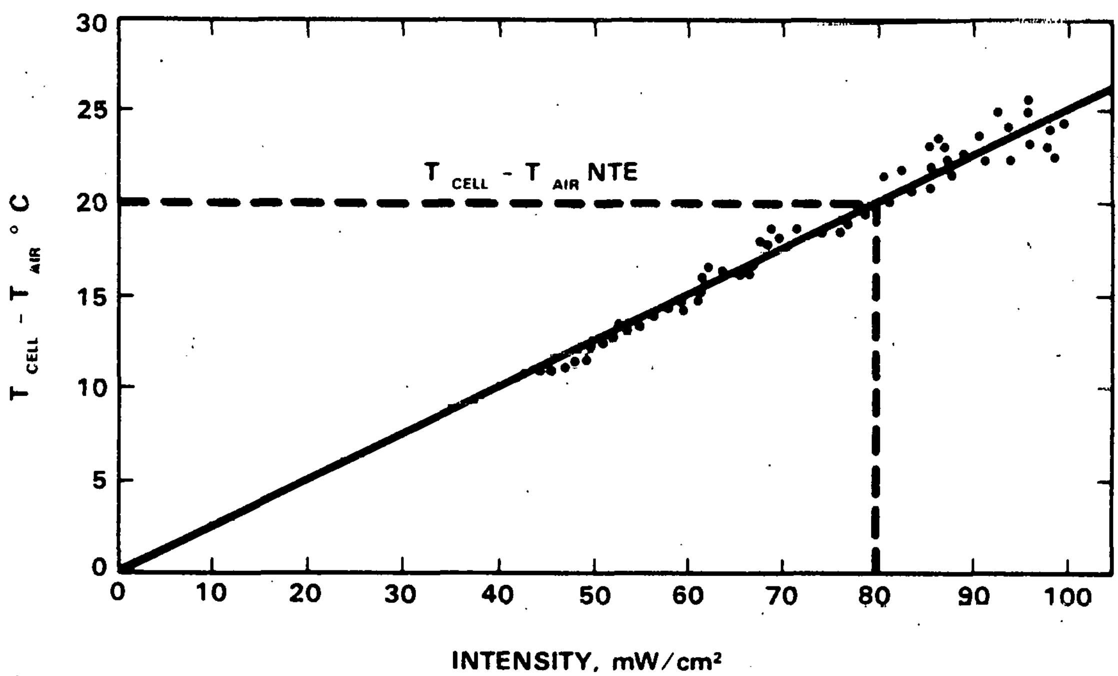


Exhibit A.2 Typical Cell Temperature Data.

* The two sets of measurements can be combined into a single set provided the average air temperature of the two sets does not differ by more than approximately 5° C. If the average air temperature is significantly different, the resulting effect appears as an increase in the scatter of the plotted data. As a result the data will be more difficult to fit and a less accurate result is possible.

A.2.3 Air Temperature and Wind Correction

A correction factor to the preliminary NOCT for average air temperature and wind velocity is determined from exhibit A.3. This value is added to the preliminary NOCT and corrects the data to 20° C and 1 m/s. T_{air} and $\bar{V}$ are the average temperature and wind velocity for the test period.

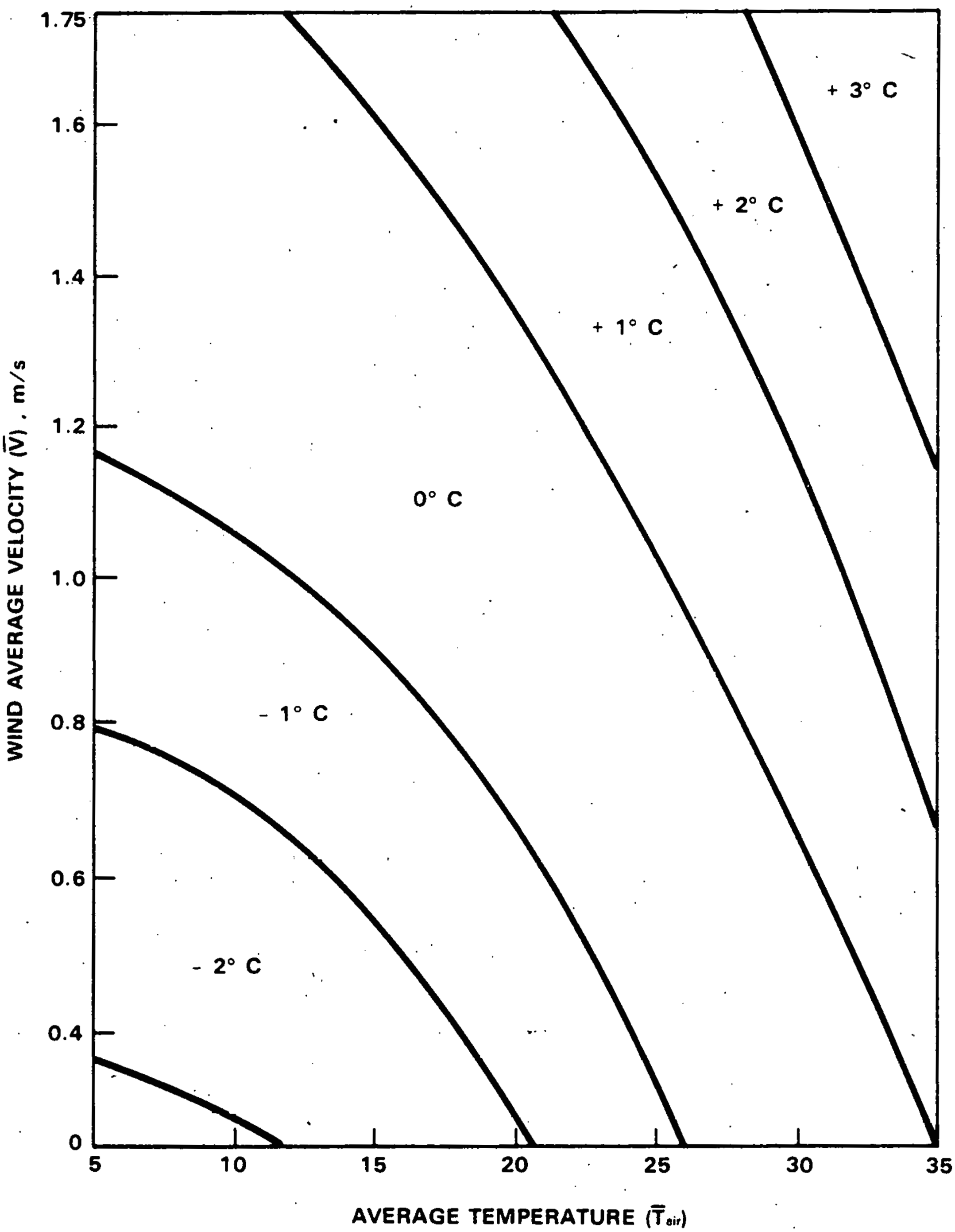


Exhibit A.3 NOCT Correction Factor.

For the test data shown in exhibit A.2, $\bar{V}$ is 1 m/s and $\bar{T}_{air}$ is 15.6° C. From exhibit A.3, the correction factor is 0° C. The NOCT is, therefore, 40.2° C.

A.2.4 Test Geometry

a. Tilt Angle. The plane of the module shall be positioned so that it is normal to the sun (±5°) at solar noon.

b. Height. The bottom edge of the module shall be 2 feet or more above the local horizontal plane or ground level.

c. Panel Configuration. The module shall be located in the interior of a 1.2 m x 1.2 m (4' x 4') panel. Black aluminum panels or other modules of the same design shall be used to fill in any remaining open area of the panel structure. The back of the panel shall be exposed.

d. Surrounding Area. There shall be no obstructions to prevent full irradiance of the module beginning a minimum of 4 hours before solar noon and up to 4 hours after solar noon. The ground surrounding the module shall not have a high solar reflectance and shall be flat and/or sloping away from the test fixture. Grass and various types of ground covers, blacktop, and dirt are recommended for the local surrounding area. Buildings having a large solar reflective finish shall not be present in the immediate vicinity. Good engineering judgment shall be exercised to assure that the module, front and back sides, is receiving a minimum of reflected solar energy from the surrounding area.

e. Wind Direction. The wind shall not be predominantly from due west; flow parallel to the plane of the array is not acceptable and can result in a lower than typical operating cell temperature.

f. Module Electrical Load. Data shall be obtained for a module open-circuit condition corresponding to zero electrical power output.

A.2.5 Test Equipment

a. Pyranometer. The total solar irradiance on the active side of the module shall be measured by a reference cell traceable to the National Bureau of Standards or by a pyranometer. The device shall be mounted on the plane of the module and within .3 m (1 foot) of the array. The pyranometer used shall have a traceable annual calibration to a recognized standard instrument and shall be either: (1) a temperature-compensated unit which has less than ±1 percent deviation in sensitivity over a range -20° to +40° C, or (2) a unit which incorporates a temperature sensor and has a sensitivity-temperature correction supplied with its calibration.

b. Wind Measurement. Both the wind direction and wind speed shall be measured at the approximate height of the module and as near to the module as feasible.

c. Air Temperature. The local air temperature shall be measured at the approximate height of the module. The measurement shall be made in the shadow of the module and shall be accurate to ±1° C. (Note: An average local air temperature is desired. This is obtained satisfactorily by increasing the thermal mass of the thermocouple by imbedding the thermocouple in a solder sphere of approximately 1/4-inch diameter.) The measurement must be appropriately shielded and vented.

d. Cell Temperature. The temperature of at least two representative interior solar cells shall be measured to ±1° C. Thermocouples shall be 36 gauge, and shall be soft-shouldered directly to the back of the cells.

e. Substrate Surface Temperature. The exterior temperature of the rear of the solar module shall be measured to ±1° C beneath a representative cell and, when practical beneath a representative space between cells. Thermocouples shall be 26 gauge, and shall be bonded down with 57-C epoxy or the equivalent.

A.2.6 Data Recording

All data shall be printed out approximately every 2 minutes. In addition, solar intensity, wind speed, wind direction, and air temperature shall be continuously recorded.

A.2.7 Cleaning

The active side of the solar cell module and the pyranometer bulb shall be cleaned before the start of each test. Dirt shall not be allowed to build up. Cleaning with a mild soap solution followed by a rinse with distilled water has proven to be effective.

A.2.8 Equipment Calibration

A calibration check shall be made of all the equipment prior to the start of the test.

APPENDIX 11.B
TEST PROCEDURES

B.1 THERMAL CYCLING TEST PROCEDURE

The module shall be subjected to the thermal cycling procedure per exhibit B.1, consisting of 50 cycles with the cell temperature varying between -40° C and +90° C. The temperature shall vary approximately linearly with time at a rate not exceeding 100° C per hour and with a period not greater than 6 hours per cycle (from ambient to -40° C to +90° C to ambient). The module circuitry shall be instrumented and monitored throughout the test to verify that no open circuits or short circuits occur during the exposure.

B.2 HUMIDITY TEST PROCEDURE

The module shall be subjected to the humidity cycling procedure per exhibit B.2. The module shall be tested in the open circuit condition, but with terminals protected from water condensation. Electrical performance test, per appendix A.1, shall be performed within 1 hour after removal from the humidity chamber, or within another mutually agreed on time period, if the testing is subcontracted.

B.3 MECHANICAL CYCLING TEST PROCEDURE

The module shall be subjected to a cyclic load test in which the module is supported only at the design support points and a uniform load normal to the module surface is cycled 10,000 times in an alternating negative and positive direction. Cycle rate shall not exceed 20 cycles/min. The module circuitry shall be instrumented to verify that no open circuitry or short circuits occur during the test. JPL Document 5101-19 "Cyclic Pressure-Load Developmental Testing of Solar Panels," February 1977, describes techniques suitable to the performance of this test.

B.4 WARPED MOUNTING SURFACE TEST PROCEDURE

The module shall be subjected to a twist test by deflection of the substrate to which it is mounted. The deviation from a true flat surface during the test shall be ±¼ inch, measured along either mounting surface as shown in exhibit B.3. The module circuitry shall be instrumented to verify that no open circuits or short circuits occur during the deflection test.

B.5 HAIL IMPACT TEST PROCEDURE

The module shall be subjected to normal impact loading with the required diameter iceball traveling at terminal velocity for the specified size. Typical hail characteristics are provided in exhibit B.4. At least three different points of impact shall be selected to include the test specimen's most sensitive exposed point, and each point will be struck at least three times (a minimum of nine impacts). The most sensitive exposed point on a test specimen must be determined experimentally through destructive testing of a sample panel. Iceballs 1.5 times the required diameter shall be fired at candidate sensitive points with increasing velocity until the panel is broken. Several different points on the panel should be broken, and the points broken at the lowest velocities should be used for subsequent testing.

The candidate points selected shall include (where applicable) the following:

- Corners and edges of the module;
- Edges of cells, especially around electrical contacts;

- o Points of minimum spacing between cells;
- o Points of support for any superstrate material; and,
- o Points of maximum distance from points of support noted above.

Some scatter is expected in hitting a location on a module. Three repeated impacts are required to assure that a sensitive point has been struck. Error of up to 1/2 inch in the location hit is acceptable. Either pneumatic or spring-actuated guns for projecting the iceballs against the modules are acceptable, however iceball velocity at impact must be controlled to within ± 5 percent of terminal velocity for the required hailstone size. Iceballs shall be generally spherical in shape with a maximum deviation in diameter of $\pm 1/8$ inch. The iceballs shall be cooled to -10° C $\pm 2^{\circ}$ as measured in the compartment where they are stored. The module shall be mounted in a manner representative of that used for actual installation of the module in the array. After each impact, the module shall be inspected for evidence of visible damage. Iceballs are the only acceptable hailstone simulation. Dropped steel balls, for example, shall not be used.

B.6 ELECTRICAL ISOLATION TEST PROCEDURE

The module 'hi-pot' test shall be conducted with the output terminals short-circuited. Test leads from a suitable DC voltage power supply shall be connected with the positive lead on the terminals and the negative lead on the module grounding stud.

In the case of modules not required to provide a grounding stud, the mounting structure shall be used as the second test point. Voltage shall be applied at a rate not to exceed 500 V/sec up to the test voltage, and shall then be held at the required test voltage for 1 minute. The module shall be observed during the test for signs of arcing or flashover. Leakage current shall be monitored during the test to verify that leakage current does not exceed 50 microamps (50×10^{-6} A).

B.7 DC/AC INVERTER

The inverter for converting DC to AC voltage shall be designed in conformance with the general provisions contained in section B.11 (See exhibit B.5), and the following.

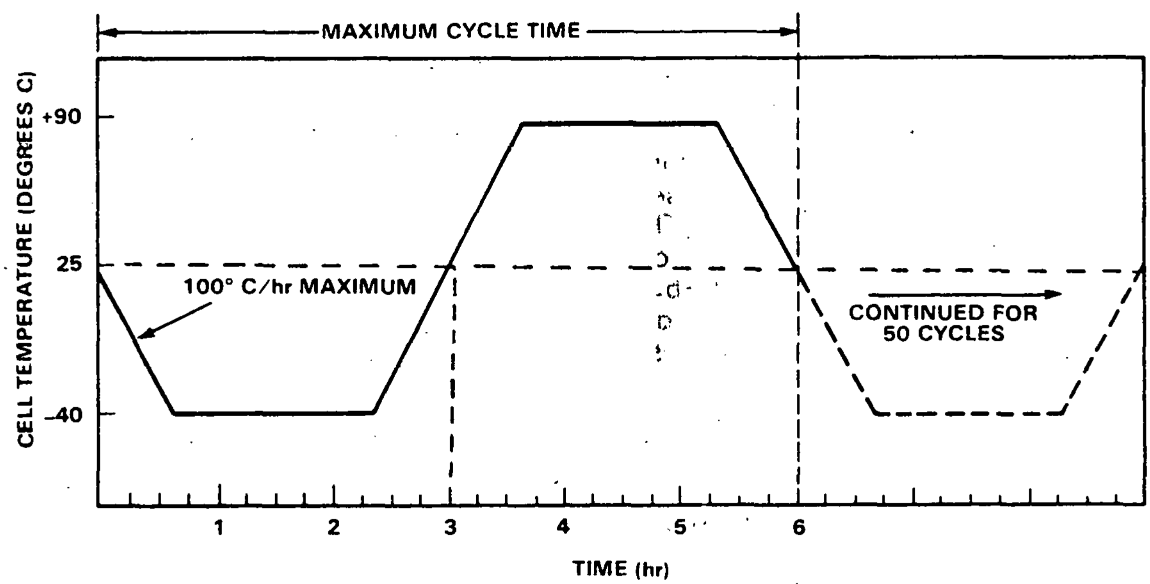


Exhibit B.1 Thermal Cycle Test.

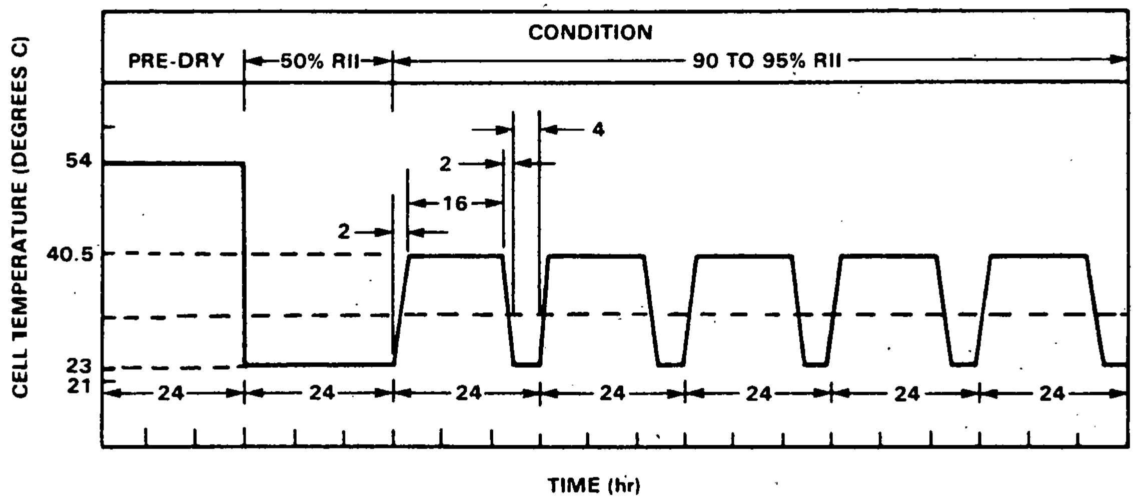


Exhibit B.2 Humidity Cycle Test.

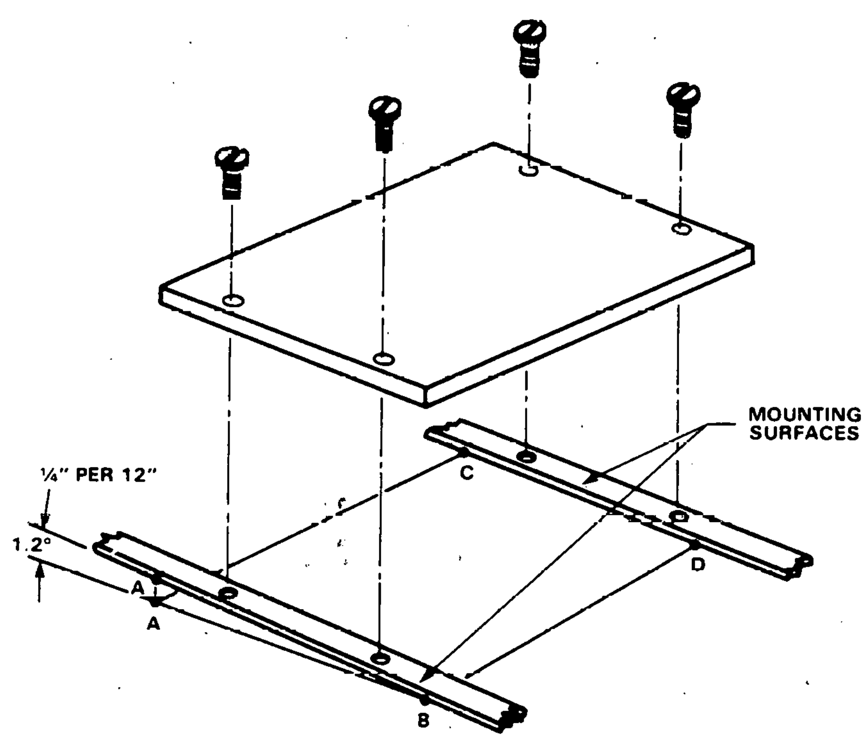


Exhibit B.3 Graphical Representation of "Twisted Mounting Surface" Requirement.

I. Design

The inverter shall be totally enclosed, passively cooled in a weatherproof* metal container, grounded in accordance with the NEC (National Electrical Code). All connectors shall be weatherproof, strain-relieved, and compatible with aluminum/copper wire and cable, with proper polarity indicated by embossing or other permanent marking. All electrical connections shall be three-wire, with one wire serving as ground, and output and input clearly labeled.

*Some applications do not need weather protection (if mounted in a shed) or need only be weather resistant.

HAIL CHARACTERISTICS
WEIGHT AND TERMINAL VELOCITY

SIZE in.	WEIGHT* lb	TERMINAL VELOCITY mph
½	0.0021	36
¾	0.0072	45
1	0.017	52
1¼	0.033	58
1½	0.057	63
2	0.136	73
2½	0.266	81
3	0.459	89

* DENSITY OF ICE TAKEN AS 0.9 gm/cm^3

Exhibit B.4 Typical Hail Characteristics.

MECHANICAL DESIGN:

- Passively cooled
- Weatherproof
- Strain - relieved, aluminun/copper wire
- 3 wire (ground)
- Polarity embossed

INPUT:

- Voltage: 10.8 to 14.5 V DC
- Current: less than 10 A
- Circuit breakers
- Lead-reversal protection

OUTPUT:

- Voltage: 115 V ± 6%, single phase, 60 ± 0.5 Hz
- Harmonic Distortion: Less than 3%
- Temperatures coefficient: Voltage: less than 0.03/° C
  Frequency: less than 0.05%/° C
- Circuit breakers
- Lead-reversal protection

EFFICIENCY:

- Vs. percent of rated input power (table)

RELIABILITY:

- - 20° C to + 50° C while operating
- 20-year life
- 25-year mean time between failures

Exhibit B.5 DC/AC Inverter Component Specifications.

2. Input

The input to the inverter shall be:

10.8 to 14.5 V DC (variable) for a 12 V System
10 A maximum

The inverter shall be self-protected from lead reversal with a keyed connector. Shorting of input leads and over-voltage protection shall be provided with circuit breakers or other devices that require manual resetting, but not replacement of a part. Fuses are not acceptable. Circuit breakers shall not emit smoke, fire, or visible arcs, shall have ambient temperature compensation and manual reset. The internal resistance shall be less than 1 micro-ohm. The circuit breakers shall fail open, but shall have a life exceeding 200 cycles.

3. Output

The output from the inverter shall be a sine wave at 115 V(RMS) ± 6 percent, single phase, 60 cycles per second (60 Hertz) frequency ± 0.5 percent. The harmonic distortion shall be no greater than 3 percent. The output voltage shall change no more than 0.03 percent per degree C change in the ambient air temperature. The output frequency shall change no more than 0.05 percent/^{o} C. The inverter shall be protected from lead reversal with a keyed connector and from a direct short of the output leads by a circuit breaker or other resettable device as described in the previous section. Fuses are not acceptable. The RMS value of an AC voltage is the DC equivalent value (the effective value).

4. Efficiency

The efficiency of the inverter, defined as the ratio of the product of RMS (root-mean-square) output voltage and current to the product of the input current and voltage, shall be no less than indicated on the following table; where P = V x I and efficiency equals Pout/Pin.

Percent of Rated Input Power	Ratio (efficiency)
10%	40%
20%	57%
30%	66%
40%	72%
50%	76%
60%	80%
70%	82%
80%	84%
90%	85%
100%	87%

5. Reliability

The inverter shall be capable of meeting these specifications when operating in ambient-air temperatures ranging from -20° C to +50° C. The mean time between failures (MTBF) for the inverter shall be no less than 25 years. Suitable redundancy shall be incorporated in the inverter to achieve this reliability. The life of the inverter shall exceed 20 years.

B.8 BATTERY VOLTAGE REGULATOR

The voltage regulator that controls the input voltage to the battery during charging operations shall be designed in conformance with the general provisions contained in section B.11, and the following.

1. Design

The regulator shall be totally enclosed, passively cooled in a weatherproof* metal container, grounded in accordance with the NEC. All connectors shall be weatherproof, strain-relieved, and compatible with aluminum/copper wire and cable, with proper polarity indicated by embossing or other permanent marking. All electrical connections shall be three-wire, with one wire serving as ground, and shall be clearly labeled for series, parallel, or partial shunt operation, and for output and input.

2. Input

The input to the battery voltage regulator shall be:

13 to 17 V DC (variable)
10 A maximum

The regulator shall be self-protected from lead reversal, shorting of input leads, and over-voltage by circuit breakers or other devices that require resetting, but not replacement of a part. Fuses are not acceptable. The control voltage into the regulator shall be the battery terminal voltage.

3. Output

The output from the regulator shall be used directly for connection to the battery. The output current shall be 10 A when the battery voltage is equal to or less than 13.0 V and shall decrease to 0 A when the battery voltage is equal to or greater than 14.4 V. The output shall be self-protected from a direct short of the output leads by a circuit breaker or other resettable device. Fuses are not acceptable. The regulator shall also be self-protected from a lead reversal at the output terminals. If the leads to the battery are reversed, no current is to flow to or from the battery.

4. Efficiency

The efficiency of the regulator, defined as the ratio of the product of output voltage and current to the product of the input current and voltage, shall be greater than 90 percent at 13.0 V and 10 A input, where P = V x I and efficiency equals Pout/Pin.

5. Reliability

The regulator shall be capable of meeting the specified requirements while operating in ambient-air temperatures ranging from -20° C to +50° C. The mean time between failures (MTBF) for the regulator shall be no less than 25 years. Suitable redundancy shall be incorporated in the regulator to achieve this reliability. The life of the regulator shall exceed 20 years.

---

*Some applications do not need weather protection (if mounted in a shed) or need only be weather resistant.

B.9 **CONVERTER**

The converter that converts the alternating-current voltage input into a direct-current output shall be designed in conformance with the general provisions contained in section B.11, and the following.

1. Design

The converter shall be totally enclosed, passively cooled in a weatherproof* metal container, grounded in accordance with the NEC. All connectors shall be weatherproof, strain-relieved, and compatible with aluminum/copper wire and cable, with proper polarity indicated by embossing or other permanent marking, with one wire serving as ground, and output and input clearly labeled.

2. Input

The input to the converter shall be:

105 to 140 V AC (variable) sine wave
57 to 63 cycle per second frequency (Hertz), single phase
10 A maximum

The convertor shall be self-protected from lead reversal, shorting of input leads and over-voltage by circuit breakers or other devices that require resetting, and not replacement of a part. Fuses are not acceptable.

3. Output

The output of the convertor shall be 14.4 V ± 1 percent, direct current at 100 A maximum. Maximum ripple shall be one volt. The output voltage is to vary no more than one percent per degree C change in ambient temperature.

The output of the converter shall be self-protected from a direct short of the output leads by a circuit breaker or other resettable device. Fuses are not acceptable. The convertor shall also be self-protected from a lead reversal and shorting at the output terminals. If the leads of a battery are reversed and connected to the converter output, no current is to flow to or from the battery.

4. Efficiency

The efficiency of the converter, defined as the ratio of the product of the output voltage and current to the product of the input current and voltage, shall be no less than indicated on the following table, where P = V x I and efficiency equals Pout/Pin.

Percent of Rated Input Power	Ratio (efficiency)
10%	40%
20%	57%
30%	66%
40%	72%
50%	76%
60%	80%
70%	82%
80%	84%
90%	85%
100%	87%

*Some applications do not need weather protection (if mounted in a shed) or need only be weather resistant.

5. Reliability

The converter shall be capable of meeting the specified requirements while operating in ambient-air temperatures ranging from -20° C to +50° C. The mean time between failures (MTBF) for the converter shall be no less than 25 years. Suitable redundancy shall be incorporated in the converter to achieve this reliability. The life of the converter shall exceed 20 years.

B.10 BATTERY SPECIFICATION

1. Design

The battery casing shall be constructed from high impact resistant plastic. The polarity of the terminals must be clearly and permanently marked. The battery shall include a means of checking electrolyte level without necessitating the removal of any components. The battery shall also include a means of adding distilled water to the electrolyte. Terminals must be protected from corrosion by suitable means and provisions must be provided to vent hydrogen gas produced by the batteries and catalytic caps must be provided which are capable of mitigating the safety hazard.

2. Input

The battery charging voltage will not exceed 14.4 V.

3. Output

Battery capacity, in Ah of charge, shall be given at a 100-hour discharge rate at -12.2° C (10° F). Battery output voltage must be in excess of 1.8 V/cell for lead-acid batteries and 1.08 V/cell for nickel-cadmium batteries throughout the discharge (10.8 V for a nominal 12 V battery). The batteries must be able to deliver the peak current demand, 32.2 A at -12.2° C (10° F) when the batteries are discharged to 60 percent of their rated capacity at -12.2° C (10° F). The state of charge of the batteries shall exceed 60 percent of rated capacity at all times unless atypical weather patterns cause a discharge below the aforementioned value, where one ampere - second equals one coulomb, and one volt equals one joule per coulomb.

4. Efficiency

The coulombic efficiency must exceed 90 percent.

5. Reliability

The batteries shall provide this service for at least 5 years. Battery self-discharge must not exceed 2 percent per month at 27° C (80° F). The battery must not freeze when discharged to 60 percent of its rated capacity at -23° C (-10° F).

B.11 TEST AND ACCEPTANCE

1. Description of the Tests

Upon completion of the entire electric power system installation, the system shall be cleaned and adjusted for proper operation. The system output at rated insolation and load shall be determined according to the test procedures described in section 3 below. All tests shall be performed by the installer under the supervision of the owner or his designee.

The contractor shall give the owner a minimum of seven (7) calendar days' notice, written or oral, before start of testing so that the operator or designee may visually inspect the final assemblies, witness the test, and review documentation to assess acceptability.

2. Acceptance Criteria

The acceptance test shall be used to demonstrate whether or not the system is electrically acceptable under this specification. Note that acceptance of the system does not relieve the contractor of the responsibilities implied by the various portions of this specification, nor does it relieve the contractor of the obligations imposed by the warranties. The acceptance test is considered the minimum requirement that must be met before the owner will assume responsibility for the operation of the system and before the contractor will receive final payment. Any provisions concerning service life shall be adhered to.

The system shall be considered acceptable according to this test procedure if: (1) the total output current of the system into the load and batteries exceeds 24.0 A when the insolation is 0.8 kW/m^2 and the ambient temperature is 25° C; and (2) when the maximum demand is placed upon the power system by the load, the current into the load exceeds 35.0 A at 12 V, whether the source of current is from the battery or array, when the insolation is equal to 0.8 kW/m^2, and the ambient temperature is 25° C.

Comment: The criteria were devised on the basis of a clean new array and system. It presumes the system meets the system-performance requirements 20 years from installation, thus, a 20-percent service life margin is included.

3. Remedies

If the system should be found unacceptable according to the acceptance test, modules and associated wiring shall be modified and/or added to the system by the contractor, so that the system performance is brought within the acceptance criteria.

4. Test Procedures

a. Measurement Accuracy

The insolation meter shall have a maximum error of $\pm$ 2 percent of the actual reading. Either a PV detector or a thermal pyranometer, calibrated for the angle of tilt, is acceptable. The insolation meter shall have been recently calibrated according to NBS standards. The voltages and currents shall be measured within $\pm$ 2 percent of the actual reading, using instruments that have been recently calibrated to NBS standards.

b. General Procedures

In recognition of the fact that the insolation and temperature cannot be controlled, the test can be conducted within 1.5 hours of noon at any insolation greater than 0.7 kW/m^2, as measured in the plane of the array, and any ambient temperature. Correction factors, described below, can be used to convert the measured performance to the standard conditions of 0.8 kW/m^2 at 25° C.

The acceptance test shall be conducted with all components and subsystems connected in the system. The load can be most conveniently and controllably applied with a resistance bank that provides the same voltage/current relationship as the operating load.

The voltage and current shall be measured at the output of the array (point A); at the input to the battery (point B); and at the output of the power conditioning equipment (point C). The points are illustrated in exhibit B.6. The instruments are to be attached at the points indicated on the drawings. The insolation meter is to be mounted at the same angle as the array in the plane of the array and such that the reflected and direct solar flux is the same as that which impinges on the array. The insolation shall be measured simultaneously with the currents and voltages at points A, B, and C (see exhibit B.7).

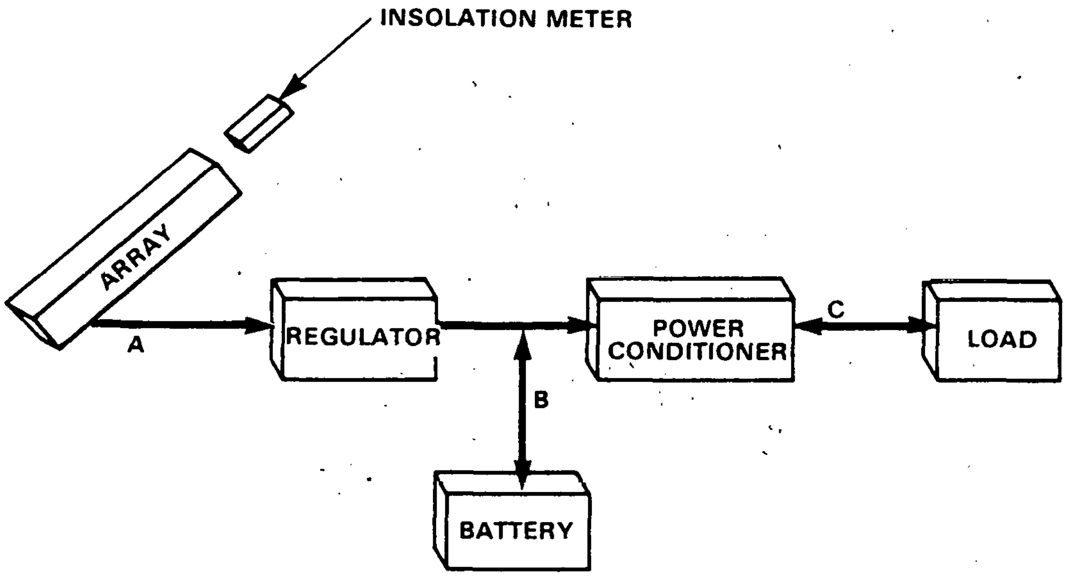


Exhibit B.6 Illustration of the Measurement Locations.

TEST AND ACCEPTANCE:

Cleaned and adjusted
Done by installer
Data corrected to 80 mW/m² and 20° C, cloudless
Includes oversizing for degradation

POWER FROM ARRAY:

Current into load plus battery: 24 A
Current into battery: less than 2.4 A

POWER INTO LOAD:

Current into load: 35 A
Current from battery: less than 10 A

ADD MODULES UNTIL SYSTEM PASSES

Exhibit B.7 Test and Acceptance Procedures.

On a cloudless day, when the insolation exceeds 0.7 kW/m^2, the system shall have the load applied to it, with the input to the load being 12 V. The currents and voltages into the load and into the batteries shall be recorded, along with the insolation and ambient temperature.

c. Test with the Power from the Array only
The first test to be conducted is the test of the system output at rated insolation and ambient temperature. During this test, the current shall flow into the load and into the battery, such that the battery is being charged. If desired (and if the system operation is not affected), the battery may be removed from the circuit during this test and a resistance load may be substituted. During this test, the current into the load shall be at least 10 times that into the batteries.

The data recorded shall be used to compute the current output at rated insolation and ambient temperature according to the following formula:

Current output at rated conditions = (measured current into the load + measured current into the battery)

$$\times \frac{0.8\ \text{kW/m}^2}{\text{measured insolation}} \times (1. + 0.004 \times (\text{ambient temperature} - 25^{\circ}\ \text{C})).$$

The current output so computed must meet the first criterion of section 2 above. If the current output does not meet this criterion, the remedies of section 3 shall be applied. If the current at the rated conditions does meet the requirements, the system shall be deemed acceptable according to the first criterion.

d. Test with Maximum Power into the Load

The second test to be conducted is the test of the maximum output capability of the system at rated insolation and temperature. On a cloudless day, when the insolation exceeds 0.7 kW/m^2, the system shall have the maximum load applied to it, with the input to the load being 12 volts. The current and voltage into both the battery and the load shall be recorded, along with the insolation and the ambient temperature. The current out of the battery shall not exceed 10 A during this test. The data recorded shall be used to compute the current output at rated insolation and ambient temperature according to the following formula:

Current output at rated conditions = measured current +(measured current - current from battery)

$$\times \frac{0.8\ \text{kW/m}^2}{\text{measured insolation}} \times (1. + 0.004 \times (\text{ambient temperature} - 25^{\circ}\ \text{C})).$$

The current output so computed must meet the second criterion of section 2 above. If the current output does not meet this criterion, the remedies of section 3 shall be applied. If the current at the rated conditions does meet the requirements, the system shall be deemed acceptable according to the second criterion.

5. Operation and Maintenance Manual

The contractor shall prepare five copies of an operations manual and five copies of a maintenance manual, which shall include troubleshooting procedures and a checklist for checkout purposes. The operation manual shall include descriptions of the systems and components, schematics, wiring diagrams, structure drawings, and instruction for taking operational data and acceptance data.

B.12 **WARRANTY**

The system shall be guaranteed by the contractor for a minimum of one (1) year from the date of final acceptance of the work by the owner in writing. The system shall be guaranteed to be free of defects of material and workmanship under the first year's operating conditions. The guarantee shall provide that any faulty materials or workmanship will be replaced or repaired, and that upon failure of this contractor to do the above, after written notice from the owner, the owner may have the work done at the expense of this contractor (see exhibit B.8).

The contractor further warrants that the electric power system delivered under this purchase order shall conform to the requirements set forth in this specification and shall meet the system specifications for a period of 10 years from the time of delivery to the site. Performance shall be measured by the same procedures as described for the acceptance test described previously in these specifications. The contractor shall repair or replace any components or subsystems that fail to meet the conditions specified herein, with an equivalent component. Components suspected of failure shall be shipped prepaid to PRC Energy Analysis Company or NASA Jet Propulsion Laboratory for inspection and then to the contractor for repair or replacement. The contractor shall return prepaid any repaired or replaced components. Components that have been returned to the contractor as defective, but which in the opinion of the contractor are not defective, shall be reported to DOE for disposition and shipping-cost determination. This warranty does not apply to modules that DOE determines to have been subjected to gross mishandling, negligence or omissions, acts of God, tampering, lightning, hail, wind loadings in excess of the local codes, and vandalism. Cosmetic degradation which exhibits no functional degradation is not covered by this 10-year warranty.

In no event shall the contractor be liable for incidental or consequential damage. This warranty is in lieu of all other warranties whether expressed, implied or statutary, including implied warranties of merchantability and fitness for a particular purpose other than that purpose set forth in the aforementioned specification.

Placed on contractor
One year for materials and workmanship
Ten years for system performance
Remedies: repair or replace to bring into specification

Exhibit B.8 Warranty.

Typical list of drawings:

1. Solar Photovoltaic Power System Location
2. Solar Photovoltaic System Site Plan
3. Grading Plan
4. Array Layout
5. Array Foundation System
6. Array Sections
7. Fence, Road and Trail Details
8. Gate Details
9. Battery Building Site Plan
10. Battery Building Plan
11. Battery Building Elevations
12. Wall Sections and Details
13. Eave Detail and Sections
14. Array Subfield Assembly
15. Subframe Assembly
16. Subframe
17. Frame
18. Module
19. Battery Building Structure
20. Utilities - Water and Sewer
21. Battery Building Plumbing Plan and Details
22. Battery Building Mechanical
23. Wiring Assembly for Subarray
24. Lightning Protection and Electrical Power
25. Battery Building Lightning Protection, Grounding and Controls
26. Battery Building Electrical
27. Generator Building Electrical
28. Door and Window Details
29. Miscellaneous Details, Sign, Etc.
30. Visitor Overlook Plan, Audio System, Etc.
31. Electrical System Schematic
32. System Wiring Diagram
33. Distributive Systems Integration
34. Interface Control

SECTION 12
PERFORMANCE CHARACTERISTICS OF TYPICAL SOLAR CELL MODULES

12.1 INTRODUCTION

A convenient manufacturing package of interconnected solar cells to produce the electrical characteristics is specified as follows:

In the package, the solar cells are:

Electrically interconnected (soldered);

Bonded onto substrate for mechanical strength; and,

Encapsulated for protection from the environment.

12.2 CONSTRUCTION/MANUFACTURING DATA

Cells used in the modules are round or half moon, 2 inch, 2-1/4 inch, 3 inch, and 4 inch.

Substrates and bonding materials are aluminum, silicone rubber, epoxy fiberglass, acrylic plexiglass, and glass.

Encapsulants are glass and silica.

12.3 TYPICAL CHARACTERISTICS

Low voltage, 5-20 volts; low-power, 5-10 watts. The electrical circuit is isolated from the chassis only with series-connected solar cells. No diode isolation or shunt diodes are used.

An assembly of solar cell modules to produce the required electrical output at the chosen field location. Solar arrays are usually designed to produce: low voltage/low power (battery charging, portable unit, remote units); intermediate voltage/intermediate power (residential applications, small commercial complexes); and, high voltage/high power (central power stations, industrial, commercial complexes).

12.4 ELECTRICAL PERFORMANCE

Important performance data for users and power conditioner designers is as follows:

Electrical characteristics.

(I-V Curve, Voltage, Current, Power)

Equivalent Circuit Parameters (Impedance is a function of resistance, capacitance, inductance, and frequency)

Impedance = square root (Resistance^2 + Reactance^2), where reactance is a function of capacitance, inductance, and frequency.

Factors degrading performance and amount of degradation.

12.4.1 ELECTRICAL CHARACTERISTICS

I-V of solar array is produced from the summation of all the solar cell I-Vs.

I-V of solar array is determined from summing the currents of all the cells at each voltage value minus the losses of the interconnects.

Assuming good matched solar cells, the I-V curve at intensity X and temp Y is shown in exhibit 12.1.

The number of modules (hence, number of solar cells connected in series-parallel) are determined by the power requirements within the following design considerations.

Allowable number of cells in series per solar array:

- Voltage breakdown;
- Safety requirements (maintenance-code);
- Reliability (loss of a single cell may result in zero output); and,
- Electromagnetic Properties.

Allowable number of cells in parallel per solar array:

- Cable IR drops and size (voltage drop = IR where R is cable resistance and I is current)
- Reliability (more cells in parallel improve reliability); and,
- Electromagnetic Properties.

Ways of meeting the design considerations:

- Divide array into sections (limit number of series-parallel solar cells);
- Arrange sections to minimize electromagnetic properties;
- Use diode isolation; and,
- Use diode shunting.

Influencing parameters are solar intensity and temperature (exhibit 12.2)

First approximation is that intensity will vary I_{sc}. and that temperature will vary V_{oc} and affect curve shape.

12.4.2 CONCLUSION

A solar array is a variable power source.

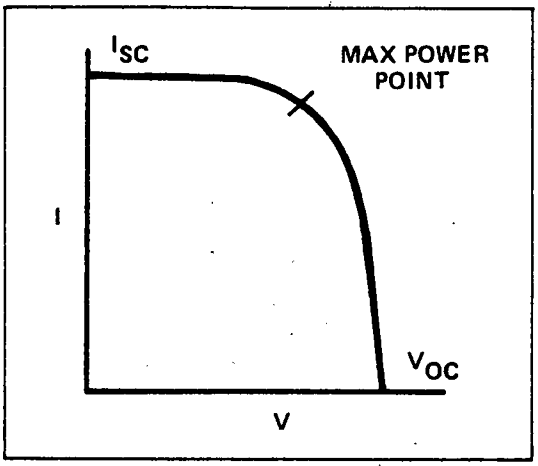


Exhibit 12.1 I-V Plot

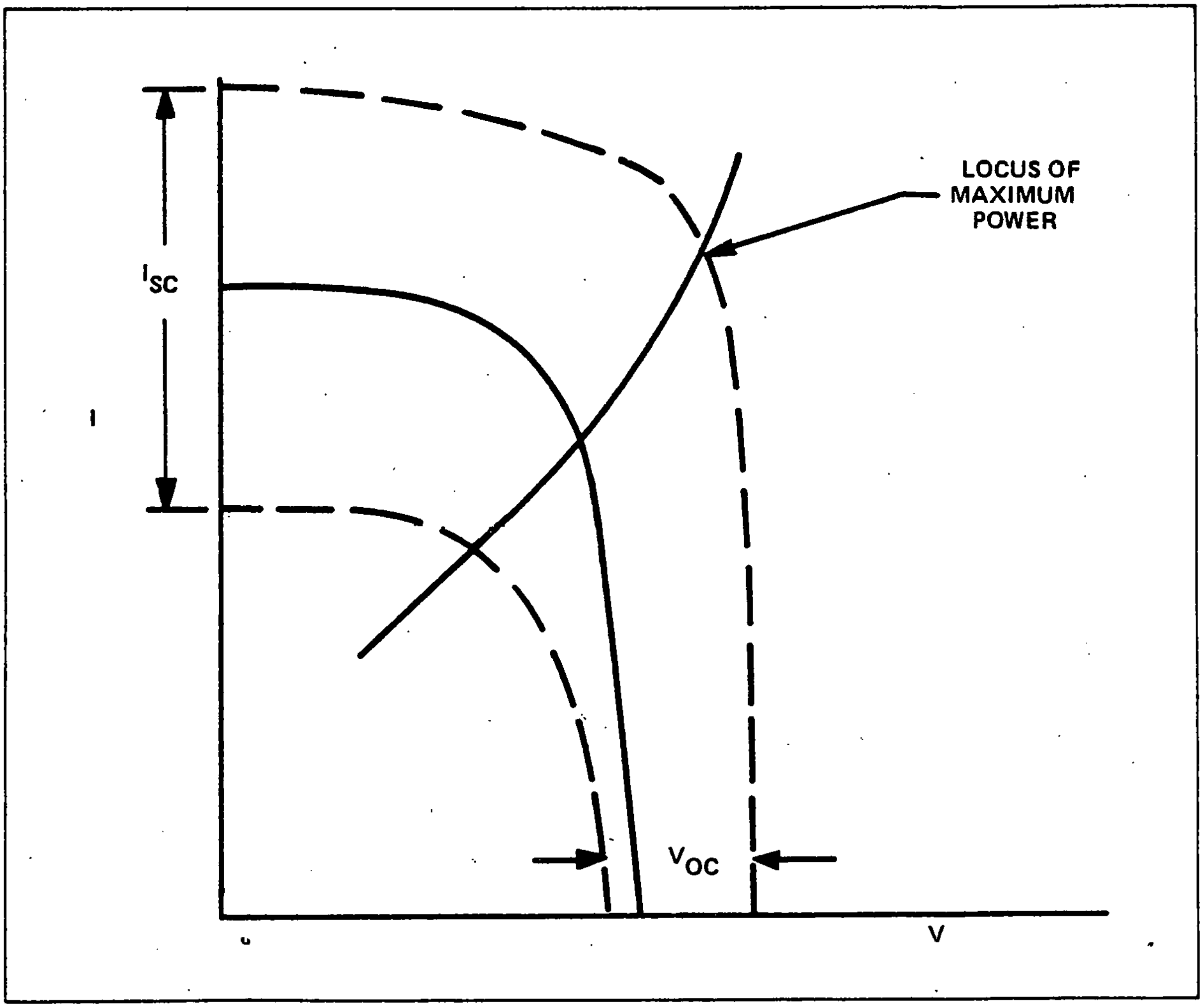


Exhibit 12.2 I-V Plot Range

12.5 GENERALLY ACCEPTED DC AND AC EQUIVALENT CIRCUITS

Generally accepted DC and AC equivalent circuits are shown in exhibit 12.3.

Using a mathematical model and measurements of solar cells, the forward-biased solar cell impedance as a function of frequency for any given DC operating point has been generated as shown in exhibit 12.4.

12.5.1 INTERESTING OBSERVATIONS

At lower cell illuminations, the impedance is higher at low frequencies. At higher illuminations, the impedance is relatively constant. The capacitance value varies with intensity. The typical impedance values are as follows:

Resistance	1.0 ohm - (small)	(Series resistance of solar cells and interconnects)
Capacitance ($C = Q/V$) (C = Capacitance, Q = Charge, V = Voltage)	8 fd/CELL - one fd is a farad of capacitance Reactance equals $-1/wc$ where $w = 2\pi f$	Multiply by number in parallel Divide by number in series C (parallel) $= C_1+C_2+C_3 \ldots$ $1/C$ (series) $= 1/C_1+1/C_2+1/C_3$

12.5.2 CONCLUSION

A solar array impedance varies with intensity, and operating point on I-V curve.

12.6 FACTORS DEGRADING PERFORMANCE

Solar array electrical characteristics may be degraded if the solar cells are shadowed, fractured or damaged.

The amount of degradation depends on the number of shadowed, fractured or damaged solar cells and the electrical circuit design (number of solar cells in series-parallel).

12.7 SHADOWED, FRACTURED, OR DAMAGED SOLAR CELLS

The amount of power dissipation of a shadowed or damaged solar cell in the solar array depends upon:

(1) The reverse voltage that can be developed across the cell by the array:
  - a) Operating Conditions (Battery Clamp)
  - b) Extreme Operating Temperatures (exhibit 12.5)

(2) The amount of current forced through the cell

(3) Reverse-bias impedance (the impedance of the illuminated solar cell is greater than that of the dark cell)

Electrical characteristics of a 2-solar cell module with one cell totally or partially shadowed and parallel connected are shown in exhibit 12.6.

12.7.1 SINGLE SOLAR CELL

The output of a shadowed single cell will degrade because the input energy is reduced to the cell and the internal energy losses in the non-illuminated cell portion are increased.

Typically, current output should be proportional to the illuminated areas:

$$I_{sc} = (I_L)(r) \quad \text{where}$$

$$r = \frac{A\ ILL.}{A\ Total} \quad A = \text{Area, and } I_L = \text{illuminated current}$$

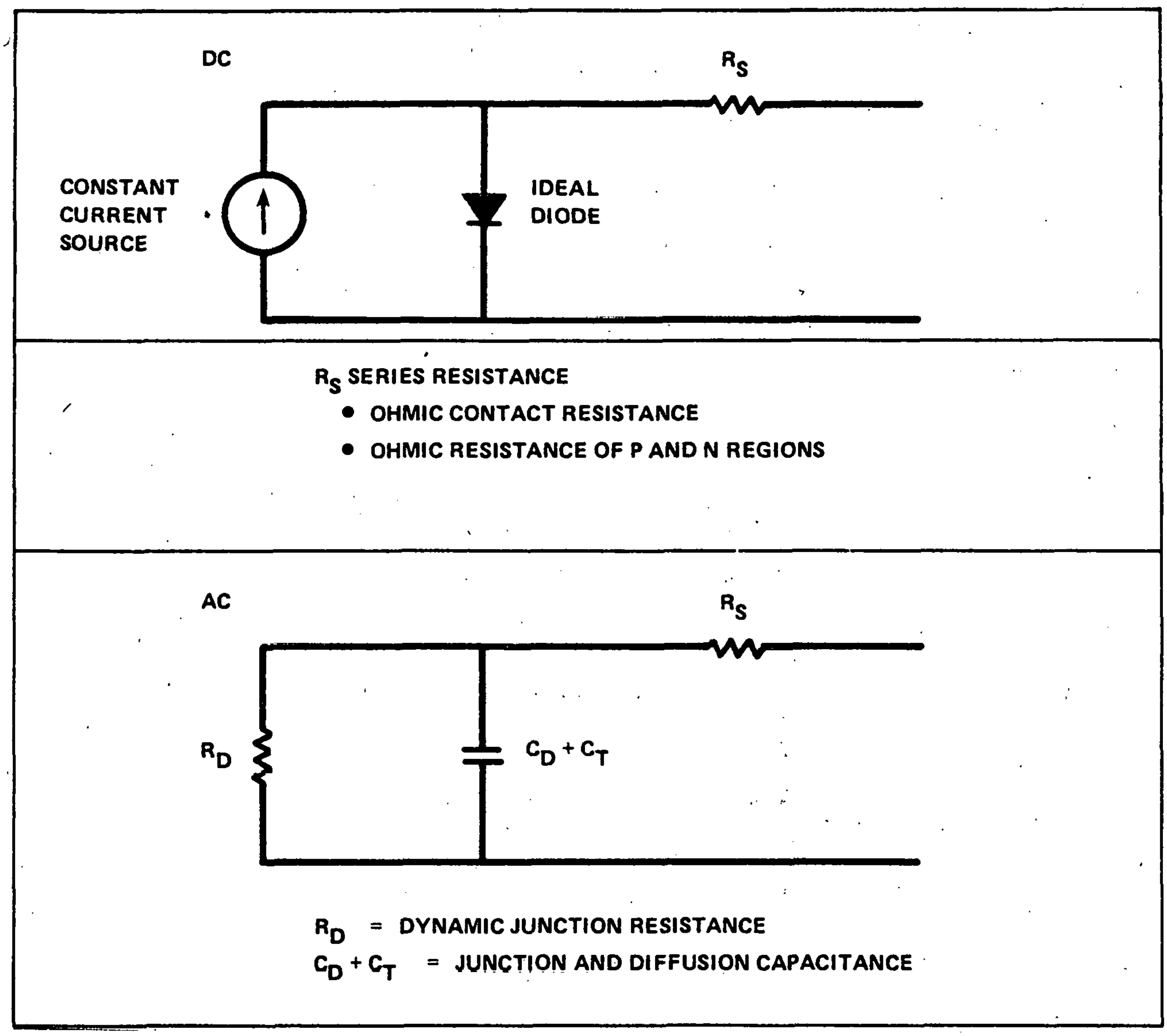


Exhibit 12.3 Generally Accepted DC and AC Equivalent Circuits

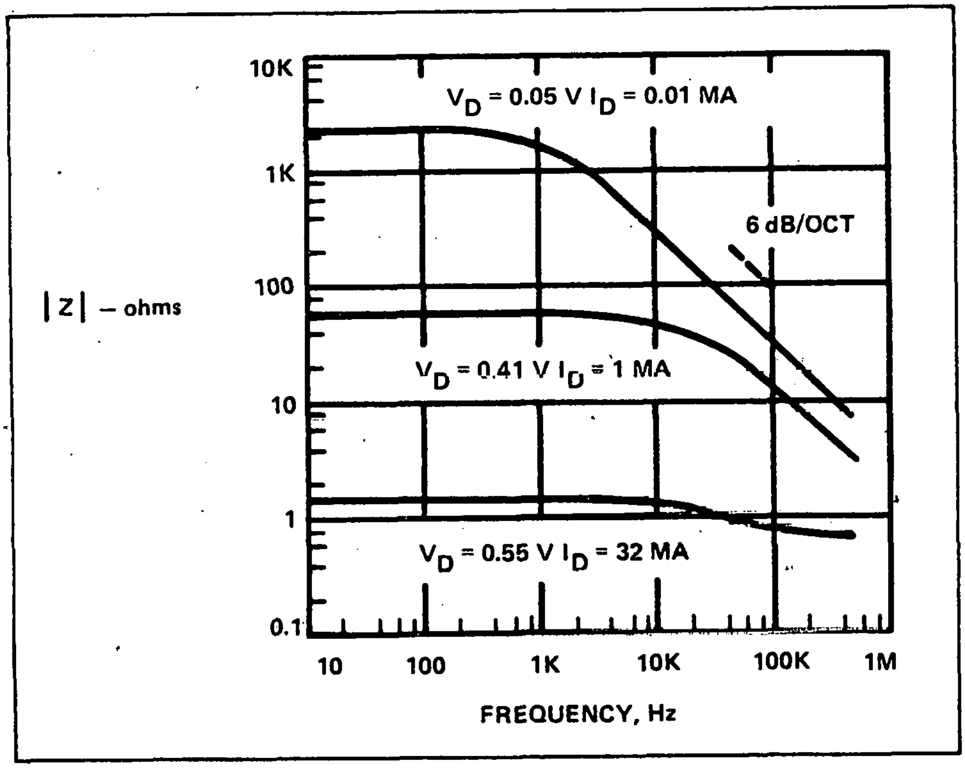


Exhibit 12.4 AC Impedance

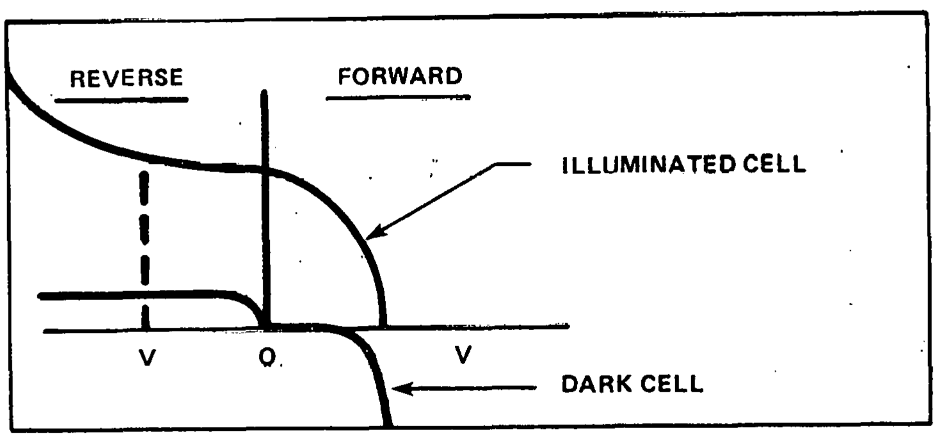


Exhibit 12.5 Reverse vs. Forward Voltage

Exhibit 12.6 Electrical Characteristics of a 2-Solar Cell Module With One Cell Totally or Partially Shadowed with Parallel-Connected Cells

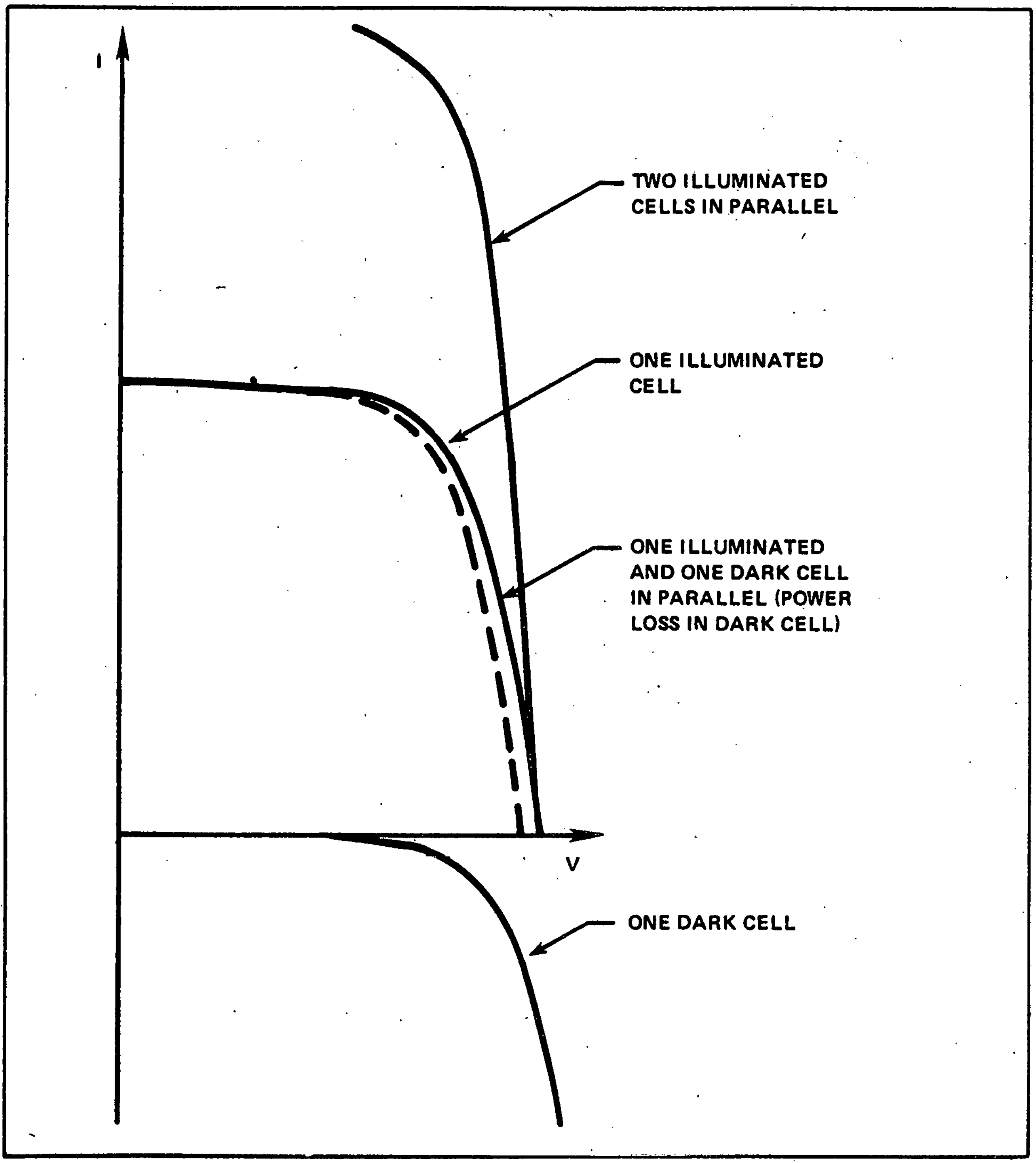
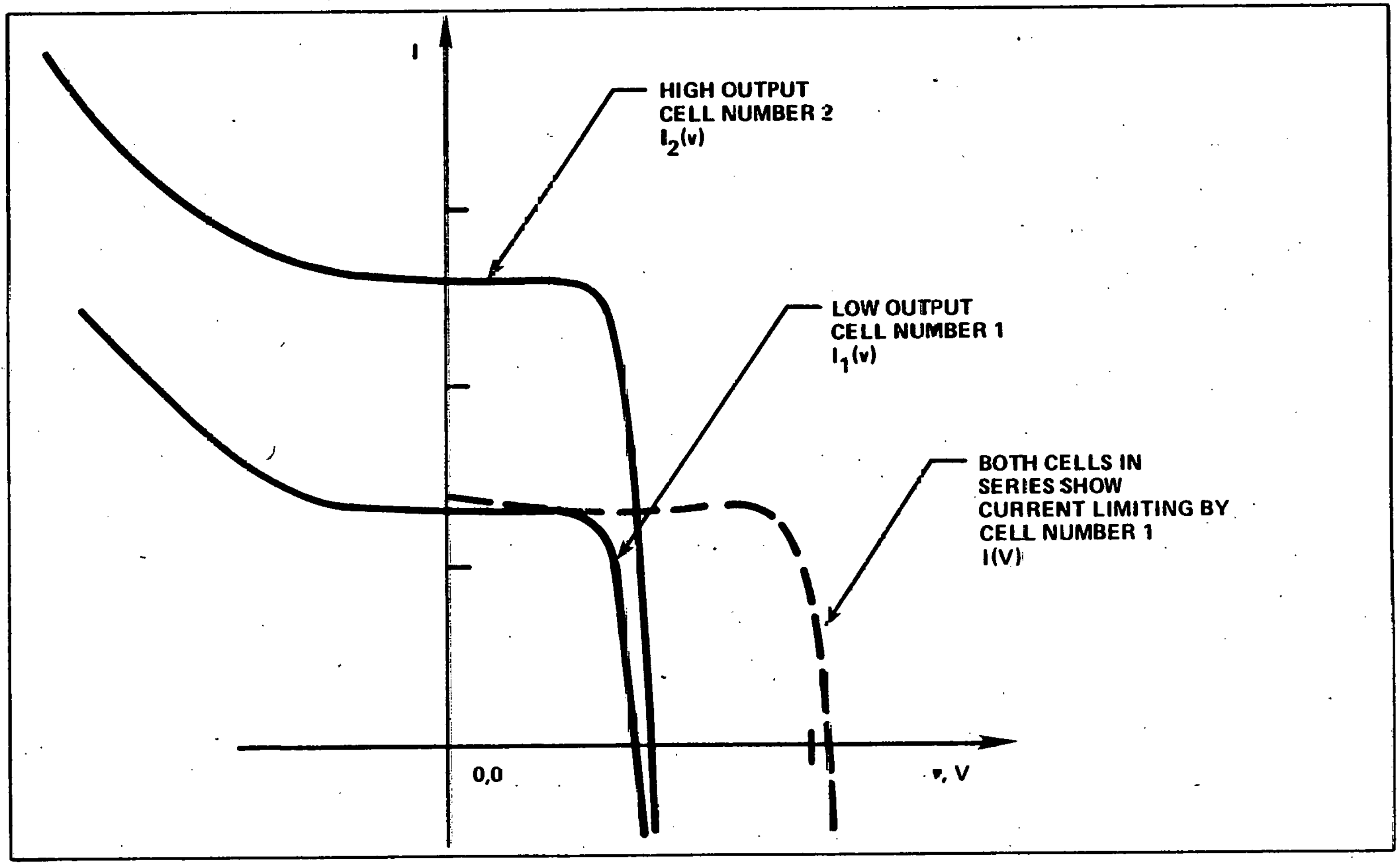


Exhibit 12.7a Series-Connected Cells (Partially Shadowed or Damaged)



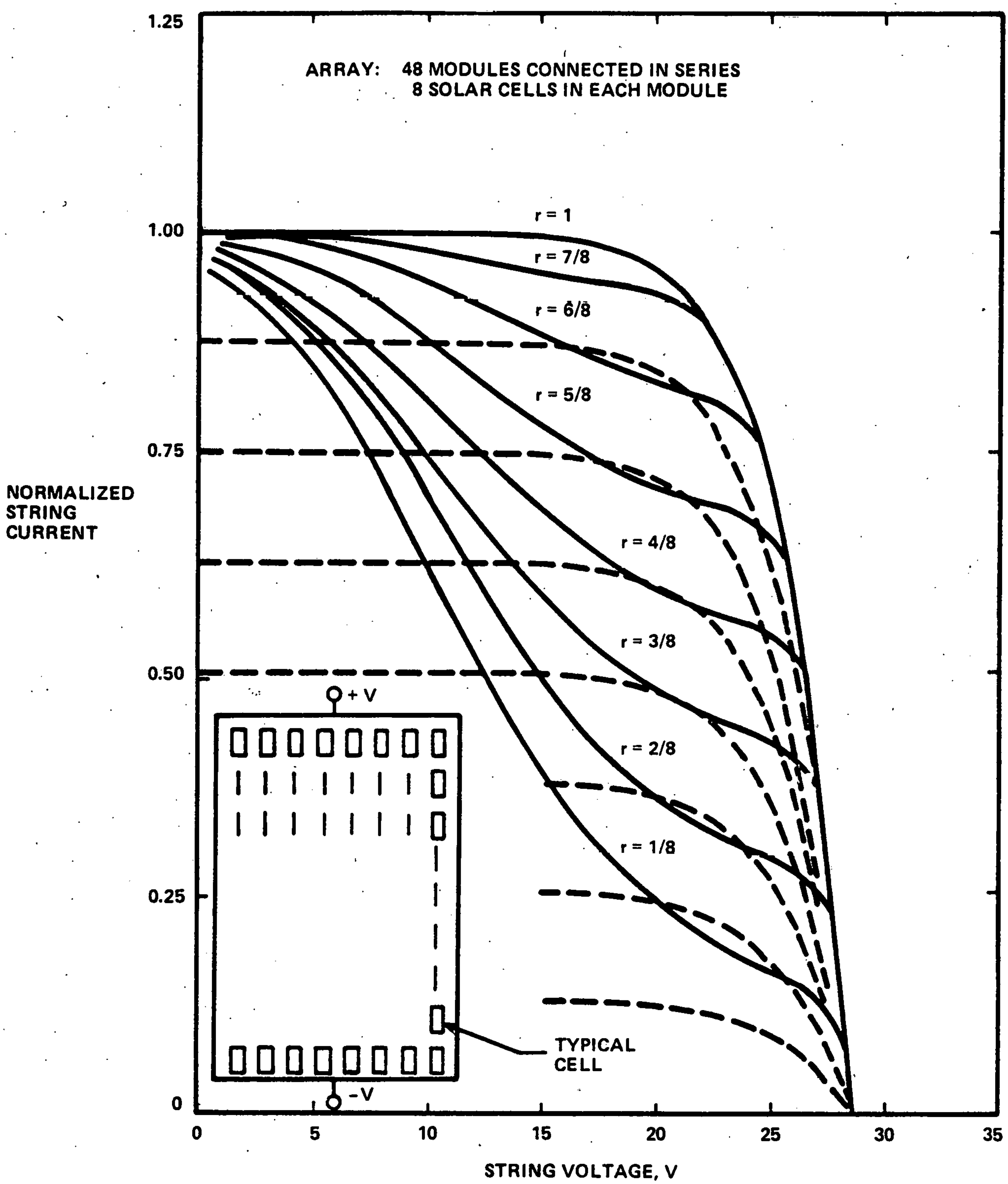


Exhibit 12.7b

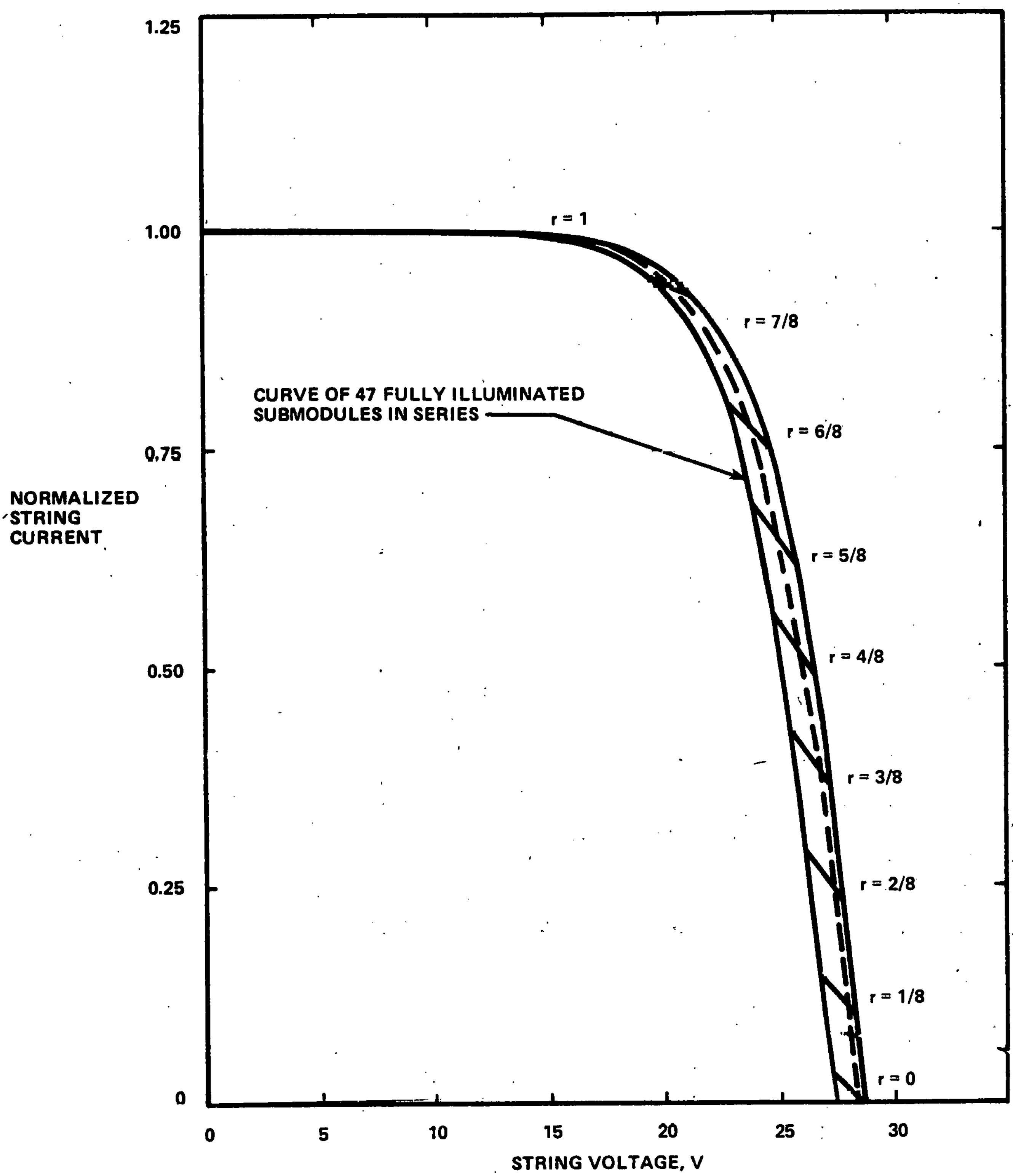


Exhibit 12.7c

Typically, the output of a fractured or damaged solar cell is reduced by the area damaged.

12.7.2 SOLAR ARRAY CIRCUIT

In a series string, the damaged solar cell restricts the current flow of the entire string; in a parallel string, the damaged cell will shunt part of the current of the good cells, as shown in Exhibit 12.7.

The damaged solar cell may become reverse-biased by the voltage developed across the cell and/or become a dissipator.

Power losses are usually higher than proportional to the loss of area, because in a series string, the shadowed cells block the current flow of the illuminated cells; and in a parallel string, the shadowed cells shunt part of the generated current of the illuminated cells. In addition, shadowed cells may become reversed-biased by the voltage developed across them; therefore, shadowed cells may become a dissipator.

12.7.3 CONCLUSIONS

The electrical characteristics of an array will be degraded depending on the number of shadowed, damaged, or fractured solar cells; the amount of cell area shadowed, fractured, or damaged; circuit configuration of the solar array (cells in series-parallel); the power dissipation developed, which will influence the operational condition of other solar cells; and the use of isolation and shunt diodes.

12.8 OPERATIONAL CONSIDERATIONS

The solar array as a power source of a system must be compatible with the system grounding requirements, safety/maintenance requirements, electromagnetic properties (conducted and radiated interference); and lightning protection (see exhibits 12.8, 12.9).

12.8.1 SAFETY/MAINTENANCE REQUIREMENTS

The solar array is an active power source during illumination. To limit the solar array voltage to 60 volts (recommended by electrical code), mechanical switches should be installed between the solar cell modules (every 60 volts). The mechanical switches can be disengaged, limiting the voltage anywhere on the solar array to 60 volts for maintenance.

12.8.2 GROUNDING REQUIREMENTS

Center-tap grounding of the solar array electrical current via a resistor is recommended. A short in the solar array can be detected via a sensing circuit consisting of two resistors and an ammeter. If a short occurs anywhere on the solar array, the current will flow through the current meter, which will be used to energize switch S_1 and remove the array from the system.

12.9 ELECTRO-MAGNETIC INTERFERENCE (CONDUCTED AND RADIATED)

12.9.1 TWO CONDITIONS

(1) Electromagnetic field generated by the electrical circuitry of the solar array as a power source.

(2) Electromagnetic field generated by the electrical circuitry of the solar array from noise fed back from the power user (power conditioners).

Exhibit 12.8 A Typical Solar Array Farm(Conceptual Design)

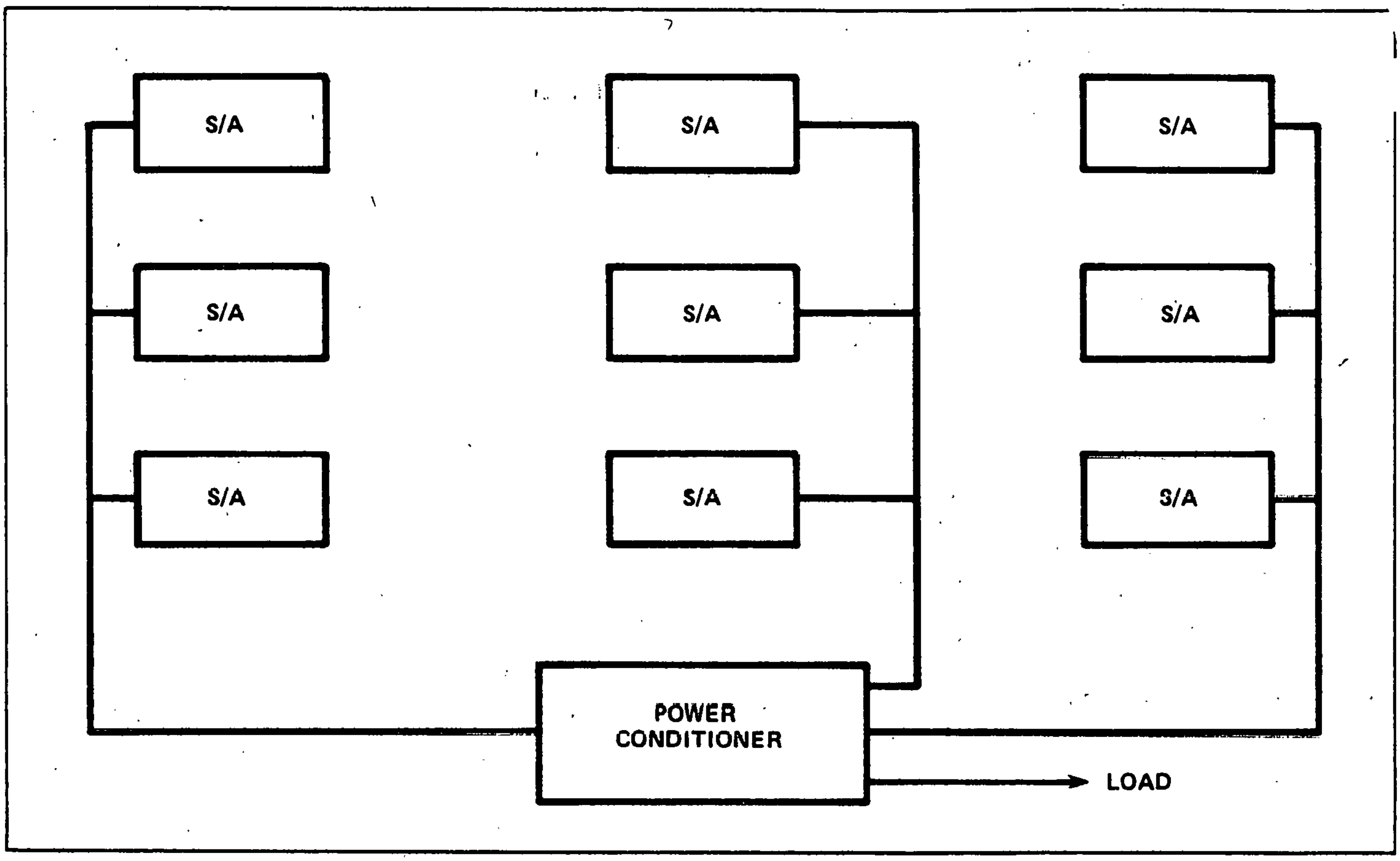
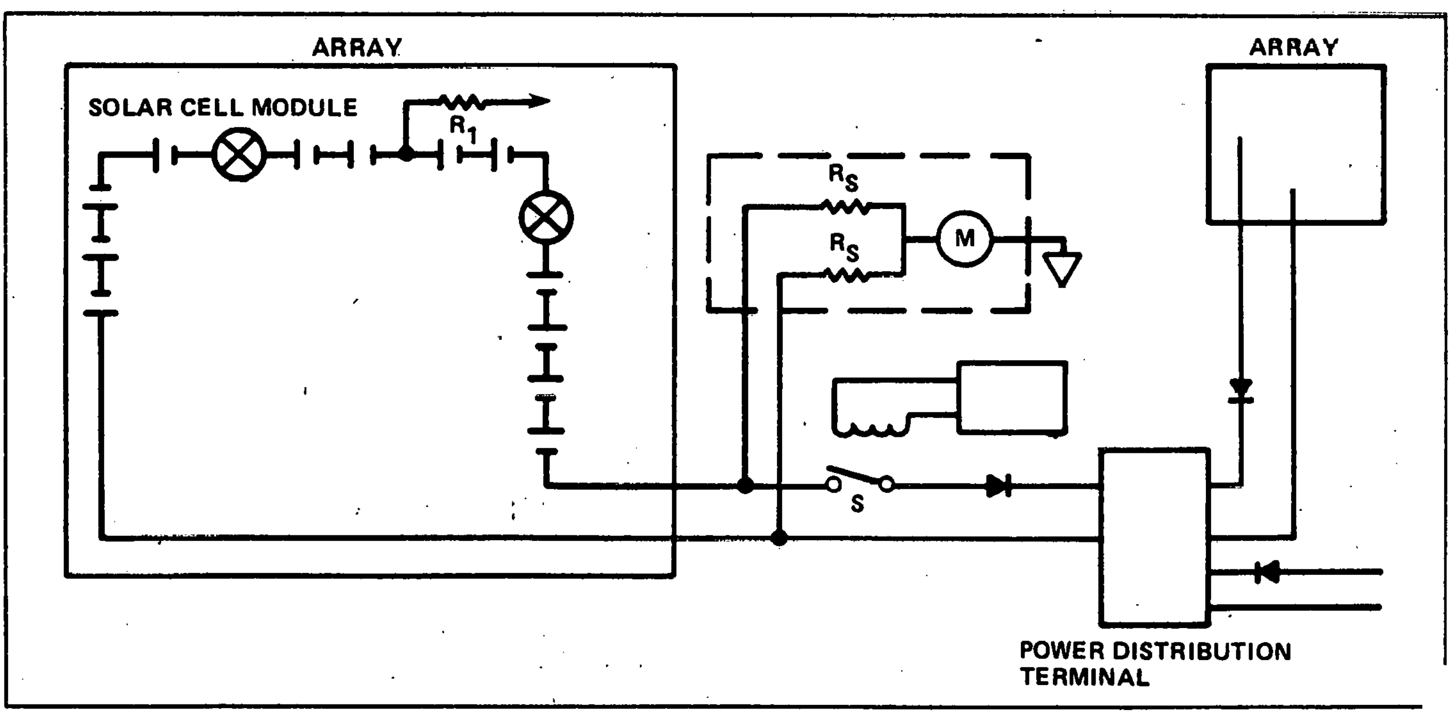


Exhibit 12.9 Terrestrial Solar Array Grounding and Safety Protection



12.9.1.1 SOLUTION

(1) The internally-generated electromagnetic interference can be limited by arranging the array section and wiring to cancel the fields.

(2) The electromagnetic interference that can be generated from the power conditioners, and input ripple fed back to the solar array circuits are unknown. A study is, therefore, recommended.

12.9.2 LIGHTNING PROTECTION

Solar arrays, like any other power generators, are exposed to the environment and are vulnerable to lightning strikes.

12.9.2.1 SOLUTION

Lightning protection in the form of lightning arresters may be required. This will depend on location and costs.

12.10 LOADING CONSIDERATIONS

There are potentially two types of loads that will be connected to the solar array; stable loads and conditionally stable loads, as shown in Exhibits 12.10 and 12.11.

Stable loads (positive resistance) are resistors, batteries, shunt regulators, and series dissipative regulators.

Conditionally stable loads (negative resistance) are low-power dissipative electronic, switching regulators.

12.11 POWER UTILIZATION CONSIDERATIONS

There are potentially two ways of obtaining power from a solar array source; directly connected to the solar array or via maximum power-point trackers, as shown in Exhibit 12.12.

12.11.1 MAXIMUM POWER POINT TRACKER

Detects and tracks maximum power of the solar array and delivers it to the load. A number of approaches are reference cells, adjustable parallel load, and impedance matching. Power loss is anticipated up to 10%.

12.11.2 OBSERVATIONS

12.11.2.1 BATTERY

Best utilization is at 12 noon.

12.11.2.2 RESISTIVE

Poor utilization at 7:30 a.m.

12.11.2.3 CONSTANT POWER

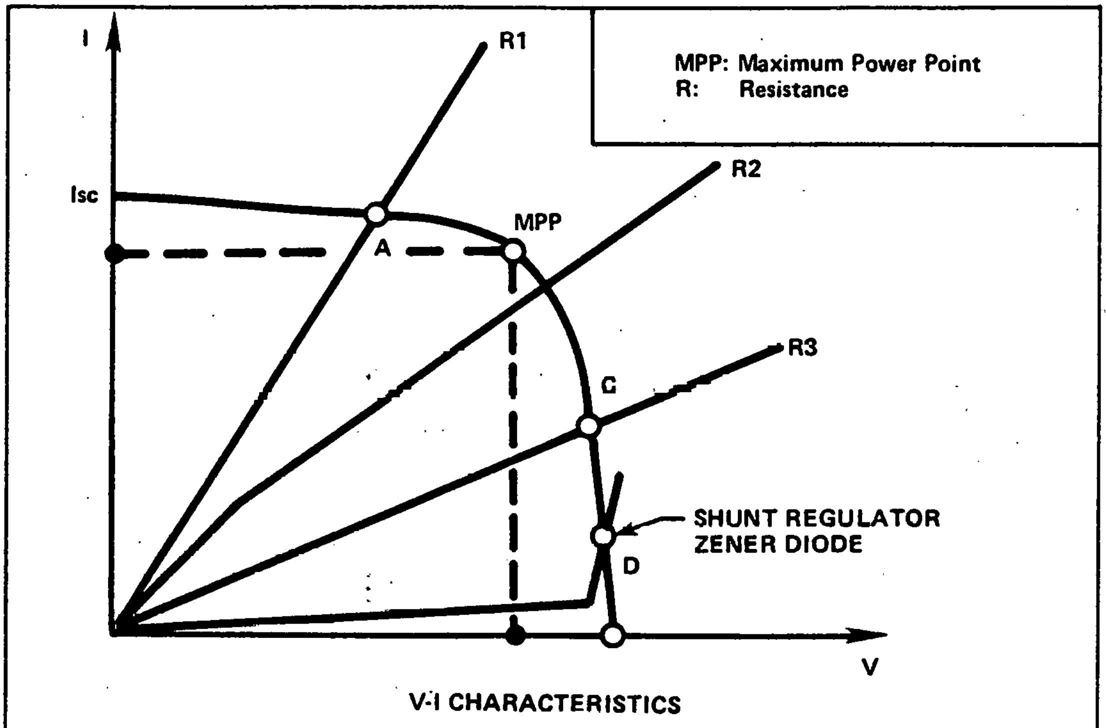
Poor utilization at 12 noon, needing other power source at 7:30 a.m.

12.12 SUMMARY OF THE KEY SOLAR ARRAY PERFORMANCE PARAMETERS AS APPLIED TO POWER CONDITIONING

The solar array is a variable power source. (The I-V characteristics: voltage, current and power vary with solar intensity and temperature.)

The impedance of the solar array is a variable parameter. (Varying with intensity.)

Exhibit 12.10 Solar Array Delivering Energy into Stable Loads



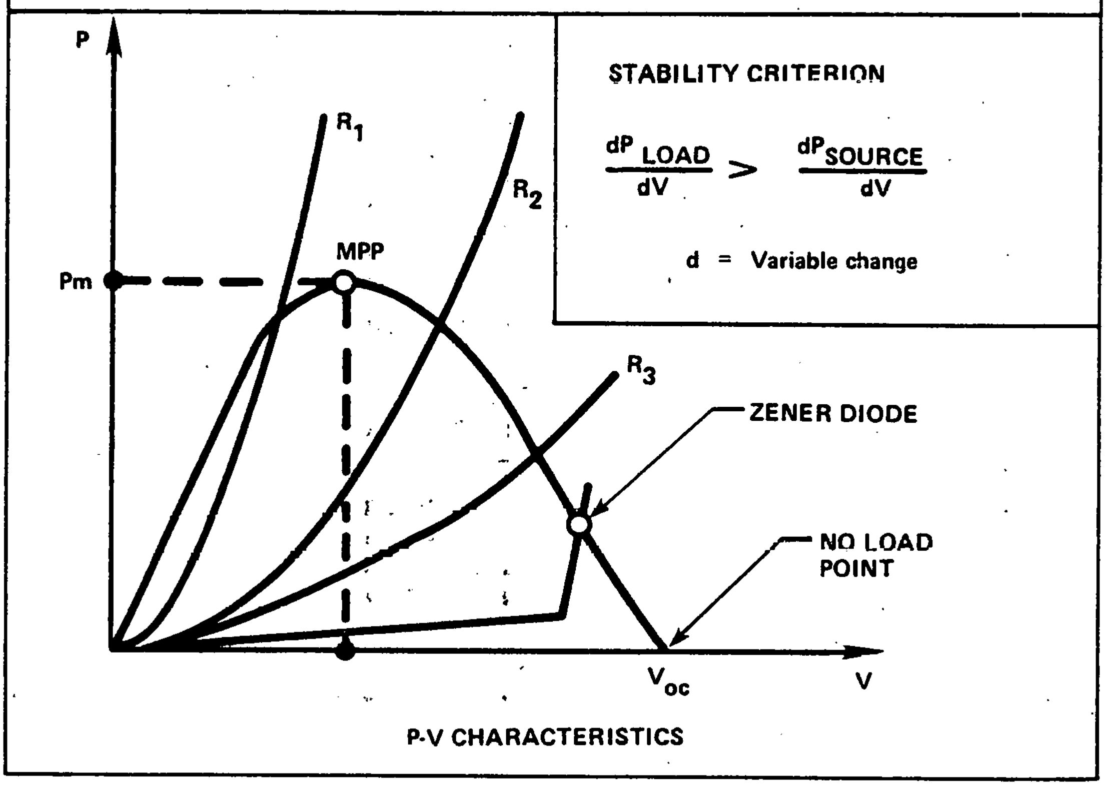


Exhibit 12.11 Solar Array Delivering Energy to a Constant Power Switching Regulator

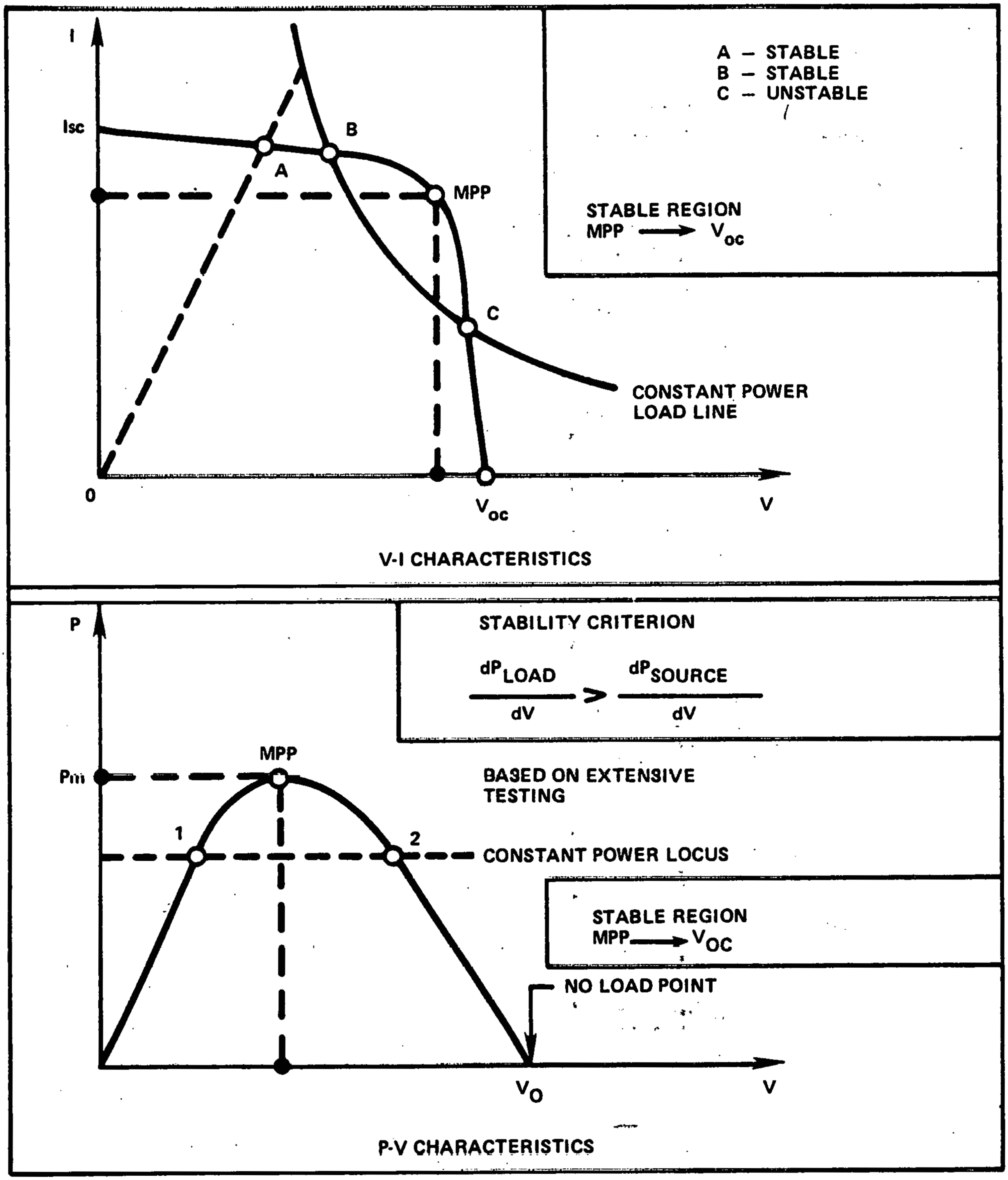
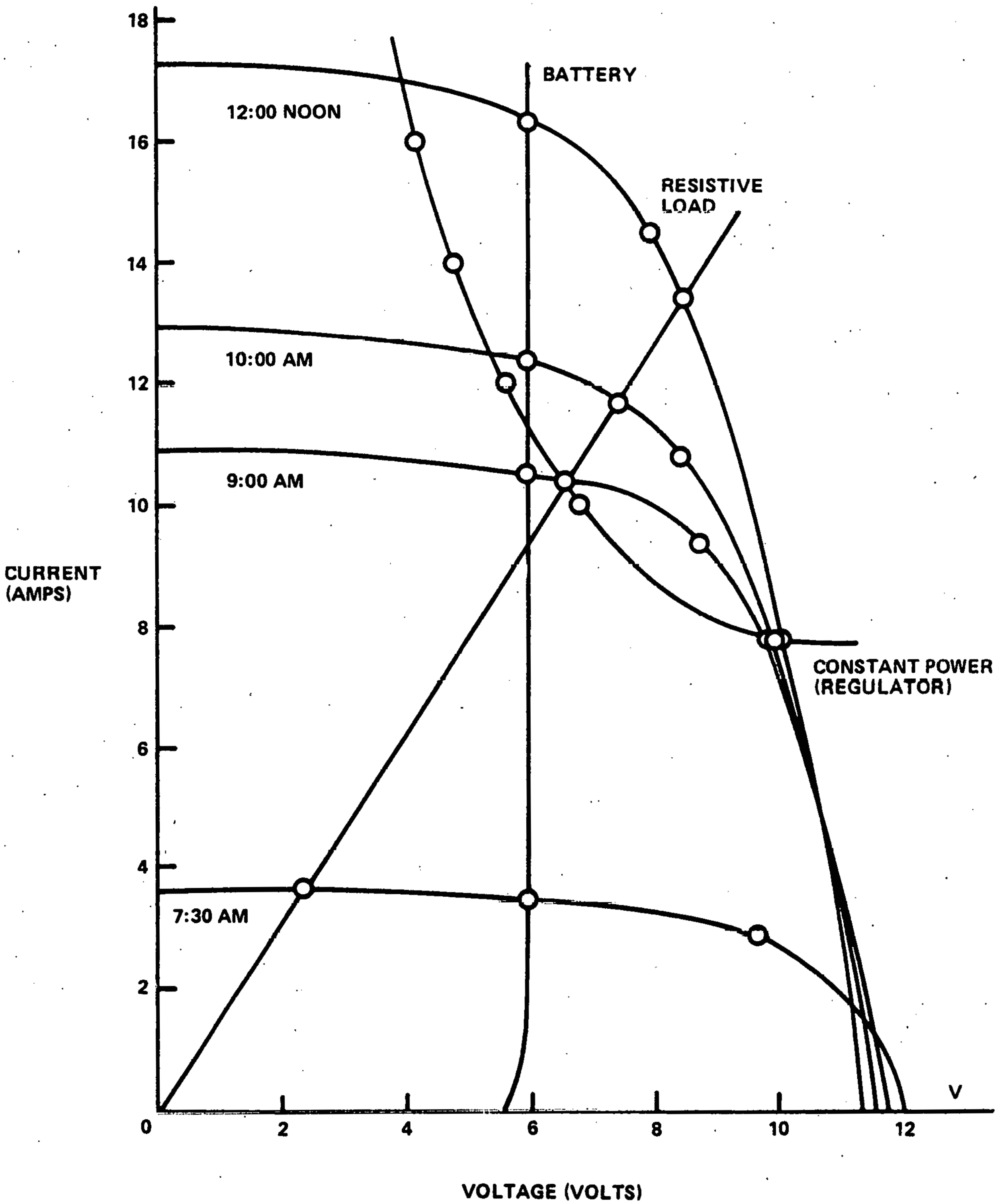


Exhibit 12.12 Power Utilization Considerations: One-Day Operation in Terrestrial Environment



Shadowed, damaged, or fractured solar cells will affect the performance characteristics of the solar array. (Using shunt and isolation diodes can reduce the effects.)

A center-tap ground of the solar array electrical circuit is recommended for grounding of the solar array power source.

With the non-dissipative (switching) regulators on, the stability criterion of the solar array must be observed.

Electromagnetic interference generated by ripple and noise feedback to the solar arrays from the power conditioners can be a serious problem.

Maximum power utilization considerations are essential inputs to the system and power conditioning designers.

Sensing networks for detecting shorts on the solar array and removing them from the power system circuit are recommended.

Lightning protection and safety-maintenance considerations (60 V voltage limit) as applied to the solar array source are worth remembering.

12.13 LIST OF REFERENCE DOCUMENTS

TITLE	AUTHOR	AVAILABILITY
SOLAR CELL ARRAY DESIGN HANDBOOK	PREPARED BY TRW FOR JPL UNDER CONTRACT	TO BE RELEASED
ELECTRICAL OUTPUT OF SHADOWED SOLAR ARRAYS	H.S. ROUSCHENBACK TRW SPACE SYSTEMS	PROCEEDINGS OF THE 7TH IEEE (1968) PHOTOVOLTAIC SPECIALIST CONFERENCE
INVESTIGATION OF SOLAR CELL INTERCONNECTION RELIABILITY OF HIGH VOLTAGE SOLAR ARRAYS, THE "HOT SPOT" PHENOMENON AND RELATED TOPICS	K.L. HANSON F.A. BLACK GENERAL ELECTRIC SPACE SYSTEMS	GE REPORT 69SD303 SEPT 69
A BRIEF STUDY OF "HOT SPOT" FAILURE MODES FOR SOLAR ARRAYS IN TERRESTRIAL ENVIRONMENTS	E.N. COSTOGUE JPL	JPL DOCUM EM-320 1976
PRELIMINARY ASSESSMENT OF SOLAR CELL SHORT CIRCUIT CURRENT MEASUREMENT IN A TERRESTRIAL ENVIRONMENT	E.N. COSTOGUE R. MUELLER JPL	JPL DOCUM EM-317 1976
A BRIEF STUDY OF LIGHTNING THEORY AND PROTECTION TECHNIQUES AND PROCEDURES AND THEIR APPLICABILITY TO TERRESTRIAL SOLAR POWER SYSTEMS, SPECIFICALLY SOLAR ARRAYS	E.N. COSTOGUE JPL	JPL DOCUM EM-330 1976

SOLAR ARRAY MAXIMUM POWER UTILIZATION APPROACHES	E.N. CASTOGUE JPL DR. Z. LINDENA EOS	PROCEEDINGS 11TH IECEC 1976
AC IMPEDANCE OF SILICON SOLAR CELLS	D.W. ZERBEL K.I. DECKER TRW SYSTEMS	PROCEEDINGS 5TH IECEC 1970

PAGES 13-1 to 13-9

WERE INTENTIONALLY

LEFT BLANK

13.2 GENERAL SYSTEM CONSIDERATIONS AND CHECKLISTS

13.2.1 SITE SURVEY CHECKLIST

1. Prior to visiting site

   a. Calculate estimates of:
   - insolation
   - peak power to load
   - daily energy to load.

   b. Make block diagram of PV system and equipment being powered:
   - array size (dimensions), including ground area required
   - battery size (dimensions)
   - power conditioner size (dimensions).

   c. Determine required load voltage (and whether AC or DC).

   d. Determine in-house and contractor responsibilities for site survey, design, review, installation, operation, and maintenance.

   e. Determine environmental restrictions (Federal, state, and local). Examples of such restrictions are: (a) no digging for cable layout, (b) no visual recognition of arrays from nature trails, (c) existing structures, special type structures, or buildings must be used.

2. At site
   (Consider all information and environmental restrictions learned in above.)

   a. Determine electrical characteristics of existing equipment to be powered by PV (voltage, current, horsepower, etc.).

   b. Check to see if the load or duty cycle can be reduced through more efficient use of, or replacement of, equipment.

   c. Check array location for:
   - shading
   - foundation/structural support
   - ground/roof area.

   d. Check possible cable locations to array and subassemblies:
   - underground or overhead.

   e. Check possible fence locations (if required).

   f. Determine the frequency of site visits that could be used to check system operation.

g. Check installation and shipping route for site accessibility.

h. Draw sketch of site layout (indicate south), including equipment, shelters, fences, cabling, sources of array shading; give dimensions. sions.

13.2.2 DESIGN CHECKLIST

A. Requirements

6 - Define power and energy requirements.

6 - Can the array output be used totally or primarily during daylight hours?

6 - Is a voltage regulator needed?

6 - Is a DC/AC inverter needed?

6 - Are batteries needed? How many and what size?

10 - Is a low-power-capacity warning system needed?

7 - Must a backup energy system be used?

10 - What instruments should be used for checkout, monitoring, and diagnosis?

B. System Design

2,4 - Determine the optimal system bus voltage, location and efficiency.

8 - Consider degradation of the array and efficiencies of the power conditioner, batteries, and connectors.

8 - Consider periodic change of the array tilt angle.

8,3 - Has array temperature been considered when computing instantaneous array output?

3 - Consider snow removal.

6 - Can the array output be stored in the end product, such as pumped water?

4 - Should the batteries be heated to retain capacity, prevent freezing, or permit recharge?

5 - Should the voltage regulator be shunt (parallel connected), partial shunt, or series?

3 - Is a diode provided to prevent battery discharge through the array?

8 - Has allowance been made for the voltage drop through the diode?

*8 - From a sketch of the I-V characteristics of the load and the I-V characteristics of the array and batteries, can a load or power-system mismatch be identified? Consider the effect of various operating temperatures and insolations, and degradation with time.

*5,8 - What control system, if any, is to be used?

3 - Can the control system be designed to make the power system more compatible with the load?

6 - Should AC or DC be used?

10,7 - Is an automatic maintenance telemetry system worthwhile?

3 - Should vandalism be considered?

7 - What provision is made for less insolation than expected?

7 - What backup power is provided (none, manual, engine, primary battery, solar-recharged emergency battery, fossil-recharged emergency battery)?

8 - What spare parts should be provided?

8 - Are the costs of spare parts included in the life cycle cost analysis?

7 - How will a malfunction be detected?

8 - Is the insolation properly computed (Aerospace/Solmet) with ground reflectance?

8 - If the energy method is used in the design computations, is the average efficiency properly chosen and justified?

*8 - If a current method is used in the design computations, is the voltage sufficient to supply the current (consider temperature and low insolation)?

8 - What is the optimal tilt, orientation, array size, and storage size?

8 - What is the projected life-cycle cost?

10 - Are sufficient permanently wired voltage meters, ammeters, and test points provided so that system performance can be readily measured?

C. Array Design

- From the manufacturer, obtain the I-V characteristics of the modules as a combined function of temperature and illumination.

2 - Incorporate a monitor panel with voltage and current meters to check current and voltage outputs of subarrays and possibly modules. Determine its location.

2 - Segment the array for maintenance safety from high voltage and temperature.

3 - Determine least-cost frame and cover that meets the safety requirements.

3 - Determine the least-cost packing density for the cells.

2,3 - Will the array or module withstand the environment (dust, sand, wind, temperature cycling, ice, freezing, high humidity, fog, snow, rain)?

2,3 - Does the design conform to the national and local codes: BOCA, UBC, SBC, ANSI, NBS, HUD, NEC, NFC, NEMA?

2,3 - Have the following structural loads been considered: weight, maintenance, snow, drifting, wind, earthquake, hail, ice, settlement, deflection, thermal cycling, humidity cycling, ground uplift, overturning, combinations of loads, and the probability of these events occurring?

3 - Can the array be mounted on an existing structure?

3 - Are soil borings required?

3 - What is the least-cost foundation?

3 - What is the least-cost structural material?

3 - Should the structure be obtained from the module manufacturer or is a special design necessary?

2 - Is lightning protection provided?

3 - Is protection from falling objects (trees, sky lab, etc.) provided?

2 - How is the maintenance person protected from high voltages and temperatures associated with a sunlit array?

2 - Are dual leads provided for each cell?

D. Power Conditioner Design

5 - Does the design conform to the national and local codes: ANSI, NBS, HUD, NEC, NFC, NEMA?

9 - How is the power conditioner protected from the weather?

5 - Is there a potential instability associated with the power conditioner?

E. Energy Storage Design

4 - Does the design conform to the national and local codes: BOCA, UBC, SBC, ANSI, NBS, HUD, NEC, NEMA, NFC?

3 - Have the following structural loads been considered in the design of the housing: weight, maintenance, snow, drifting, wind, earthquake, hail, ice, settlement, deflection, thermal cycling, humidity cycling, ground uplift, overturning, combinations of loads, and the probability of these events occurring?

4 - Should lead-acid (pure lead, lead-calcium, sealed, SLI), silver-zinc, or nickel-cadmium (pocket-plate?) batteries be used? Consider: cost, availability, depth of discharge, life (cycles, years), and capacity vs. temperature.

4 - Must the battery area be vented to prevent hydrogen buildup? (can catalytic caps or overcharge prevention be used instead)?

4 - Obtain the I-V characteristics of the batteries as a combined function of temperature and state of charge.

4 - How many batteries can be charged in series?

4 - Are the batteries arranged to minimize shorting and shocking?

4 - How rapidly will the batteries self-discharge?

8 - What is the impact of a failure of one battery? What provisions are made to offset this impact?

F. Backup Energy System Design

7 - What power source is used if photovoltaics need repair or routine maintenance?

7 - Is an automatic backup power system provided (if needed)?

7 - How is the readiness of the backup power system maintained and checked?

13.2.3 PROCUREMENT CHECKLIST

1. Procurement Determination

   a. Sole Source
   b. Competitive Bid

2. Review of Bid

   a. Review Sole Source price or low bid for compliance with all agency regulations.

   b. Award Contract.

   c. Review submittals for all equipment being furnished for project. Determine if shop drawings comply with project specifications and quantities.

   d. Review manufacturers' warranties for all equipment being furnished.

   e. Review contractors' bonding and warranties for all material and workmanship to complete project as specified.

13.2.4 INSTALLATION CHECKLIST

Tools and equipment required:

- Rachet handle
- Sockets and wrenches
- Screw driver
- Slip joint and locking pliers
- Crimping tool and terminals

- o Wire strippers
- o Diagonal cutters
- o Compass
- o Inclinometer.

1. Handling and Unpacking

   - Careful handling and unpacking of arrays is imperative. Check for shipping damage, if any and note same.

2. Mounting Structure

   - Orientation
   - Tilt angle
   - Secure
   - Grounding and lightning protections

3. Wiring

   - Proper series or parallel module interconnect
   - Polarity protection/marking
   - Proper wire guage
   - Cable runs
   - Weatherproofing
   - Disconnects installed

4. Batteries

   - Proper number and size
   - Correct interconnects
   - Secure base and housing
   - Venting
   - Safety notices
   - Safety equipment (mild basic solution for lead-acid, mild acid solution for nickel-cadmium batteries to neutralize accidental spills on personnel or equipment).

13.2.5 TEST AND ACCEPTANCE CHECKLIST

Tools and equipment required, also see installation checklist:

- o Voltage and current meters
- o Insolation meter.

1. Prior to acceptance testing insure that:

   a. System has been properly cleaned and adjusted by installer.

   b. Expected results are available (corrected to reference insolation, temperature, etc.).

   c. Test instruments (not built into system) are available and calibrated.

      i. Mechanical Check:

         - mounting in service
         - grounding connected and properly installed
         - lightning protection connected and properly installed
         - weatherproofing installed as required
         - drainage provided, if necessary
         - safety codes being followed.

      ii. Electrical Measurements and Record:

         - insolation
         - array output voltage, current
         - battery input voltage - open circuit, current - short circuit
         - output of power conditioning equipment voltage, current.

2. Documentation

   Ensure that appropriate warranty operation, maintenance, and associated documentation are supplied at time of sign-off. Representative drawings which might be provided include:

   1. Solar photovoltaic power system location
   2. Solar photovoltaic system site plan
   3. Grading plan
   4. Array layout
   5. Array foundation system
   6. Array sections
   7. Fence, road, and trail details
   8. Gate details
   9. Battery building site plan
   10. Battery building plan
   11. Battery building elevations
   12. Wall sections and details
   13. Eave detail and sections
   14. Array subfield assembly
   15. Subframe assembly
   16. Subframe
   17. Frame

18. Module
19. Battery building structure
20. Utilities--water and sewer
21. Battery building plumbing plan and details
22. Battery building mechanical
23. Wiring assembly for subarray
24. Lightning protection and electrical power
25. Battery building lightning protection, grounding and controls
26. Battery building electrical
27. Generator building electrical
28. Door and window details
29. Miscellaneous details, signs, etc.
30. Visitor overlook plan, audio systems, etc.
31. Electrical System Schematic
32. System Wiring Diagram
33. Distributive Systems Integration
34. Control Interface

13.2.6 OPERATIONS AND MAINTENANCE CHECKLIST

Equipment required:

- o Ammeter
- o Volt meter
- o Flat surface thermometer
- o Hydrometer
- o Immersion thermometer
- o Air thermometer.

1. <u>Battery Checks</u>

   a. Is the electrolyte level low? Replenish with distilled water, if necessary.

   b. Check the state of charge, correcting the hydrometer reading for the temperature of the electrolyte. The specific gravity of the electrolyte should not differ by more than 0.02 between batteries.

   c. Is the state of charge consistent with the season and recent weather conditions?

2. Array Checks

a. Is the array free from excessive dirt buildup? If not, wash with water or mild detergent solution. Do not use solvents, strong detergents, or abrasives.

b. Check the array for breakage, inspecting both the modules and their supporting structure.

c. Disconnect the array. Follow all safety precautions (shading the array from the sun will reduce the possibility of injury).

d. Remove any cover on the array. Measure the open circuit voltage across the array. Is it consistent with design values?

e. Measure the short circuit current produced by the array. Is the measurement consistent with the design value (taking into account insolation conditions)? If not, procede to the troubleshooting guide.

13.2.7 SPECIAL SAFETY CONSIDERATIONS

All photovoltaic system designs shall comply with the safety measures set forth in the various articles of the National Electrical Code that pertain to Direct Current (DC) Systems and all other articles that are pertinent.

The following are suggestions that should be incorporated into all systems above 50 V.

1. Provide black cloth or other suitable material to completely cover array to prevent power generation when maintenance is being performed on live electrical parts.

2. Any modules whose combined voltage exceeds 50 V shall be provided with a disconnecting means to facilitate maintenance and troubleshooting procedures.

3. All systems shall have total lightning protection.

4. All systems shall have a driven ground frame when system voltage exceeds 50 V.

5. All modules shall have adequately sized, factory installed junction boxes as an integral part of the individual module.

6. Each module junction box shall have insulated stand-off terminal blocks secured firmly to the junction box with metal screws or bolts.

7. All module junction boxes shall have weathertite covers and weathertite cable entrances and exits.

8. Provision for battery disconnecting means is required.

9. Provision for array disconnecting means is required when array and distribution panel are not within sight of each other.

10. All loads on system shall have adequate disconnecting means and branch circuit protection.

11. Adequate ventilation is imperative when batteries are in an enclosure.

12. Face mask, gloves, and acid neutralizing agent shall be provided to protect personnel servicing installations.

13. All batteries shall have flame arrestors.

13.3. SPECIFIC SYSTEMS DESIGNS

13.3.1 NATIONAL ELECTRICAL CODE (NEC)

13.3.1.1 SAMPLE AREAS OF CONCERN

The following sections of the NEC should be studied for compliance with the photovoltaic design being developed.

ARTICLE	TITLE
Article 90-02 (b)	Not Covered
Article 110-17	Guarding of Live Parts
Article 210-10	UNGROUNDED Conductors Tapped from Grounded Systems
Article 215-07	UNGROUNDED Conductors Tapped from Grounded Systems
Article 250-03	Direct-Current Systems
Article 250-22	Point of Connection for Direct-Current Systems
Article 250-93	Size of Direct-Current System Grounding Conductor
Article 250-131	Service of Less Than 1,000 Volts
Article 280	Lightning Arrestors
Article 480	Storage Batteries
Article 720	Circuits and Equipment Operating at Less Than 50 Volts

TYPES OF BATTERIES

ACTIVE MATERIAL	TYPE	VOLTS/CELL	W-h/lb	FEATURES
Zinc-Carbon	Primary	1.5	35	Low cost, wide variety of small sizes
Alkaline-Manganese	"	1.5	42	Good low-temperature operation, high efficiency under high-drain duty, more costly than zinc-carbon
Mercury	"	1.3-1.4	56	Excellent high-temperature performance. Relatively flat discharge characteristics
Lithium	"	2.95	150	Highest energy density, temperature range and shelf life of primary cells, contains no water
Lead Acid	Secondary	2.0	12	Least expensive and most readily available of secondary cells
Nickel Cadmium	"	1.2	16	Excellent low-temperature operation, low weight, low maintenance, higher initial cost than lead
Lithium-Sulfur	"	≈1.5	≈60	Operate at high temperature, 400° C, not currently commercially available, projected costs $25/kWh
Sodium/Sulfur	"	2.2	≈95	Operate at high temperature, ≈300° C, very low self-discharge, projected costs are $20/kWh, should be commercially available in mid 1980's
Sodium/Chloride	"	2.12	≈70	Not commercially available, projected costs $20/kWh with efficiencies of greater than 90%, operates at 200° C

WARRANTY

It is understood and agreed that the equipment offered will be free from defects in material, workmanship and performance for a period of not less than one year after acceptance by the Government. During the guarantee period all broken or defective parts not caused by misuse or accident through fault or negligency by the Government must be replaced, and all necessary equipment adjustments occasioned by such defective parts shall be made at the contractor's expense including labor, parts and transportation costs, if any.

MANUFACTURERS PHOTOVOLTAIC MODULE/ARRAY QUALITY ASSURANCE TEST DATA

Site Location: ____

Tilt Angle: ________ Regulator: BVR ________ Design Load: ____________________ AH/day

Battery: Model ________ connected _____ cells in series by ____________________ banks in parallel

THE FOLLOWING QA TEST DATA PERTAINS TO EACH PHOTOVOLTAIC MODULE AND TOTAL ARRAY.

Module Performance

Module Model: ____________ Serial #: ____________

Rated Output*: ____________ Amps at ____________ Volts

Rated Short Circuit Current*: ________________ Amps

No. of Series-Connected Solar Cells: ________________

No. of Parallel-Connected Solar Cells: ________________

Array Performance

No. of Separate Modules in Array: ________________

_____ Model _____ modules on _____ frame(s).

Rated Short Circuit Current* of frame(s): ________ amps ea

_____ Model _____ modules on _____ frame(s).

Rated Short Circuit Current* of module(s): _____ amps ea

Module Performance

MODEL ________ module

Rated Short Circuit Current*: _____ Amps

No. of Series-Connected PV Cells: _____

No. of Parallel-Connected PV Cells: _____

MODEL ________ module

Rated Short Circuit Current*: _____ Amps

No. of Series-Connected PV Cells: _____

No. of Parallel-Connected PV Cells: _____

* At 100 mW/cm^2 sunlight intensity and 28° C cell temperature.

13.3.2 PHOTOVOLTAIC WATER PUMPING SYSTEM

Project #00003 Sweetwater, Arizona Well #9T216
Latitude = 36° - 40'
Longitude = 109° - 30'

13.3.2.1 REQUIREMENTS

General - The water system must supply continuous drinking water year-round for 24 people, 50 animals, and 1 watering point. The estimated consumption will not exceed 2,400 gal/day.

The estimate was calculated in the following manner (gallons per day):

CONSUMER		EACH	TOTAL
people	=	50	1200
animals	=	12	600
watering point	=	600	600
Total daily consumption	=		2400

Well Supply - The maximum daily consumption (2,400 gallons) must be supplied by the well. Additionally, the well must retain a depth of water necessary to prevent damage to the interior of the well, which requires that the well supply the maximum daily consumption with normal depth level retention. This well will yield 20 gal/min without pump down.

Pumping - The pump driven by photovoltaics must be capable of supplying the maximum daily consumption during daylight hours year-round.

The walking beam positive displacement pump was selected for the application. The available well is 350' deep with a 2.5 in. drop pipe. The motor required is a 1 hp permanent magnet. The driver pully, mounted on the motor, will be 4 in. in diameter. The pump will pump 648 gal/hr at 35 strokes/min.

Storage - The water storage tank must be capable of storing at least 10 days of water or 24,000 gallons.

Sensing Tank Storage - The purposes of the sensors are four-fold;

- to de-activate the pump motor when the tank is at full capacity to prevent overflow and unnecessary pumping;
- to actuate the pump motor to refill the tank in its normal day-to-day mode;
- to actuate the pump motor to run all day, if necessary, to supply the demand water;
- to de-activate the pump motor in the event of an extreme low water condition that probably indicates a malfunction in the storage tank or distribution system.

- Sensor at high water mark to cut off pump motor when tank has 24,000 gallons.

- Sensor (intermediate) at 19,200 gallons remaining mark to turn on pump during daylight only.

- Sensor at lower intermediate mark (9,600 gallons remaining mark) to turn on both battery and array.

- Sensor at critical empty (4,800 gallons remaining mark) to turn off pump motor which can then only be started by manual override.

<u>Array and Battery Monitoring</u> - Electrical system monitoring is required to ensure proper operation and maintenance of all components.

o Voltage meter, located in the pump house, shall isolate and monitor voltage on each array string, which also indicates total array voltage.

o Voltage meter, located in the pump house, shall isolate and monitor voltage of each battery and total battery voltage through manual switching.

o Ammeter shall measure total array output current via manual switching or fixed wiring.

o Ammeter shall measure pump motor current via manual switching.

<u>Electrical Storage Batteries</u> - Must be capable of storing sufficient energy to drive the positive displacement pump to provide 4 days' supply of water in the event of emergencies or extreme low insolation.

13.3.2.1 LOAD STATISTICS AND COMPUTATIONS

<u>Water Requirement:</u>

6 families + 90 head of cattle

<u>4 people/family at 50 gal/person = 200 gal/day</u>

6 families = 200 x 6	=	1,200 gal/day
50 cows @ 12 gal/cow	=	600 gal/day
<u>1 watering point</u>	=	<u>600 gal/day</u>
Total gal/day	=	2,400

Existing well:

well depth	=	350' pumping depth
pump	=	walking beam positive displacement
drop pipe	=	2½"
cylinder	=	2¼'
rod	=	#1 hollow
GPM	=	10.8
GPH	=	648

<u>Motor Horsepower</u> $= \dfrac{\text{GPM} \times \text{lb/gal} \times \text{well depth (ft)}}{\text{foot pounds/horse power min.}}$

$= \dfrac{10.8 \times 8.355 \times 350}{33{,}000}$

$= .957$ hp

<u>Motor Drive for Pump</u>:

use 1 hp permanent magnet motor

1 hp motor rated at 10.6 A full load @ 90 V (1,725 rpm)

<u>Driver Pulley</u> (Diameter):

Driver Diameter $= \dfrac{\text{diameter of driver} \times \text{transmission speed} \times \text{strokes/min}}{\text{speed of driver motor}}$

D. D. $= \dfrac{6.5'' \times 30.9 \times 35}{1{,}725}$

D. D. $= \dfrac{7{,}029.75}{1{,}725}$

D. D. = 4.07" diameter (use 4" diameter pulley)

<u>Array Requirements</u> (Hours per day):

90 V motor being driven

batteries = 45 cells @ 2 V = 90 V

battery storage = 156 Ah

battery selected = 3 sets of 15QP75-5 as manufactured by C and D batteries.

Latitude = 30° - 40'

Longitude = 109° - 30'

Equivalent hr/day (with 20% safety) for south facing panel tilted at angle to latitude = 4.54 hr/day

Amp Demand for System: 2,400 gal/day ÷ 648 GPH from pump

= 3.70 hours of pumping/day

Motor demand on array = 3.70 hours of pumping x 10.6 A

= 39.22 Ah/day

Battery demand on array = 39.22 x 1.10 = 43.14 Ah

(for 90 percent efficiency of battery - multiplying factor of 1.10)

The required rated array output = 43.14 ÷ 3.7 hours of pumping

Pump Amp Draw = 11.66 Amps

<u>Array Sizing</u> (Modules)

battery charging voltage = 45 cells x 2.6 V cell

= 117 volts on array

each module = 16 V

array voltage = 117 ÷ 16.7 V/module

= 7 modules

use 7

<u>Optimizing Array Size</u> (Strings)

7 modules in series = 7 x 16.7 = 116.9 V

array voltage = 116.9 V @ 1.12 A/string

Hours of good sun for this location = 5 hr/day

array output = 43.14 Ah ÷ 5 hr = 8.63 A

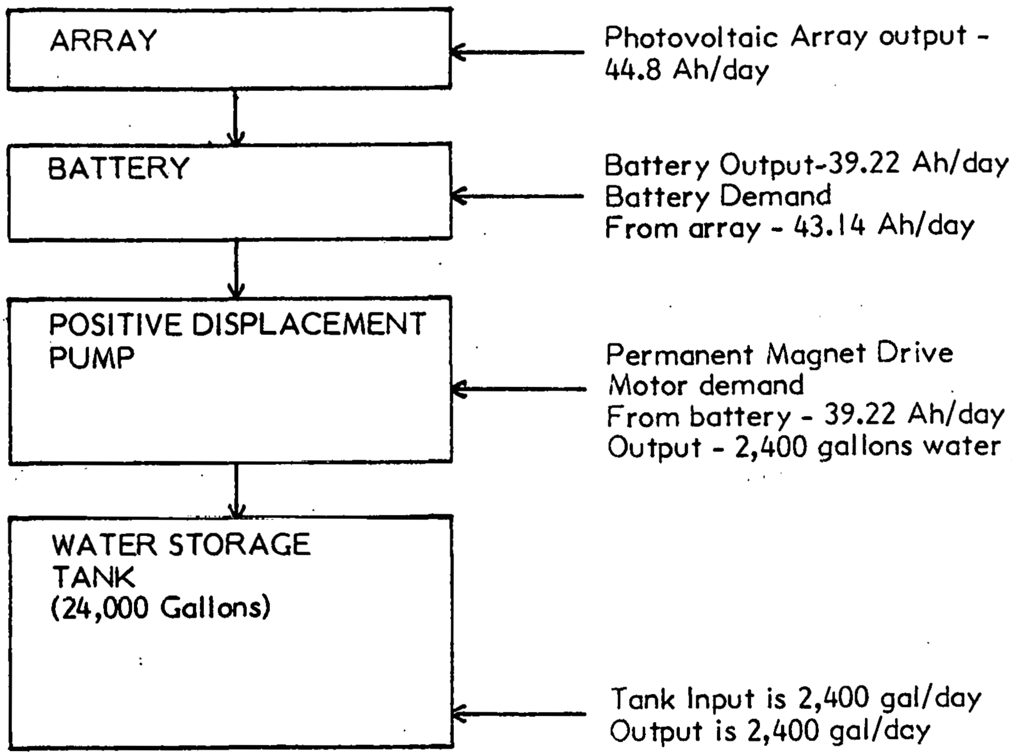
Each string of modules = 8.63 ÷ 1.12A/string

= 7.7 strings

use 8

<u>Array size (Ah/day)</u>= 7 modules series connection = 1 string at 116.9 V

8 strings of 7 modules	=	56 modules
actual array output	=	8.96 A
array output (Ah/day)	=	8.96 x 5 hr
	=	44.8 Ah/day

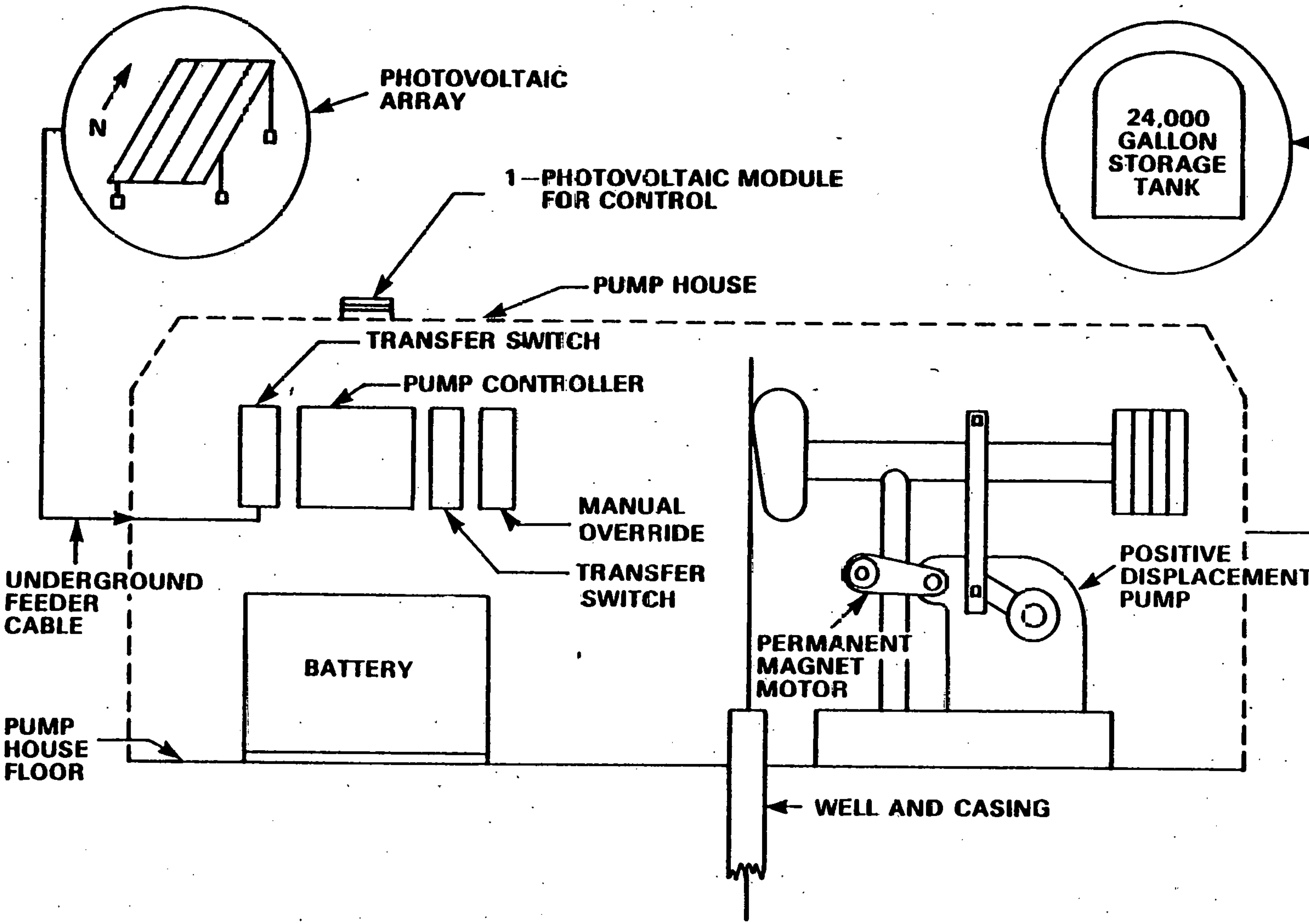


#00003

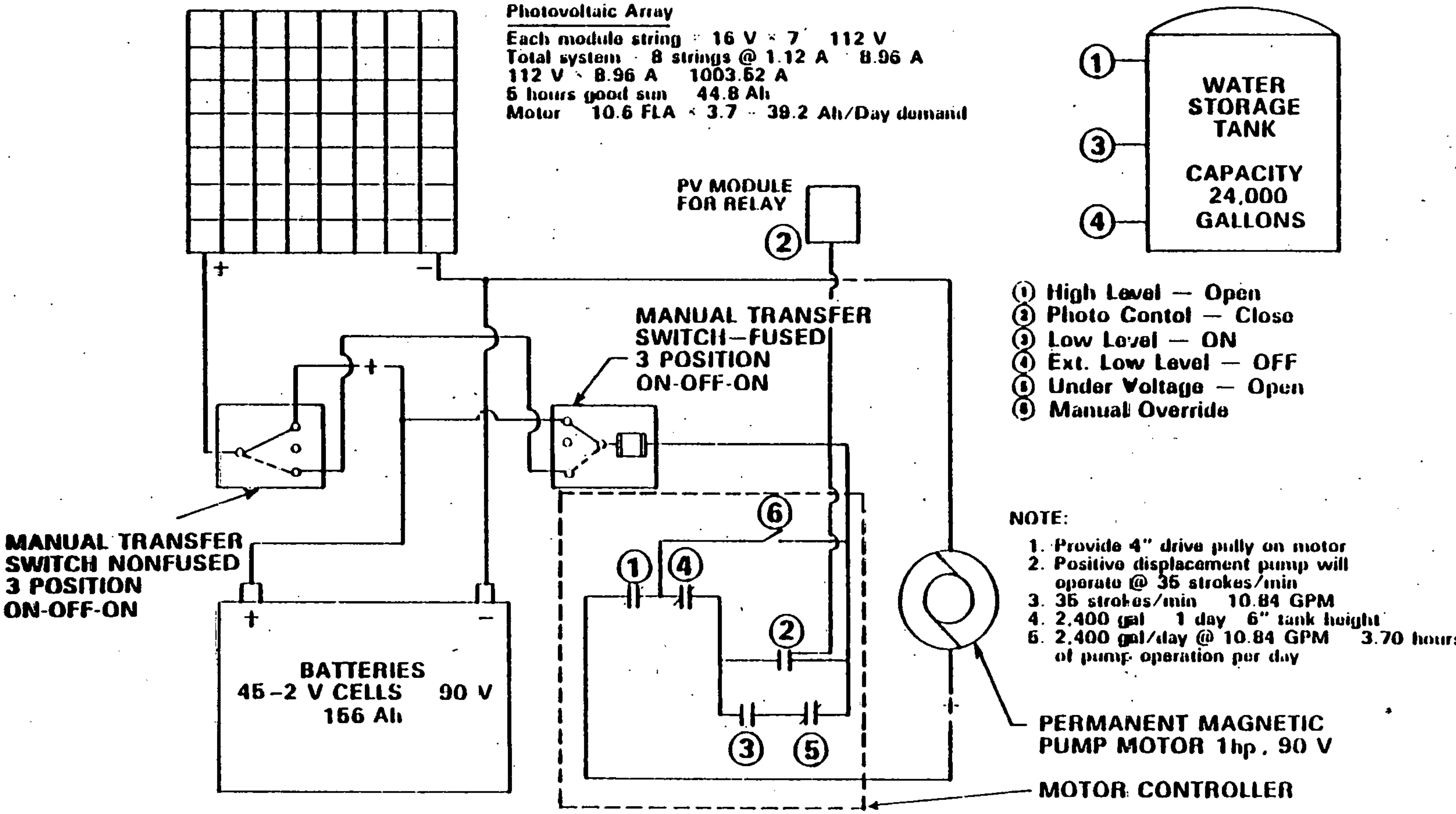
Sweetwater Well #9T216

SYSTEM FLOW

GENERAL SYSTEM LAYOUT
(Not to Scale)

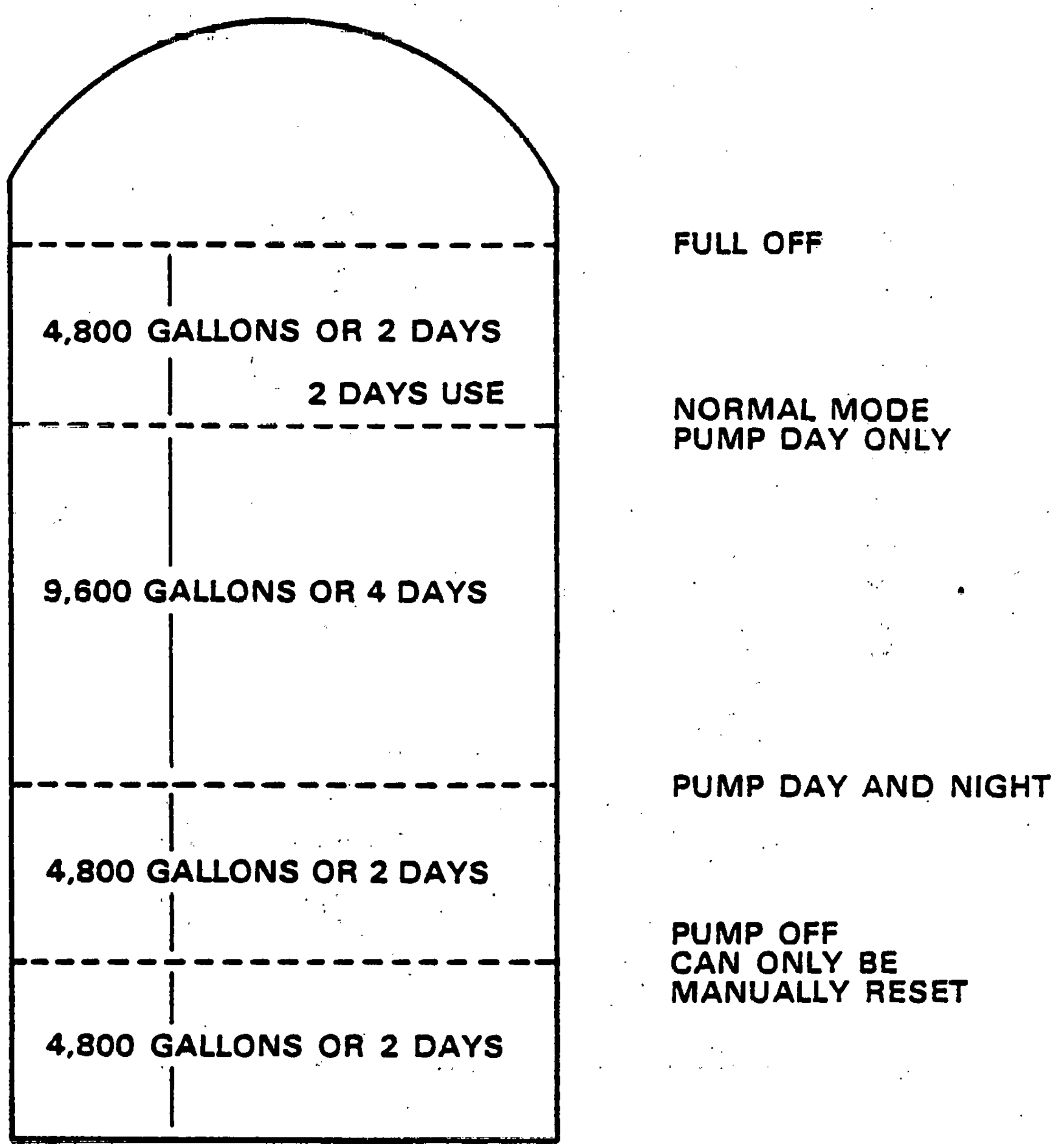


SYSTEM CONTROL

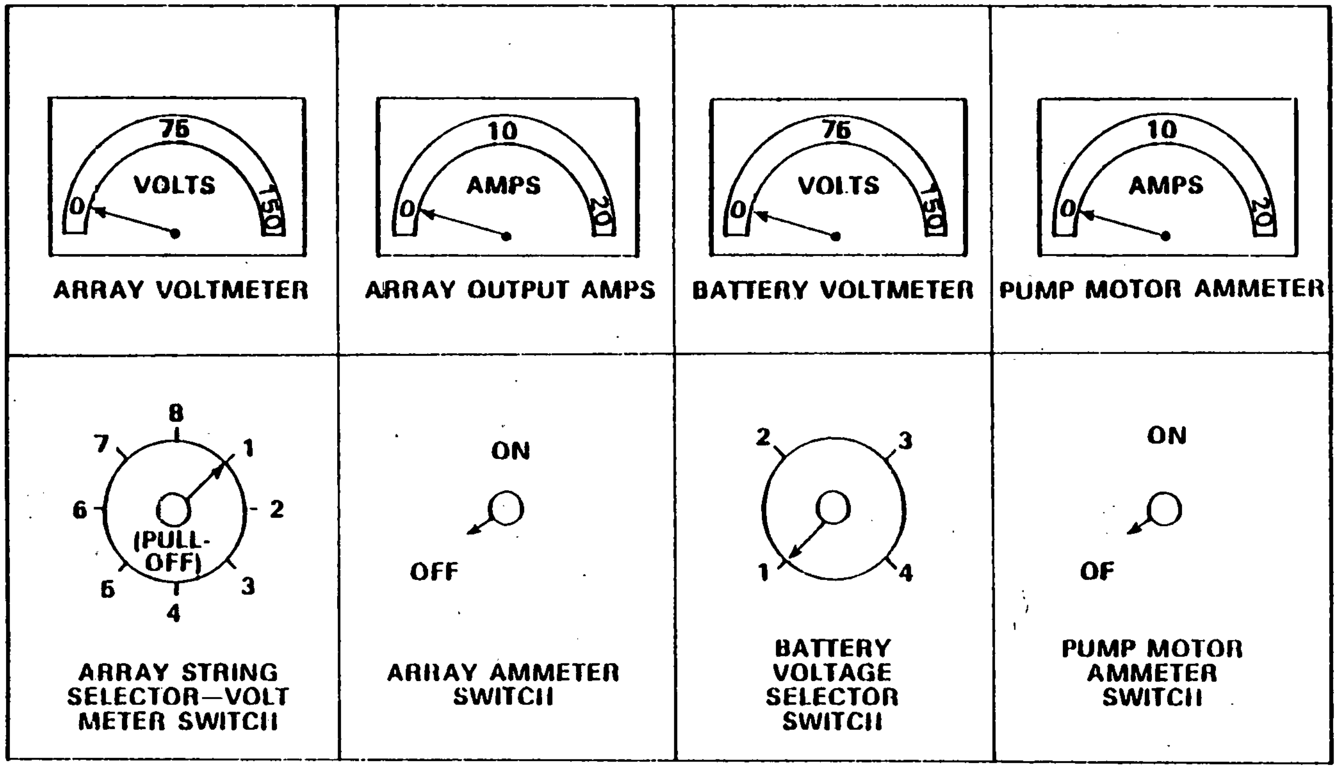


Application #00003
Well #9T26

STORAGE TANK CONTROL LEVELS



MONITOR PANEL



#00003 Sweetwater Well 9T216

13.3.3 DOMESTIC PHOTOVOLTAIC POWER

13.3.3.1 REQUIREMENTS

General

The photovoltaic system shall provide electricity for remotely located homes where hookup to utility grid lines is not economically feasible or where utility backup is necessary. The electricity supply shall be adequate to allow refrigeration of food, house lighting, television or radio or both, and cistern water pumping.

Refrigeration

A 6 cu ft refrigerator shall provide cold storage for the average family. The power requirement is as follows:

12 V DC motor, 60 W, 5 A
25 percent duty cycle (average)
Total Ah required = 24 hr x duty cycle x 5 A = 30 Ah.

Lighting

The domicile will be equipped with 4 fluorescent lights, 2-40 W and 2-10 W. A conservative estimate would be 4 hours of usage per night. The charge requirement for lighting is as follows:

$$2 \times 40\ W \div 12\ V \times 4\ hr + 2 \times 10\ W \div 12\ V \times 4\ hr = 33.33\ Ah.$$

Television

Television usage is estimated at approximately 4 hr/day. Charge requirements = 4 hr x 24 W ÷ 12 V = 8.0 Ah.

Cistern Water Pump

A permanent magnet, positive displacement water pump shall be used, which draws 5 A under full load. The pump shall fill a pressurized tank, which shall then supply the domicile's water needs. A positive displacement pump was chosen over a centrifigal or screw type pump due to its higher efficiency (80 percent versus ≈ 50 to 35 percent). An average family requires 200 gal/day; the pump provides 9.4 gal/min. Charge requirements = 200 gal ÷ 9.4 gal/min ÷ 60 min/hr x 6 A = 6.38 Ah.

Food Preparation

If cooking cannot be done by an alternative method (i.e., LNG, wood, etc.,) a microwave oven can be incorporated into the domicile's design. This unit will increase the electrical power needs by almost 65 percent and, as a result, increase the cost of the PV power system by several thousand dollars (33 percent). Incorporating a microwave oven into the house design (option 2) is only recommended if there is no reasonable alternative heat source available for food preparation.

Microwave Oven (Option 2)

The microwave oven is equipped with its own inverter and transformer circuits. The size of the microwave oven used does not appreciably alter the energy required as a larger oven would be on a proportionately shorter time (i.e., it is the number of Btu's absorbed by the food that is important). A 725 W unit, 60.5 A at 12 V, if used for all three meals, would be used approximately 50 min/day. 50 min/day ÷ 60 min/hr x 60.5 A = 50.4 Ah/day.

Total Charge Requirements Per Day (Average)

Option 1

Refrigerator	=	30.0 Ah/day
Lighting	=	33.3 Ah/day
Television	=	8.0 Ah/day
Cistern Pump	=	6.4 Ah/day
Total	=	77.7 Ah/day

Option 2

Refrigerator	=	30.0 Ah/day
Lighting	=	33.3 Ah/day
Television	=	8.0 Ah/day
Cistern Pump	=	6.4 Ah/day
Microwave	=	50.4 Ah/day
Total	=	128.1 Ah/day

System Component Sizing

Option 1

Array - 220 Wp - 13.75 Ap 11-12 V panels

Battery 680 Ah @ 12 V

Volt regulator - yes, to prevent excessive outgassing due to overcharge

Option 2

Array - 340 Wp - 21.25 Ap

17 to 12 Volt panels

Battery = 1,121 Ah @ 12 V

Volt regulator - yes, to prevent excessive outgassing due to overcharge

Control of PV Power System

- o A manual switch shall be provided to isolate the load for maintenance purposes.
- o The system shall be fused to prevent battery drain if a short circuit develops. Standard buss (car fuses) fuses are acceptable and readily available for this purpose.

Array and Battery Monitoring

- o Voltage meter with switches located in the battery storage box that will isolate and monitor either the battery or array voltage.
- o Ammeter with switches located in the battery storage box that will monitor either the total array output current or the total load current.

Electrical Storage

- o Shall be provided by lead-acid batteries that exhibit low self-discharge.
- o Venting or recombiner caps shall be provided to prevent dangerous hydrogen gas buildup.
- o Sufficient storage shall be provided to prevent dangerous hydrogen gas buildup.
- o Battery shall undergo a maximum 60 percent depth of discharge.

Safety Considerations

Disconnect switches between the panels shall not be required due to the low (i.e., 12 V) system voltage. An opaque cover shall be available for use during maintenance to cover the array, thereby effectively turning the array "off." Due to the location of the battery storage in a residence, special care must be taken to ensure proper venting of gases and protection of the battery terminals against accidental shorting.

13.3.3.2 SUMMARY OF DOMICILE DESIGN

1. Schematic of Design
2. Computation of Load-Option 1 (no microwave)
3. Total Daily Requirement - Option 1

4. Initial Array Sizing - Option I

5. Month-by-Month Calculations - Option I: Based on Exhibit I

   Exhibit I.A - 11 panels (winter months used for sizing) — 50° Tilt
   Exhibit I.B - 10 panels (yearly average used) — 50° Tilt
   Exhibit I.C - 10 panels — 40° Tilt

6. Choice of Exhibit I.A, Exhibit I.B, or Exhibit I.C (which design is optimal?)

7. State of Charge Batteries - Option I

8. Option II - Microwave Oven Load Computation

9. Initial Array Sizing - Option 2

10. Month-by-Month Calculations:

    Exhibit 2.A - 17 panels 50° Tilt
    Exhibit 2.B - 16 panels 50° Tilt

11. Battery State of Charge - Option 2

12. Estimated Costs of Installed Systems - Options I and 2

13.3.3.3 LOAD COMPUTATION

Refrigeration 6 ft^3

12 V DC Motor, 60 W, 5 A — 25% duty cycle
5 A x 24 hr ÷ 4 = 30 Ah

Lighting - 4 Fl lights, 4 hr/day — 2-40 W 12 V, 3.33 A; 2-10 W 12 V, 0.83 A

2 x 3.33 A x 4 hr + 2 x 0.83 A x 4 hr = 33.33 Ah

TV - 4 hr/day — 24 W, 12 V, 2 A

2 A x 4 hr = 8 Ah

Cistern Water Pump - 12 V, 72 W, 6 A

Pump delivers 9.4 gal/min

Need 200 gal/day

200 gal/day ÷ 9.4 gal/min ÷ 60 min/hr x 6 A = 6.38 Ah

DAILY LOAD - OPTION I (No microwave)

Refrigeration	30.0 Ah
Lighting	33.3 Ah
TV	8.0 Ah
Water Pump	6.4 Ah
Total	77.7 Ah/Day

Initial Array Size (First Estimate)

$$\text{A peak} = \frac{\text{Average Daily Load (Ah)*}}{\text{Average Monthly Equivalent Hours Peak Sun (Winter Average)}}$$

$$\text{Ap} = \frac{77.7}{\frac{(6.08 + 6.03 + 6.2)}{3}} = 12.73 \text{ Ap Total}$$

Panel chosen produces 1.25 A at 60° C under an insolation of 100 mW/cm^2

$$\text{Panels needed} = \frac{12.73}{1.25} = 10.18 \text{ or } 11 \text{ panels}$$

If a yearly insolation average is used, the initial estimate would be:

$$\text{Ap} = \frac{77.7}{6.7} = 11.57 \text{ A}$$

$$\text{Panels needed} = \frac{11.57}{1.25} = 9.26 \text{ or } 10 \text{ panels.}$$

*Provision for degradation is not included. The calculations that follow can be used for a trade-off study regarding adding more storage capability vs. adding more modules or, if necessary, management interventions in critical design areas.

Exhibit I

COMPUTATION OF SYSTEM PERFORMANCE - 55° Tilt, 35° Latitude

1. Array size (Ah) = 13.75 p (at 1.85 at 60° C, 100 mW/cm²)

Panels required = $\frac{12.73}{1.25}$ = 10.18

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m² - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 4 x Col.A	From Load Analysis	Col.C-Col.B (Enter 0.0 if Col.B=Col.C)
JAN	6.25	85.9	77.7	0
FEB	6.35	87.3	77.7	0
MAR	6.67	91.7	77.7	0
APR	6.30	86.6	77.7	0
MAY	6.17	84.8	77.7	0
JUN	6.46	88.8	77.7	0
JUL	6.04	83.05	77.7	0
AUG	5.99	82.36	77.7	0
SEP	6.48	89.1	77.7	0
OCT	6.55	90.1	77.7	0
NOV	6.10	83.9	77.7	0
DEC	6.11	84.01	77.7	0
2. Total				0.0

3. Long term storage required = $\frac{\text{days}}{\text{month}}$ x Line 2 (Ah) = 0.0

4. Total storage = (Line 3) + (Short term storage) 7 days x (maximum value in Col. C)
= 544 Ah

Exhibit I.A

COMPUTATION OF SYSTEM PERFORMANCE - 50° Tilt

1. Array size (Ap) = 13.75 Ap

1.25 A/panel @ 60° C @ 100 mW/cm²

$\frac{12.73}{1.73}$ = 10.18 panels

use 11 panels = 13.75 A

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m^2 - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 1 x Col.A	From Load Analysis	Col.C-Col.B x $\frac{days}{month}$ (Enter 0.0 if Col.B=Col.C)
JAN	6.2	85.3	77.7	0
FEB	6.37	87.6	77.7	0
MAR	6.38	87.7	77.7	0
APR	6.62	91.0	77.7	0
MAY	6.57	90.3	77.7	0
JUN	6.91	95.0	77.7	0
JUL	6.45	88.7	77.7	0
AUG	6.35	87.3	77.7	0
SEP	6.73	92.5	77.7	0
OCT	6.63	91.2	77.7	0
NOV	6.08	83.6	77.7	0
DEC	6.03	82.91	77.7	0
				0.0

2. Long term storage required = Sum Col. D = 0.0

3. Total storage = (Line 2) + (Short term storage) 7 days x (maximum value in Col. C)
= 544 Ah

Exhibit I.B

COMPUTATION OF SYSTEM PERFORMANCE - 50° Tilt

1. Array size (Ap) = 12.5 Ap

10 panels
1.25 A/panel @60° C @ 100 mW/cm²

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m² - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 1 x Col.A	From Load Analysis	Col.C-Col.B x $\frac{days}{month}$ (Enter 0.0 if Col.B=Col.C)
JAN	6.2	77.5	77.7	6.2
FEB	6.37	79.6	77.7	0
MAR	6.38	79.8	77.7	0
APR	6.62	82.8	77.7	0
MAY	6.57	82.1	77.7	0
JUN	6.91	86.4	77.7	0
JUL	6.45	80.6	77.7	0
AUG	6.35	79.4	77.7	0
SEP	6.73	84.1	77.7	0
OCT	6.63	82.9	77.7	0
NOV	6.08	76	77.7	51.0
DEC	6.03	75.4	77.7	71.3
				128.5

2. Long term storage required = Sum Col. D = 128.5

3. Total storage = (Line 2) + (Short term storage) 7 days x (maximum value in Col. C)
= 672 Ah

Exhibit 1.C

COMPUTATION OF SYSTEM PERFORMANCE - 40° Tilt, 35°, Latitude

1. Array size (Ap) = 12.5 Ap (1.25 at 60° C, 100 mW/cm²)

$\frac{11.6}{1.25} = 9.28$

need 9.28 panels = 10 panels

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m^2 - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 1 x Col.A	From Load Analysis	Col.C-Col.B x $\frac{days}{month}$ (Enter 0.0 if Col.B=Col.C)
JAN	5.94	74.3	77.7	105.4
FEB	6.28	78.5	77.7	0
MAR	6.99	87.4	77.7	0
APR	7.11	88.9	77.7	0
MAY	7.22	90.3	77.7	0
JUN	7.65	95.6	77.7	0
JUL	7.11	88.9	77.7	0
AUG	6.93	86.6	77.7	0
SEP	7.06	88.3	77.7	0
OCT	6.65	83.1	77.7	0
NOV	5.90	73.81	77.7	117.0
DEC	5.75	71.9	77.7	179.8
				402.2

2. Long term storage required = Sum Col. D = 402

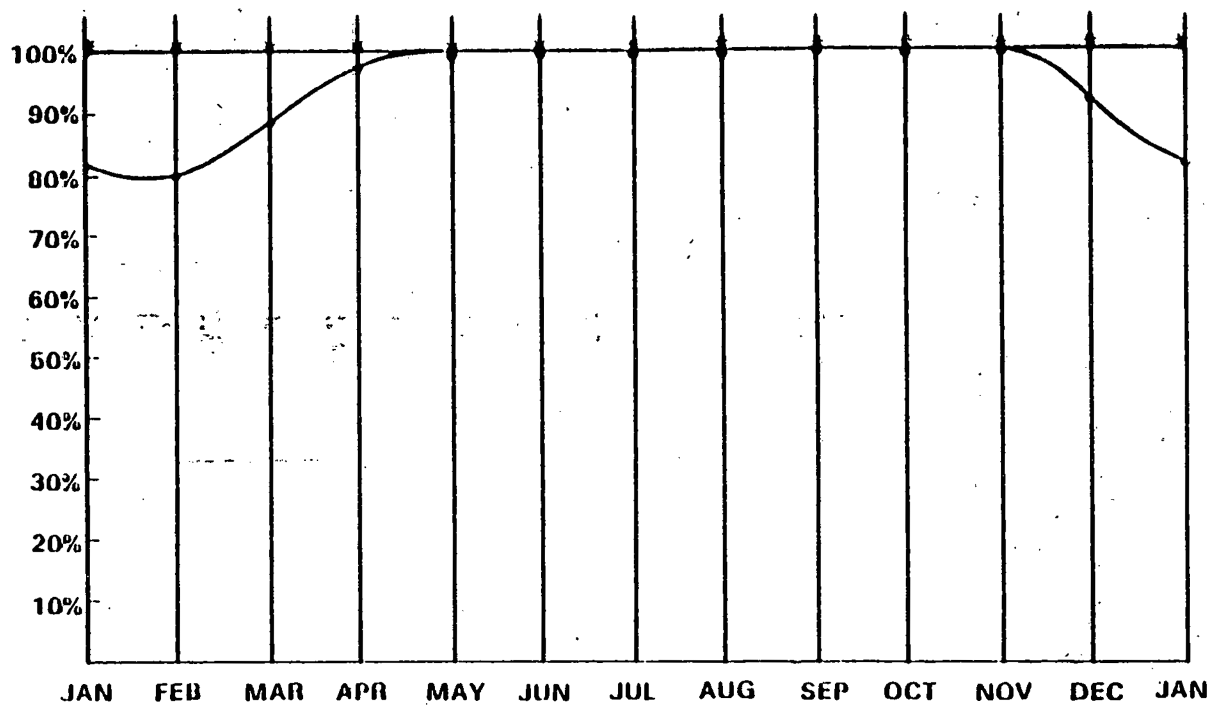
3. Total storage = (Line 2) + (Short term storage) 7 days x (maximum value in Col. C)
= 946 Ah

BATTERY DISCHARGE

Domicile

X — Min. battery storage used (11 panels) (50° Tilt)

• — 10 panel Array (50° Tilt)



13.3.3.4 DESIGN OPTIONS

- Using 11 panels, seasonal battery storage is not needed, tilt angle used is 50° (latitude + 15°).

- Using 10 panels, seasonal battery storage needed is 128.5 Ah of charge with the array at 50° tilt (latitude + 15°).

- Using a latitude tilt and 10 panels, the seasonal storage needs grow to 402.2 Ah.

- Optimal choice is either 1 or 2:

  Choice is between 1 extra panel and 128.5 additional Ah of battery charge.

  Cost of panel (12 V, 20 Wp) @ 11.25/Wp = $225.00

  Cost of additional lead-acid calcium grid battery storage (128.5 @ 12 V @

  170/kWh @ 500 hour rate @ 60% depth of charge) = $437

- Difference = $(437-225) = $212

- Percent difference = 212/225 = 94.27.

- Therefore use additional panel.

13.3.3.5 DOMICILE: MICROWAVE OVEN (OPTION 2)

The microwave oven is equipped with its own inverter and transformer circuits. It requires an input of 60.5 A at 12 V (725 W) and has an on time of approximately 50 min/day. The size of the microwave oven used does not appreciably alter the load requirement for cooking as a larger oven would be on a proportionately shorter time and a smaller oven would be on longer (i.e., it is the number of Btu's absorbed by the food that is important).

If it is assumed that the oven is used for all three meals, the on time would average approximately 50 min/day.

The charge per day (Ah/day) equals 60.5 A x 50 min/day x 1 hr/60 min = 50.4.

PANELS REQUIRED: INITIAL ESTIMATE

$$Ap = \frac{128.1}{\frac{(6.08 + 6.03 + 6.2)^*}{3}} = 20.99 \text{ Ap Total}$$

Number of panels = $\frac{20.99}{1.25}$ = 16.8 or 17 panels

(1.25 A @ 60° C @ 100 mW/cm² insolation)

*Insolation used is for a 50° tilt on the array

Exhibit 2.A   50° Tilt

Exhibit 2.B   50° Tilt

Exhibit 2.A

COMPUTATION OF SYSTEM PERFORMANCE - 50° Tilt

1. Array size (Ap) = 21.25   1.25 A/panel @ 60° C

$$\frac{20.99}{1.73} = 16.8$$

use 17 panels = 21.25

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m^2 - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 1 x Col.A	From Load Analysis	Col.C-Col.B x $\frac{days}{month}$ (Enter 0.0 if Col.B=Col.C)
JAN	6.2	131.75	128.1	0
FEB	6.37	135.4	128.1	0
MAR	6.38	135.6	128.1	0
APR	6.62	140.7	128.1	0
MAY	6.57	139.6	128.1	0
JUN	6.91	146.8	128.1	0
JUL	6.45	137.1	128.1	0
AUG	6.35	134.9	128.1	0
SEP	6.73	143.0	128.1	0
OCT	6.63	140.9	128.1	0
NOV	6.08	129.2	128.1	0
DEC	6.03	128.1	128.1	0
				0.0

2. Long term storage required = Sum Col. D = 0

3. Total storage = (Line 2) + (Short term storage) 7 days x (maximum value in Col. C)
= 897 Ah

Exhibit 2.B

COMPUTATION OF SYSTEM PERFORMANCE - 50° Tilt

1. Array size (Ap) = 20 Ap

Use 16 panels = 20 Ap

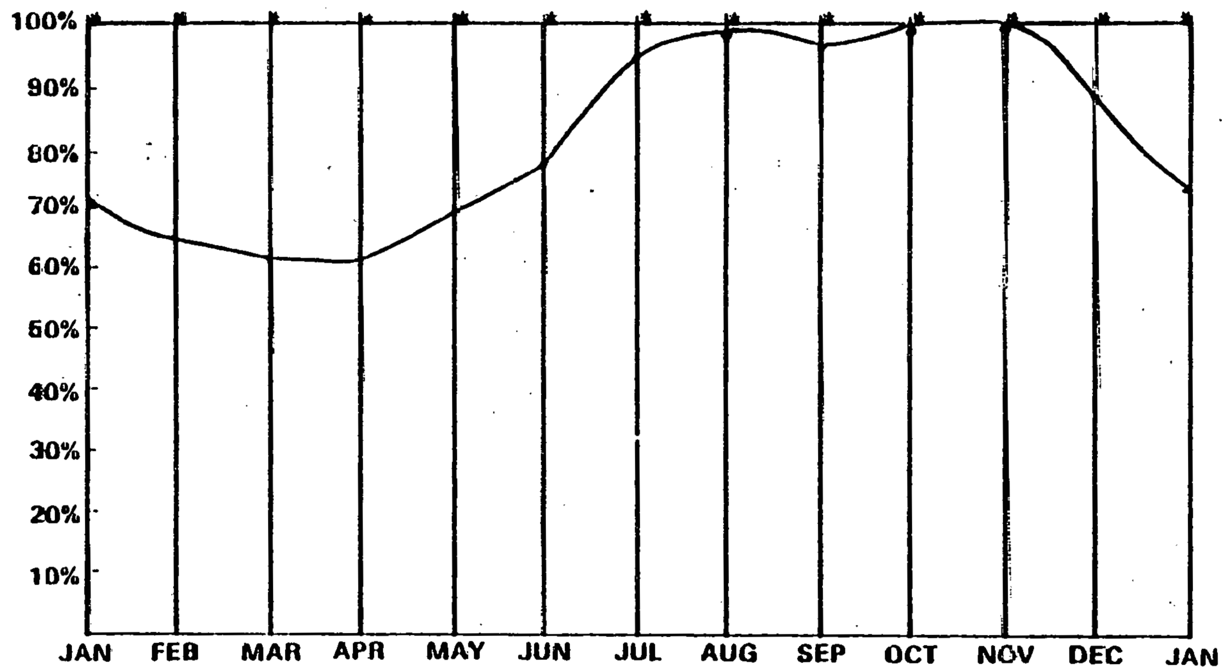
Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m² - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 1 x Col.A	From Load Analysis	Col.C-Col.B (Enter 0.0 if Col.B=Col.C)
JAN	6.2	124.0	128.1	124.0
FEB	6.37	127.4	128.1	19.6
MAR	6.38	127.6	128.1	15.5
APR	6.62	132.4	128.1	0
MAY	6.57	131.4	128.1	0
JUN	6.91	138.2	128.1	0
JUL	6.45	128.0	128.1	0
AUG	6.35	127.0	128.1	34.1
SEP	6.73	134.6	128.1	0
OCT	6.63	132.6	128.1	0
NOV	6.08	121.6	128.1	195.0
DEC	6.03	120.6	128.1	232.5
				623.8

2. Long term storage required = Sum Col. D = 623.8

3. Total storage = (Line 2) + (Short term storage) 7 days x (maximum value in Col. C)
= 1521 Ah

BATTERY DISCHARGE

(Microwave Oven) X = 17 panels
Domicile—Option 1 • = 16 panels



13.3.3.6 ESTIMATED COST OF PV DOMICILE SYSTEM

(7-Day No Sun Battery Storage)

Component	Basic System	Microwave Option
Photovoltaic panels	$ 2,970 (264 Wp)	$ 4,590 (408 Wp)
Structure	$ 219	$ 262
Fence* (Roof Mounted)	$ 0	$ 0
Power conditioner	$ 264	$ 408
Storage batteries with shelter (60% depth of discharge allowed)	$ 1,903 (907 Ah)	$ 3,125 (1495 Ah)
Total	$ 5,356	$ 8,385
Total installed with fees	$ 8,085	$12,662

13.3.4 NAVIGATIONAL AND AIRCRAFT AIDS

13.3.4.1 REQUIREMENTS

General

Rising battery costs and environmental concerns in disposal of spent batteries have made photovoltaics an economically viable and attrative source of power for navigational aids. Hundreds of commercial navigational aids are now operative.

Specific

The photovoltaic system shall produce sufficient power to operate a channel marker light during twilight and nighttime periods. The light operates at 24 V DC with a current draw of 3.1 A (74.4 W). The power requirements of the marker buoy will peak during the winter months due to the long hours of darkness. Coast Guard regulations concerning private PV navigational aids require a minimum of 30 days of battery storage to be included in the power system.

Load - 24 V, 3.1 A

Array Size - 12-12 V panels, 220 Wp (7.5 A peak @ 29.4 V)

Battery size - 1,336 Ah - 24 V

Voltage regulator - A voltage regulator shall not be required, as the maximum charging current of 7.5 A is equal to 0.6 percent of the storage battery capacity and, therefore, little outgassing due to overcharge should result.

Control of PV Power System

- The light will operate only during the nighttime hours, therefore, power shall be supplied to the load by a photocell control.

Array and Battery Monitoring

- Voltage meter located in the battery housing that will isolate and monitor either the battery or array voltage.
- Ammeter located in the battery housing that will monitor the total array output current.

Electrical Storage

Shall be provided by low self-discharge, lead-acid batteries. A minimum of 30 days of storage is required by the Coast Guard for private aids.

Safety Considerations

Disconnect switches between the panel shall not be required due to the low (i.e., 24 V) system voltage. An opaque cover shall be available for use during maintenance to cover the array, thereby effectively turning the array "off."

13.3.4.2 SUMMARY OF NAVIGATION AID DESIGN

1. Schematic of Design (Either Engineering Drawing or Block Diagram)
2. Computation of Load.
3. Initial Array Sizing for Minimum Storage Design.
4. Month-by-Month Calculation for 14 Panels (Exhibit 3.A).
5. 30-Day Battery Storage Design - Initial Array Sizing.
6. Month-by-Month Calculation — 40° Tilt Exhibit 3.B; 60° Tilt Exhibit 3.C
7. Battery State of Charge (Graph) for Each Design.
8. Cost Difference Between Designs.
9. Estimated Cost of Installed System.

13.3.4.3 LOAD COMPUTATION

Load - Channel Marker Lights
20 V DC, 3.1 A, or 81.6 W, battery used has a coulombic efficiency of 90 percent

Month	Hours of Nighttime	Ah/Day Required
Jan	14.9	50.7
Feb	14	47.6
Mar	12.8	43.4
Apr	11.7	39.7
May	10.9	36.9
Jun	10.6	35.9
Jul	10.9	37.1
Aug	11.8	40.1
Sept	12.9	43.9
Oct	14.1	27.9
Nov	15.0	50.9
Dec	15.3	52.0

$$\text{Ah/day} = \frac{\text{(hours of nighttime)} \times \text{(A demand of load)}}{\text{(coulombic efficiency of battery)}}$$

13.3.4.4 MINIMUM BATTERY STORAGE DESIGN

$$\text{Initial estimate of array current} = \frac{\text{Avg. winter load}}{\text{Avg. winter insolation } (60^{\circ} \text{ tilt})}$$

$$= \frac{50.9 + 52.0 + 50.7 + 47.6}{6.08 + 6.14 + 6.27 + 6.28} = 8.12 \text{ A}$$

Panels needed @ 1.25 A/panel @ 60° C @ 100 mW/cm^2

$$\text{Panels needed} = \frac{8.12}{1.25} = 6.49$$

Because system is 24 V, use 7 x 2 = 14 panels

Exhibit 3.A

COMPUTATION OF SYSTEM PERFORMANCE - 60° Tilt, 35° Latitude

1. Array size (Ap) = 8.75 Ap

Panels needed minimum storage 6.49 x 2 =
use 7 x 2 = 14 panels

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m² - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 4 x Col.A	From Load Analysis	Col.C-Col.B (Enter 0.0 if Col.B=Col.C)
JAN	6.27	54.9	50.7	0
FEB	6.28	55.1	47.6	0
MAR	6.46	56.5	43.4	0
APR	5.95	52.1	39.7	0
MAY	5.73	50.1	36.9	0
JUN	5.96	52.2	35.9	0
JUL	5.60	49.0	37.1	0
AUG	5.59	48.9	40.1	0
SEP	6.19	54.2	43.9	0
OCT	6.43	56.2	47.9	0
NOV	6.08	53.2	50.9	0
DEC	6.14	53.7	52.0	0
2. Total				0.0

3. Long term storage required = $\frac{\text{days}}{\text{month}}$ x Line 2 (Ah) =

4. Total storage = (Line 3) + (Short term storage) 7 days x (maximum value in Col. C)
= 364 Ah

Exhibit 3.B

COMPUTATION OF SYSTEM PERFORMANCE - 40° Tilt, 35° Latitude

1. Array size (Ap) = 7.5 Ap

(5.22 x 2) panels needed
use 6 x 2 panels = 12 panels

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m² - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 4 x Col.A	From Load Analysis	Col.C-Col.B (Enter 0.0 if Col.B=Col.C)
JAN	5.94	44.6	50.7	6.1
FEB	6.28	47.1	47.6	0.5
MAR	6.99	52.4	43.4	0
APR	7.11	53.3	39.7	0
MAY	7.22	54.2	36.9	0
JUN	7.65	57.4	35.9	0
JUL	7.11	53.3	37.1	0
AUG	6.93	52.0	40.1	0
SEP	7.06	53.0	43.9	0
OCT	6.65	49.9	47.9	0
NOV	5.90	44.3	50.9	6.3
DEC	5.75	43.1	52.0	8.9
2. Total				21.8

3. Long term storage required = $\frac{\text{days}}{\text{month}}$ x Line 2 (Ah) = 668 Ah

4. Total storage = (Line 3) + (Short term storage) 7 days x (maximum value in Col. C)
= 1032 Ah

Exhibit 3.C

COMPUTATION OF SYSTEM PERFORMANCE - 60° Tilt, 35° Latitude

1. Array size (Ap) = 7.5 Ap

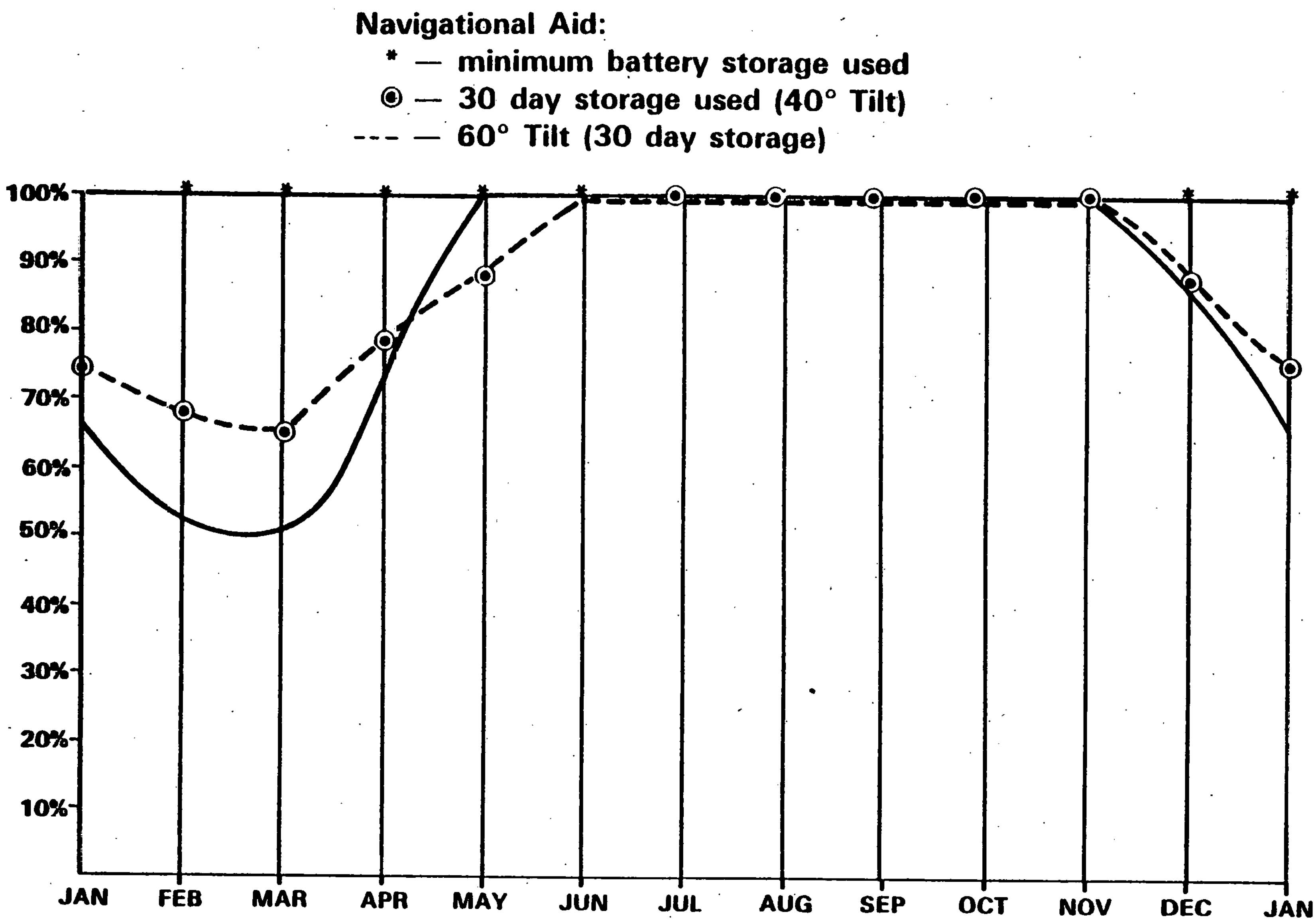
12 panels
6 x 2

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m² - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 4 x Col.A	From Load Analysis	Col.C-Col.B (Enter 0.0 if Col.B=Col.C)
JAN	6.27	47.0	50.7	3.7
FEB	6.28	47.1	47.6	0.5
MAR	6.46	48.5	43.4	0
APR	5.95	44.6	39.7	0
MAY	5.73	43.0	36.9	0
JUN	5.96	44.7	35.9	0
JUL	5.60	42.0	37.1	0
AUG	5.59	41.9	40.1	0
SEP	6.19	46.4	43.9	0
OCT	6.43	48.2	27.9	0
NOV	6.08	45.6	50.9	5.3
DEC	6.14	46.1	52.0	5.9
				15.4

2. Total

3. Long term storage required = $\frac{\text{days}}{\text{month}}$ x Line 2 (Ah) = 470.6 Ah

4. Total storage = (Line 3) + (Short term storage) 7 days x (maximum value in Col. C)
= 834.6 Ah



Navigational Aid:
* — minimum battery storage used
◉ — 30 day storage used (40° Tilt)
--- — 60° Tilt (30 day storage)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN

13.3.4.5 DESIGNING TO COAST GUARD REQUIREMENTS

A Coast Guard requirement states that 30 days of battery storage must be used on private navigation aids.

If one uses an average Ah/day requirement (43.8 Ah/day), an estimate of the 30-day storage required can be obtained.

$$30 \times 43.8 = 1{,}314 \text{ Ah}$$

One can design a system that will use this battery capacity so batteries reach a minimum of 50 percent capacity during the winter months (657 Ah). This will minimize the array current needed.

The first estimate will use the average load and monthly insolation to obtain an estimate of the needed array current.

$$\frac{\text{Avg. load}}{\text{Avg. insolation}} = \frac{43.8}{6.7} = 6.52 \text{ A (peak rated array output)}$$

Panels needed @ 1.25 A/panel @ 60° C @ 100 mW/cm^2

$$= \frac{6.25}{1.25} = 5.2 = \text{use } 6 \times 2 = 12 \text{ panels}$$

This design leads to a battery storage requirement of:

$$68 \times 2 \text{ (50 percent depth of battery discharge)} = 1{,}336 \text{ Ah @ 24 V}$$

which conforms to the Coast Guard requirement of 30 days' battery storage.

13.3.4.6 PRICE DIFFERENCE BETWEEN THE TWO DESIGNS

2 panels @ $300/panel	=	$ 600
668 Ah @ 24 V @ $170/kWh or $4.08/Ah	=	$2,725
Difference		$2,125

The price difference is irrelevent in this case, since the first design will not meet Coast Guard requirements.

13.3.4.7 ESTIMATED COST OF PV NAVIGATIONAL AIDS

Costs of Components (Installed)

Cost of PV panels for marine environment is estimated at $15.00/Wp.

Photovoltaic panels	$ 4,290	(220 Wp)
Structure	$ 200	
Fence, power conditioner	not required	
Storage batteries	$ 5,564	(1,336 Ah)
Total	$10,054	
Total with fees	$13,472	

13.3.5 TELECOMMUNICATIONS

13.3.5.1 REQUIREMENTS

General

The photovoltaic system shall provide year-round power for an unattended radio repeater. The site is sufficiently remote to preclude the extension of the existing utility grid.

Specific

The repeater operates 7 days a week; it is active for 5 hours per day. Operating on 12 V DC, it draws 11 A (132 W) while simultaneously receiving and retransmitting (the active mode), and draws 1/2 A (6 W) while listening only (the squelched mode). This load profile equates to a total power requirement of 64.5 Ah/day. (.774 kWh/day).

Control of PV Power System

1. Power is being supplied to the load at all times, so control hardware is not needed.

2. The system shall be fused to prevent battery drain if the repeater should fail in a short circuit mode. Standard buss fuses are available for this purpose.

Array and Battery Monitoring

1. Voltage meter with switches located in the battery storage box that will isolate and monitor either the battery or array voltage.

2. Ammeter with switches located in the battery storage box that will monitor either the total array output current or the total load current.

Data and Calculations

o Load - Radio Repeater

12 V DC, 11 A (132 W) active, 1/2 A (6 W) squelched

Repeater operates 24 hr/day

- 5 hours active	= 55.0	Ah
- 19 hours squelched	= 9.5	Ah
Total daily charge requirement	= 64.5	Ah

Initial Estimate of Array =

$$\frac{\text{average load}}{\text{average winter insolation (50 tilt)}} = \frac{64.5 + 54.5 + 64.5 + 64.5}{6.20 + 6.37 + 6.08 + 6.03} = 10.45$$

Panels needed: (@ 1.25 A/panel @ 60 C @ 100 mW/cm^2)

Panels needed $= \frac{10.45}{1.25} = 8.36$ Use 9 panels

Using 9 panels, seasonal battery storage is not needed (at 50^{o} tilt: latitude + 15)

Providing 7 days' short term battery storage at an average Ah/day requirement of 64.5 yields

$7 \times 64.5 = 451.5$ Ah

Allowing for 60 percent depth of discharge $451.5 \text{ Ah} \div .6 = 752.5 \text{ Ah}$

Array - 180 Wp - 11.25 Ap

Battery - 753 Ah @ 12 V

Voltage regulator required

Costing

PV panels	=	$1,947
Structure	=	181
Fence	=	1,281
Power conditioning	=	160
Battery and shelter	=	2,366
Subtotal		5,935
Fee (34 percent)		2,018
TOTAL		$7,953

TELECOMMUNICATIONS

COMPUTATION OF SYSTEM PERFORMANCE - 55° Tilt, 35° Latitude

1. Array size (Ap) = 11.25 Ap 9 Panels @ 1.25 A/panel

Column:	A	B	C	D
Item:	**Average Day Insolation on a Tilted Array**	**Electrical Output of Array**	**Electrical Demand**	**Energy From Backup**
Units:	(kWh/m² - Day)	(Ah/Day)	(Ah/Day)	(Ah/Day)
Instructions: / Month	From Insolation Analysis	Line 4 x Col.A	From Load Analysis	Col.C-Col.B (Enter 0.0 if Col.B=Col.C)
JAN	6.25	70.31	64.5	0
FEB	6.35	71.44	64.5	0
MAR	6.67	75.04	64.5	0
APR	6.30	70.88	64.5	0
MAY	6.17	69.41	64.5	0
JUN	6.46	72.68	64.5	0
JUL	6.04	67.95	64.5	0
AUG	5.99	67.39	64.5	0
SEP	6.48	72.90	64.5	0
OCT	6.55	73.69	64.5	0
NOV	6.10	68.13	64.5	0
DEC	6.11	68.74	64.5	0
2. Total				0.0

3. Long term storage required = $\frac{\text{days}}{\text{month}}$ x Line 2 (Ah) = 0

4. Total storage = (Line 3) + (Short term storage) 7 days x (maximum value in Col. C)
= 451.5 Ah

13.4 PRACTICAL LESSONS LEARNED FROM SYSTEMS

13.4.1 EXAMPLES OF INSTALLED SYSTEMS

EXAMPLE 1

TIME: 12 noon (local time)

LOCATION: 36° N x 109° W

WEATHER: Extremely clear; 4° F

1. System Description

- o Array has 108 modules; array angle 50° to horizontal.
- o Battery bank consisted of 14 Willard EV88's @ 6 V each = 84 V.
- o Pump motor = 3.5 hp permanent magnet 25 AFL 2,750 rpm, driving 50 W Jensen jack and hypro pump.
- o Field connections were checked and determined to be properly wired.
- o System is designed to operate continuously 12 hr/day with capacity of 5,800 gal/day, for the Jensen Jack and 7 GPM transfer water for the hypro centrifugal pump.

2. Actual Operating Description

- o Control box sets voltage at high of 96 V and low of 78 V. These voltages are for on and off switching.
- o The longest consecutive period of time the system operated was 4 months due to high battery depth of discharge caused by failure of control box.
- o System had been in operation approximately one year.

3. Initial Observation

- o System appeared to be properly installed.
- o Electrical connections were completed in a professional manner.
- o System was permanently wired with no quick disconnects to facilitate system test measurements and maintenance.
- o System did not contain a monitor test panel.

4. <u>Findings</u>

- The new voltage control box failed after one day of operation.
- Visual inspection revealed no broken modules or damaged cells. When manually operated without control box, system output was excellent.

EXAMPLE 2

TIME: 12 noon (local time)

LOCATION: 36° N x 109° W

WEATHER: Extremely clear; 35° F

1. System Description

   o Array consisted of 104 modules; array angle 45° to horizontal.

   o Battery bank consisted of 12-8 V C & D #LCPSA-5.

   o Pump motor = 1/2 hp Doeer permanent magnet 4.7 AFL 1,725 rpm.

   o Field connections were checked and determined to be properly wired.

   o System is designed to operate continuously 24 hr/day with capacity of 2 gal/min.

2. Actual Operating Description

   o Pump must be manually switched on and off to prevent excessive battery discharge.

   o The longest consecutive period of time the system operated was 4 hours due to high battery depth of discharge.

   o System had been in operation approximately one month.

3. Initial Observation

   o System appeared to be properly installed.

   o Electrical connections were completed in a professional manner.

   *o System was permanently wired with no quick disconnects to facilitate system test measurements and maintenance.

   *o System did not contain a monitor test panel.

4. Findings

   *o The voltage regulator prevented the array from charging beyond 100 V measured value. As a result batteries never reached their full charge of 117.6 V to 120 V and in effect drastically reduced storage capability.

---

* Discrepancy

*o Visual inspection revealed that several modules contained damaged cells which reduced current output of the array.

*o One of the modules electrical interconnects was miswired resulting in a string voltage output of 4 V. The string, which was prewired at the manufacturer's facility, should produce approximately 20 V, open circuit. The miswiring caused the total array open circuit voltage to be only 135 V after bypassing the defective voltage regulator. After correcting the wiring, the open circuit voltage measured 150 V.

Because miswiring occurred at the manufacturer's facility, the individual strings could not have been adequately tested prior to shipment.

*o During the test, the operating point on the I-V curve at battery full charge was significantly below the maximum power point of the curve. The temperature during the test condition was approximately 1° C; therefore, during periods of higher temperatures (i.e., late spring or summer), the voltage will drop due to temperature effects on cells, and the array will not charge the battery.

*o The pump is unbalanced causing inefficient mechanical operation.

*o The electrical motor (1/2 hp) driving the motor pump is oversized and should be replaced by 1/3 hp motor.

5. Test Conducted

Test 1 - array + regulator + batteries -

array voltage - 100 V
array current - 0 A

Test 2 - array + battery (bypass regulator with blocking diode)

array voltage - 110 V
array current - 11 A

Test 3 - array short circuit current - 18.5 A
array open circuit voltage - 135 V

Test 4 - individual string tests -

String 1	= 19 V
String 1 + 2	= 39 V
String 1 + 2 + 3	= 56 V
**String 1 + 2 + 3 + 4	= 60 V

---

* discrepancy

** abnormally low

Determined by above test, there was a set of conductors in the manufacturer's junction box somewhere in the fourth set of incorrectly connected modules. Removed the covers on the J-boxes of these modules and found that the positive and negative leads were indeed incorrectly connected. The leads were switched and then another test of the fourth set was done which read 75 V. Proceeded to test the total array without going further into the manufacturer's J-boxes. This test produced 150 V, open circuit from the array.

The next test was at the panel in the pump house:

> There we read 150 V, open circuit, and 105 V connected to batteries
> with 13.8 A current output.

All above voltage and current tests were done with a new Simpson 260 meter with a Simpson DC adaptor that had a range of 25 A DC.

13.4.2 SYSTEMS INTEGRATION

1. Design must include systems analysis and synthesis.

2. Electrical, mechanical, structural, etc., areas must be considered.

3. Safety must be designed into the system.

4. Maintenance and performance must be designed into the system.

   - o Quick disconnectors

   - o Monitor panels

   - o Miscellaneous items such as covering for the array during maintenance

13.4.3 ARRAYS

1. Bypass diodes should be used on modules.

2. Cells should not be chipped or cracked.

3. Excessive torque on panels will cause some encapsulating glass to crack.

4. Array and system should be grounded per existing codes.

5. Maintenance considerations must be considered at system design.

6. Array should be able to be isolated and be monitored at control/test panel.

7. Tilt angle is important but a good procedure to follow is latitude plus 15°.

8. Panels should be structurally supported from both sides rather than the middle.

13.4.4 BATTERY AND STORAGE

1. Battery capacity should be calculated not to exceed maximum discharge rate.

2. Voltage regulators must be chosen to allow batteries to charge fully which usually requires overcharging per manufacturer's specifications.

3. Gassing is important to fully recharge battery.

4. Consider venting or catalytic caps.

13.4.5 BALANCE OF SYSTEMS SUBASSEMBLIES (Keep System Simple)

1. Direct current

2. Minimum distance between subassemblies

3. Lightning protection

4. Grounding

5. Quick disconnects

6. Monitor panels

7. System efficiency

SECTION 14
ADDENDUM

14.1 PHOTOVOLTAIC SYSTEM RFP RECOMMENDED ADDENDUM

14.1.1 A COMPREHENSIVE NARRATIVE DESCRIPTION AND MATHEMATICAL MODEL FOR THE DETERMINATION OF THE PHOTOVOLTAIC SYSTEM DESIGN

The contractor shall describe in detail the operation of the system and relationship of the components to the system, to the load and to the overall operation. Also included shall be mathematical computations needed to describe the system and specify all of the parameters essential in completing the system optimization including percent of oversizing necessary for degradation purposes.

14.1.2 RESULTS OF THE MODULE AND SYSTEMS QUALITY PERFORMANCE TESTS CONDUCTED AT THE MANUFACTURERS FACILITY

The information should be comprehensive and pertain to each photovoltaic module, total array and total system.

14.1.3 FAILURE ANALYSIS METHODOLOGY

A detailed description should be provided to include narrative explanation of the rationale and probability of component and system failure, the maintenance and isolation procedures which should be used in the event of component or overall system failures, the component replacement techniques including requirements for spares and the procedures to be used for the handling and analysis of malfunctioned components.

14.1.4 COMPREHENSIVE TEST AND ACCEPTANCE PROCEDURES

Test procedures required for system test and acceptance must be specified in detail for each of the sub-assemblies, the structure, if required, and the total system.

14.1.5 DESIGN, HARDWARE DELIVERY AND INSTALLATION SCHEDULE

Comprehensive schedules must be provided and coordinated with manufacturers, suppliers, etc.

14.2 PURCHASE DESCRIPTION (5500 Watt Solar Cell Array)

U.S. ARMY MOBILITY EQUIPMENT
RESEARCH AND DEVELOPMENT COMMAND
Fort Belvoir, Virginia 22060

6 March 1978

1.0 SCOPE.

1.1 This Purchase Description covers the requirements for design, fabrication, and testing of Silicon Solar Cell Modules with high efficiency and high packaging density installed and interconnected into suitable frames. The solar cell modules shall meet the JPL Environmental Requirements No. 5-342-1, Rev B.

2.0 Applicable Documents.

MIL-STD-810 Environmental Test Methods
JPL-No-5-342-1, Rev B Dec 1979 Silicon Solar Cell Module Performance, Environmental Test
Handbook H-28 Screw-thread Standards for Federal Services
MIL A-8625C Anodic Coatings for Aluminum and AL-Alloys

3.0 Requirements.

3.1 Module Description. The solar cell module design shall attempt to maximize the performance of the modules with respect to the following:

a. Maximize power output per module unit area. This effort will reduce solar array area requirements and thus reduce support structure and electrical interconnection costs.

b. Minimum cost per unit energy produced.

c. Service life. Maximize the service life of the module with a goal of 10 years.

3.2 Electrical Performance.

3.2.1 Module Characteristics.

3.2.1.1 General. The module geometry shall be such that they can be installed in subarrays of about 4 x 8 feet. Each subarray shall have the voltage range specified in paragraph 3.2.1.3.

3.2.1.2 Module Output Power. The average module output power, when measured according to the JPL requirements 5-342-1, Rev B, shall not be less than 10 W/ft^2.

3.2.1.3 Subarray Voltage. The individual module voltage is of no consequence and is, therefore, not specified in the P.D. The subarray voltage, (a subarray consists of a number of modules installed in a 4 x 8 feet frame) shall be in the range of 125 Vdc to 300 Vdc. The low voltage (125 Vdc) shall correspond to the peak power point at 50°C ambient temperature; the upper voltage (300 Vdc) shall correspond to the open circuit voltage at -40°C.

3.2.1.4 Subarray Output Power. The average subarray output power, when measured according to the JPL requirements quoted, shall not be less than 300 watts.

3.2.2 Electrical Insulation. The electrical insulation of the module shall provide a minimum insulation resistance to ground of 100 megohms and shall withstand 1500 Vdc for one minute between circuitry and any metallic substrate, support, or frame.

3.2.3 Output Terminals and Interconnection Box. Each module shall contain redundant output terminals to permit interconnection of modules into either parallel or series arrangements. Output terminals shall be capable of carrying 5 A, minimum. The output terminals shall be located within a waterproof interconnection box.

3.3 Mechanical Requirements.

3.3.1 Module Geometry. The basic module geometry shall be such that it can be mounted into a subarray not greater than 4 x 8 feet, including a border for handling and fastening.

3.3.2 Interface Dimensional Tolerances. Tolerances on all external module dimensions shall be maintained at a level consistent with module interchangeability. Surfaces, mounting holes and other attachment fasteners shall be maintained with a tolerance not to exceed + 1/32 inch. Surfaces not associated with the attachment interface shall be maintained with a tolerance of + 0, -1/8 inch.

3.4 Solar Cell Frames and Mounting Stands.

3.4.1 General. The solar cell modules shall be mounted and interconnected in suitable frames and associated stands. The frames shall be designed as to withstand the environmental characteristics specified herein.

3.4.2 Panel Structure.

3.4.2.1 Mechanical Construction. The structure shall be self-supporting, consisting of a panel frame assembly, interpanel wiring, and four legs with baseplates and provisions for tie-down.

3.4.2.2 Ground Clearance. Each panel structure shall be of sufficient height to prevent a build-up of wind blown debris or snow from reducing the electrical performance of the system (18 inches minimum).

3.4.2.3 Tilt Angle. The illuminated surface of the panel shall be positioned at an angle of 45° from the horizontal.

3.4.2.4 Interchangeability. The solar cell modules and the array panels shall be interchangeable.

3.4.2.5 Identification Markings. All the panel structures shall be permanently marked with identification numbers.

3.4.2.6 Materials. The panel structure shall be made of aluminum with a corrosion resisting treatment, acceptable to the C.O. Note: Anodizing according to MIL-A-8625C is an acceptable treatment.

3.4.2.7 Grounding. The panel structure shall incorporate a ground stud or 3/8 hole for connecting ground cables/strips.

3.5 System Design Requirements.

3.5.1 Lifetime Consideration. The system shall be designed for a minimum lifetime of 10 years.

3.5.2 Transportability. The system shall withstand, without damage, shock and vibration encountered in shipment.

3.5.3 Fungus Resistance. Materials used in the fabrication of the system shall not support the growth of fungus, except that the requirement need not apply to components within hermetically sealed enclosures.

3.5.4 Environment. The solar cell array shall be designed to operate in and/or survive the following environments:

Environment	Operate	Survive
Ambient Temperature	-40°C to +50°C -40°F to +122°F	
Thermal Cycling		-40°C to +90°C 100°C/hour with cycle 4 hours
Humidity		2 to 100%
Cyclic Load		+50 lb/ft² to -50 lb/ft² 100 times
Elevation	Sea Level to 10,000 ft	
Wind		Up to 120 knots
Hail		1" Ø
Rain		Shall withstand sustained rainstorms at rates up to 5" per hour. Water entry into connector shall be considered unacceptable.

3.5.5 Fasteners (Except Electrical). Screw threads shall conform to Handbook H-28; American National coarse threads are required where threads are provided in aluminum, magnesium or plastic parts and are preferred for all other parts. Bolts, screws, and other fasteners used on rotating parts shall be provided with positive locking devices or means which do not depend on spring action or friction for their locking action, such as lock plates, lock wire, snap rings, castellated nuts, and cotter pins. Means for locking fasteners on all non-rotating parts shall also be provided. Swedging, peening, or stalking of threads will not be acceptable as a locking device or means for parts subject to adjustment, disassembly, or removal. The number of different sizes and types of bolts, screws, nuts, washers, etc., shall be the minimum practicable. Sheet metal screws shall not be used except in fastening of nameplates and instruction plates.

3.5.6 Corrosion Resistance. All fasteners (bolts, screws, studs, etc.) and their associated hardware (washers, lockwashers, pins, etc.) shall be made of stainless steel, except that the following need not comply with this requirement.

a. Fasteners within hermetically sealed components.

b. Fasteners within components which operate immersed in or filled with a fluid which will form a protective film.

c. Fasteners in parts which are not subject to adjustment, disassembly, or removal for servicing, maintenance and repair during the life of the component of which they are a part.

3.5.7 Fasteners (electrical). Lock devices shall be provided each fastener used in making an electrical connection. Each fastener, locking device, and other hardware (washers, etc.) shall be made of corrosion-resisting material or shall be treated to be corrosion-resisting. Fasteners (bolts, screws, studs, etc.) shall not be depended on to carry current; they shall serve merely to hold current-carrying parts (lugs, terminals, etc.) in firm contact with each other. Where flow of current through a stud cannot be avoided, the stud and all its associated hardware (nuts, locking devices, washers, etc.) shall be made of corrosion-resisting material. Positive means (such as pins or square shanks) shall be provided for preventing turning of studs in their mountings when nuts are tightened or loosened; lock-washers which depend on friction or spring action will not be acceptable for this purpose. Except for devices with integral studs, unused length of threads on studs (or screws used as studs) shall not exceed three threads of the stud or one-fourth inch, whichever is smaller. All threads of a nut used in making an electrical connection shall engage mating threads on the corresponding stud (i.e., length of stud is sufficient to allow complete passage through the nut).

3.5.8 Wiring. All wire shall be neatly laced into harnesses through the use of fungus resistant cord or self-locking nylon straps. Harnesses shall be so run and clamped (with insulated clamps) as to protect insulation against contact with sharp corners and edges, pinching, sharp bending and twisting, and abrasion because of vibration or contact with moving parts. The clamps shall also serve to prevent transmittal of mechanical stress to internal connections of electrical components. Where a cable or wire is run between parts which move relative to each c her, sufficient slack shall be left in the harness. Wires shall not be spliced at any point throughout the length of their runs. All harnesses used to interconnect assemblies shall terminate in qualified connectors at each end or branch. Connectors outside of enclosures shall be potted where wires exist or seals shall be used to prevent entrance of water, dust, dirt, etc. Open, exposed connections shall not be permitted. Not more than two terminal lugs shall be attached to any one stud or stud-type terminal boards. Solder terminals on electrical components shall not have more than two wires attached, unless specific written approval is obtained from the Contracting Officer's Technical Representative.

3.5.9 Wires and Cables. All wire and cable shall have conductor size not less than AWG Number 16. The following exceptions are permissible:

a. Wire used in coils and windings and wire used as short "jumpers" on printed circuit boards, etc., may be solid and smaller than AWG Number 16.

b. Wiring located within a hermetically sealed electrical component may be smaller than AWG Number 16.

c. Wire size smaller than Number 16 may be used within electrical enclosures if specific written approval is obtained from the Contracting Officer's Technical Representative.

4.0 Quality Assurance Provisions.

4.1 Responsibility for Inspection and Test. Unless otherwise specified in the contract, the contractor is responsible for the performance of all inspection and test requirements as specified herein. Except as otherwise specified, the supplier shall utilize his own facilities or any commercial laboratory acceptable to the Government. In addition, the Government reserves the right to perform or repeat any tests or inspections set forth in this Purchase Description at any time such tests or inspections are deemed necessary by the Contracting Officer to assure equipment conforms to prescribed requirements. It is required that the contractor proposes solar cell modules equivalent in design and materials to modules which have previously met the pertinent Jet Propulsion Laboratory Environmental Requirements No. 5-342-1, Rev B, part III Test Requirements.

4.2 Inspection and Identification.

4.2.1 Visual Inspections. The Contracting Officer's Technical Representative shall make a physical inspection of all modules, frames, and stands to determine conformance with this Purchase Description, prior to the tests. The inspection shall include, but not necessarily be limited to the items of Table 1.

4.2.2 Module Identification. All modules shall be appropriately identified.

TABLE I

VISUAL EXAMINATION

1. Workmanship
2. Safety
3. Identification
4. Treatment and Painting
5. Welds
6. Soldering
7. Electrical Wiring, Connectors and Connections
8. Output Terminals
9. Corrosion Resistant Treatment and Materials
10. Cracked or Dirty Silicon Cells
11. Encapsulation

4.3 Acceptance Test.

4.3.1 General. The acceptance tests consist of the pre-manufacturing tests and the manufacturing tests. They shall be performed according to the specified JPL document, taking into consideration the different voltage and power levels of the modules. The pre-manufacturing tests are intended to characterize the expected module performance and to provide a high level of confidence that the modules and subarrays will function within the specified performance requirements in a terrestrial environment.

4.3.2 Pre-manufacturing Tests.

4.3.2.1 Electrical Performance. Perform current-voltage (I-V) characteristic tests on 5% of the modules.

4.3.2.2 Electrical Insulation Tests. Perform insulation resistance tests on 50% of the modules.

4.3.2.3 Environmental Tests. Perform environmental tests on 5% of the modules.

4.3.3 Manufacturing Acceptance Tests.

4.3.3.1 Electrical Performance Tests. Five percent of the solar cell modules shall be subjected to the electrical performance test.

4.3.3.2 Electrical Insulation Test. Five percent of the solar cell modules shall be subjected to the electrical insulation test.

4.3.3.3 Thermal Cycling Test. Five individual modules shall be subjected to the thermal cycling test.

4.3.3.4 Subarray Acceptance Test. All components shall be mounted on one subarray to demonstrate its ability to support same.

4.3.3.5 Compatibility Test. One subarray shall be operated and monitored for a minimum of 14 hours to verify system performance.

5.0 Preparation for Delivery.

5.1 Preservation and Packaging. Preservation and packaging of the solar cell modules, frames and stands shall be in accordance with good commercial practice to provide protection against deterioration and damage from the supplier to the destination.

5.2 Packaging. The solar cell modules, frames and stands shall be packed to insure carrier acceptance and safe delivery to destination at lowest rates in compliance with Uniform Freight Classification rules or National Motor Freight Classification rules.

6.0 Notes.

6.1 Intended Use. It is intended that the 4000 watt solar cells described herein be used for two applications, one in Yuma, AZ and the other in Dugway Proving Ground, UT.

6.2 Definitions.

6.2.1 Cell. A semiconductor device typically in wafer form that converts light energy to electrical energy.

6.2.2 Module. A grouping of one or more cells encapsulated into an integral, indivisible unit.

6.2.3 Subarray. A grouping of one or more modules into a free-standing unit, with module(s) electrically connected and terminals provided for connection to the array or load.

6.2.4 Array. The entire solar cell subsystem. An array normally consists of a number of panels, although an array could consist of a single module, which, itself, could consist of a single cell.

14.3 REJECTION CRITERIA FOR JPL LSSA MODULES

(5101-21, Rev. A)

Contents

REJECTION CRITERIA FOR JPL LSSA MODULES

14.3.1 OBJECTIVE

The objective of this document is to define the rejection criteria for silicon solar cell modules procured for the JPL Low-Cost Silicon Solar Array Project. The criteria, terminology, and illustrations are derived from the details of specific module designs. Any module design for which these criteria are inapplicable because of difference in detail shall necessitate the definition of additional or alternate rejection criteria.

14.3.2 APPLICABLE DOCUMENTS

The latest approved revisions of the following publications shall apply:

A. JPL Silicon Solar Cell Module Design, Performance, and Acceptance Test Requirements document.

B. Contractor interface control drawing.

C. Contractor top assembly drawing.

14.3.3 INSPECTION REQUIREMENTS

Magnification: Inspection shall be performed using 6x magnification. Higher magnification shall be used for evaluation or clarification.

14.3.4 REJECTION CRITERIA FOR MODULES

The following defects shall be cause for module rejection.

A. Module Identification

1. Module serial number location and orientation other than the position indicated on the manufacturer's drawing.
2. Required markings or identification which cannot be correctly read or interpreted.
3. Markings or identification which show signs of peeling or readily coming off.
4. Missing contractual markings or identification.
5. Incorrect markings or identification.

B. Module Mechanical Features

1. Module length, width or depth out of the tolerance specified on the manufacturer's drawing.
2. Module mounting hole size or location out of the tolerance specified in the

manufacturer's drawing.

3. Cracked or damaged structural elements.

C. Solar Cells

1. Cracked or broken solar cells (exhibits 1-11).
2. Cells in edge-to-edge contact (exhibit 12).
3. Cells in edge contact with metal module substrate (exhibit 13).
4. Overlapping cells (exhibit 14).

D. Interconnects and Soldering

1. Collector or interconnect delamination (exhibits 27a, 27b, 27c).
2. Alligatored contact. Silicon fracture under collector (exhibit 28).
3. Extensive collector dewetting from silicon in the interconnect-to-collector contact area (exhibit 29).
4. Less than 50% solder fillet on soldered area of interconnect-to-collector or back contact.
5. Fractured, overstressed, or damaged interconnects (exhibits 30-34).
6. Solder joints obscured by flux.
7. Broken or nicked wire strands at solder joints in excess of these criteria:

   7-strand wire: 1 strand broken, 2 strands nicked

   9-strand wire: 2 strands broken, 3 strands nicked

8. Insulation of wire buried into solder joint (exhibit 35).
9. Solder joints which lack a solder fillet to all wires or other elements contained within the solder junction (exhibits 36, 37).
10. Broken or fractured solder joints at output terminals (exhibits 37 and 38).
11. Split, burnt, crushed or cut insulation on any of the lead wires.
12. Cut, overstressed, or broken single strand wire.
13. Interconnect misalignment with less than 50% of interconnect in contact with collector (exhibit 39).
14. Stress relief loop frozen by solder (exhibit 40).
15. Wire or other interconnects in or near contact with other conductors, including conductive substrates.

16. Folded interconnects (exhibit 41).

17. Damaged flat or printed circuit paths having less than 75% of current-carrying conductor remaining.

18. Interconnect rework, i.e., patching or solder coating, is not acceptable for exhibits 30-34.

E. Encapsulation

1. Encapsulant cracking or splitting over active elements (exhibit 42).

2. Frame seal delamination (exhibits 43, 44).

3. Holes or air bubbles in the encapsulant, regardless of size, which could serve as a direct moisture path from the outside environment to an internal module component (exhibit 45).

4. Bubbles or delamination between output terminals or terminals to substrate (exhibits 46, 47).

5. Uncured or insufficiently cured encapsulant characterized by excessively sticky surfaces and/or streaks of liquid on the surface of the encapsulant.

6. Interlayer delamination.

7. Air bubbles or uncured encapsulant which move about under light finger pressure.

8. Delaminations and Bubbles.

   a. Delamination or bubbles less than 2 mm across the largest dimension are acceptable at any location on the module.

   b. Delamination or bubbles larger than 2 mm but smaller than 3 mm across the largest dimension are acceptable under the following constraints:

      (1) There shall be none over cells, interconnects and/or terminals.

      (2) There shall be no more than 10 per module.

      (3) None shall be located where it can provide a path from one conductor to another or from a conductor to metallic frame or substrate (exhibits 44, 45).

      (4) Delaminations or bubbles shall be at least 2 cm apart.

   c. Delaminations or bubbles greater than 3 mm are not acceptable (exhibit 44).

9. Internal conductors, interconnects, or cells within 1.5 mm of the external surface of the encapsulant (unglassed modules only) (exhibits 48, 49).

10. Cracked or fractured glass or other protective coating.

11. Deep scratches over 5 cm in length in any direction or location on module cover glass.

12. Inadequate adhesion of encapsulant in reworked areas, as indicated by the following procedure:

    a. Clean the surface to be evaluated with methyl or ethyl alcohol.

    b. Cut a 2 to 3 inch length of Scotch Brand Pressure Sensitive tape No. 600 or equivalent and apply immediately to the area to be tested; hold a tab end above the surface.

    c. Rub tape so that air bubbles are removed.

    d. Pull tape from the surface. Reject if encapsulant comes away from the module and remains on the tape.

    NOTE: Do not perform this test before the encapsulant has been completely cured (i.e., a minimum of 48 hours at room temperature).

F. Foreign Material

1. Any metallic particle (including solder) resting on the cell junction (exhibit 50).

2. Any metallic particle (including solder) trapped between the interconnect and the cell junction (exhibit 50).

3. Any metallic particle trapped between an internal conductor, such as an interconnect, and a conductive substrate.

G. Hardware

1. Loose or missing hardware.

2. Damaged hardware such as threaded terminal posts and missing plated or chemically treated areas.

3. Encapsulant on external electrical contacts, mounting bosses, or mounting hardware surfaces.

4. Incorrect hardware.

H. Final Test and IV Data

1. Data missing or incorrect.

2. Data out of specification tolerances.

FIGURES 1 TO 50

REJECTION CRITERIA FOR JPL LSSA MODULES

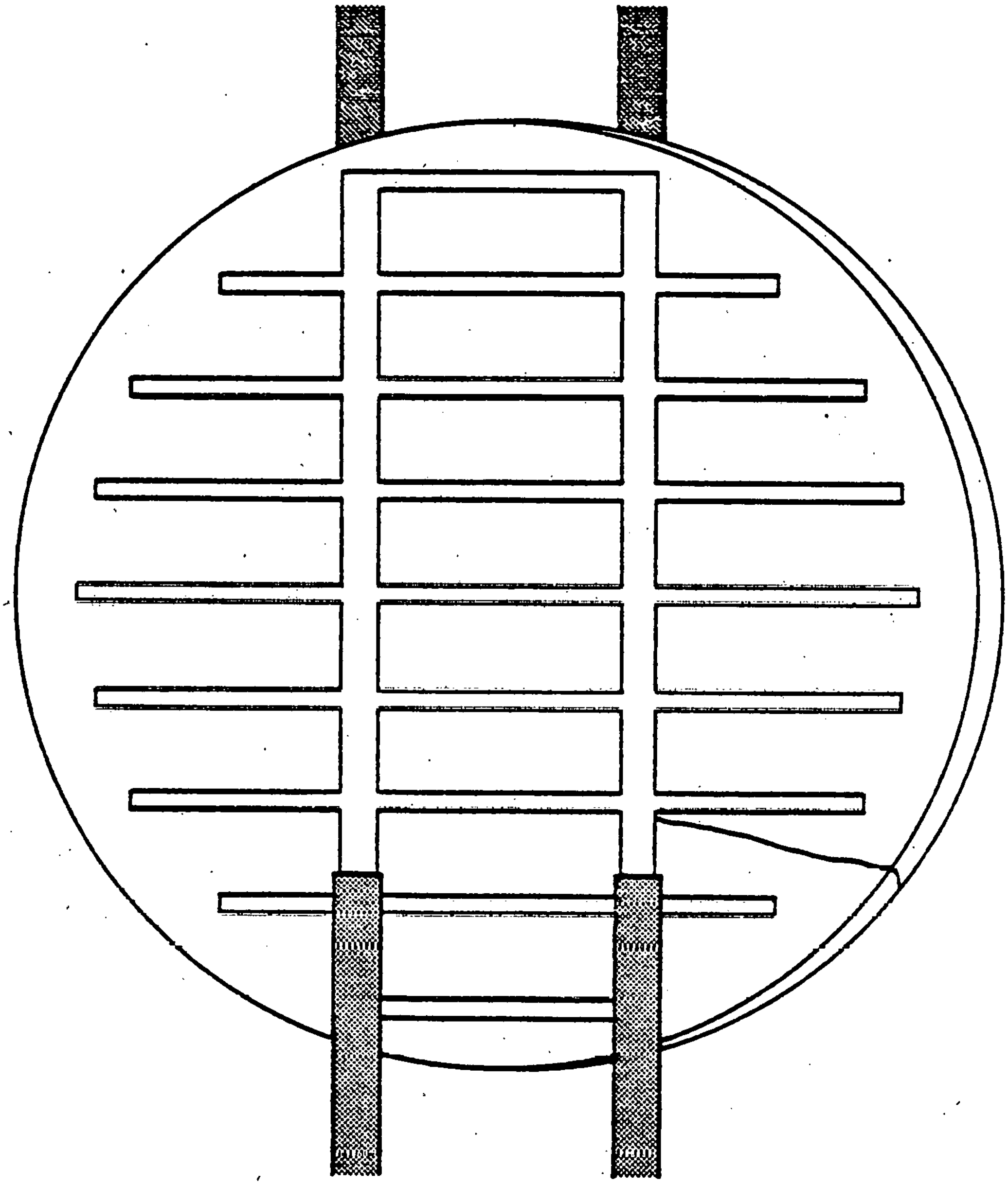


Figure 1. Terminated Crack. Reject.

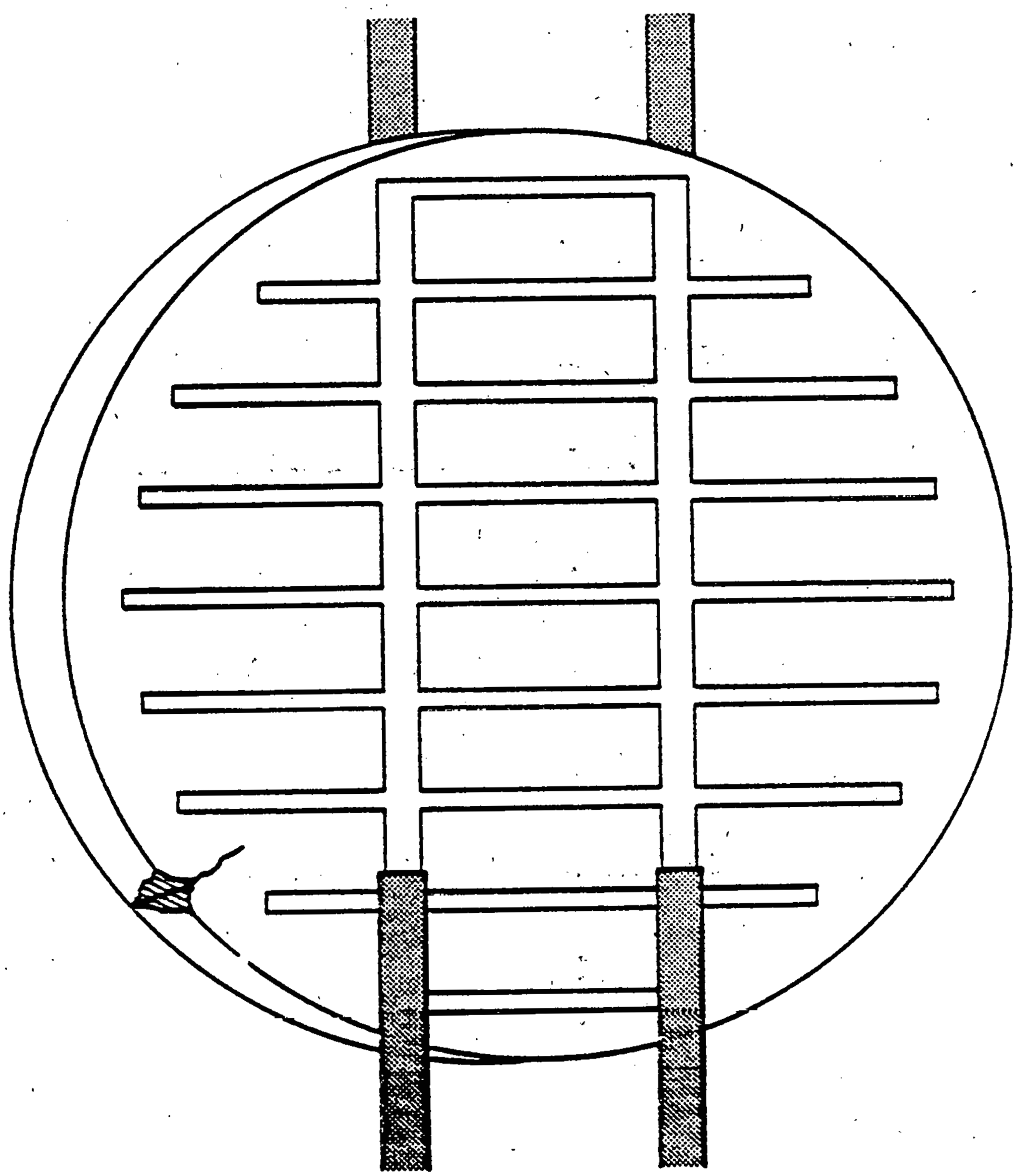


Figure 2. Short Terminated Radial Crack Started From Edge Chip. Reject.

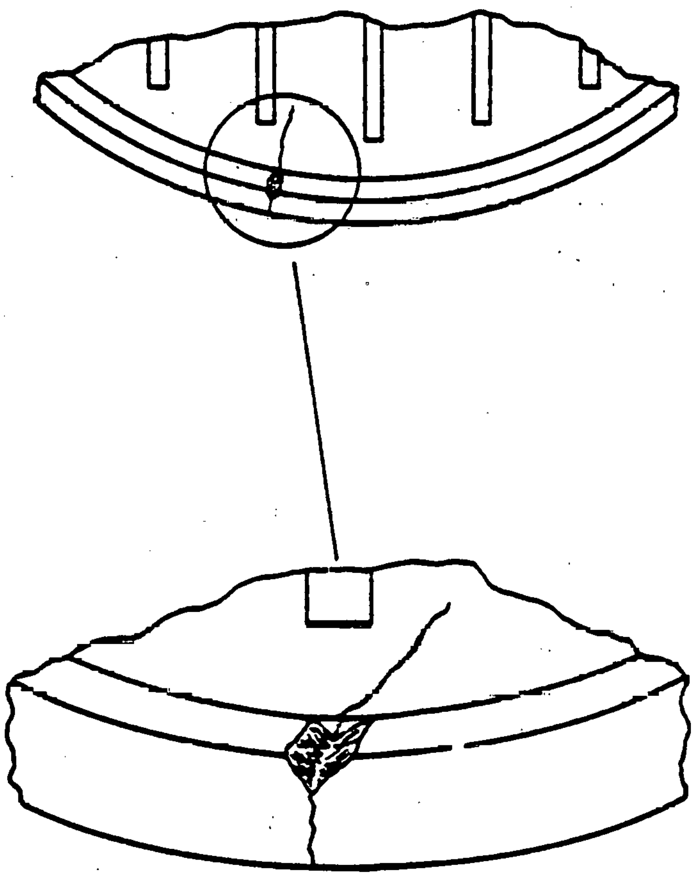


Figure 3. Crack Emanating From Cell Rim Defect. Reject.

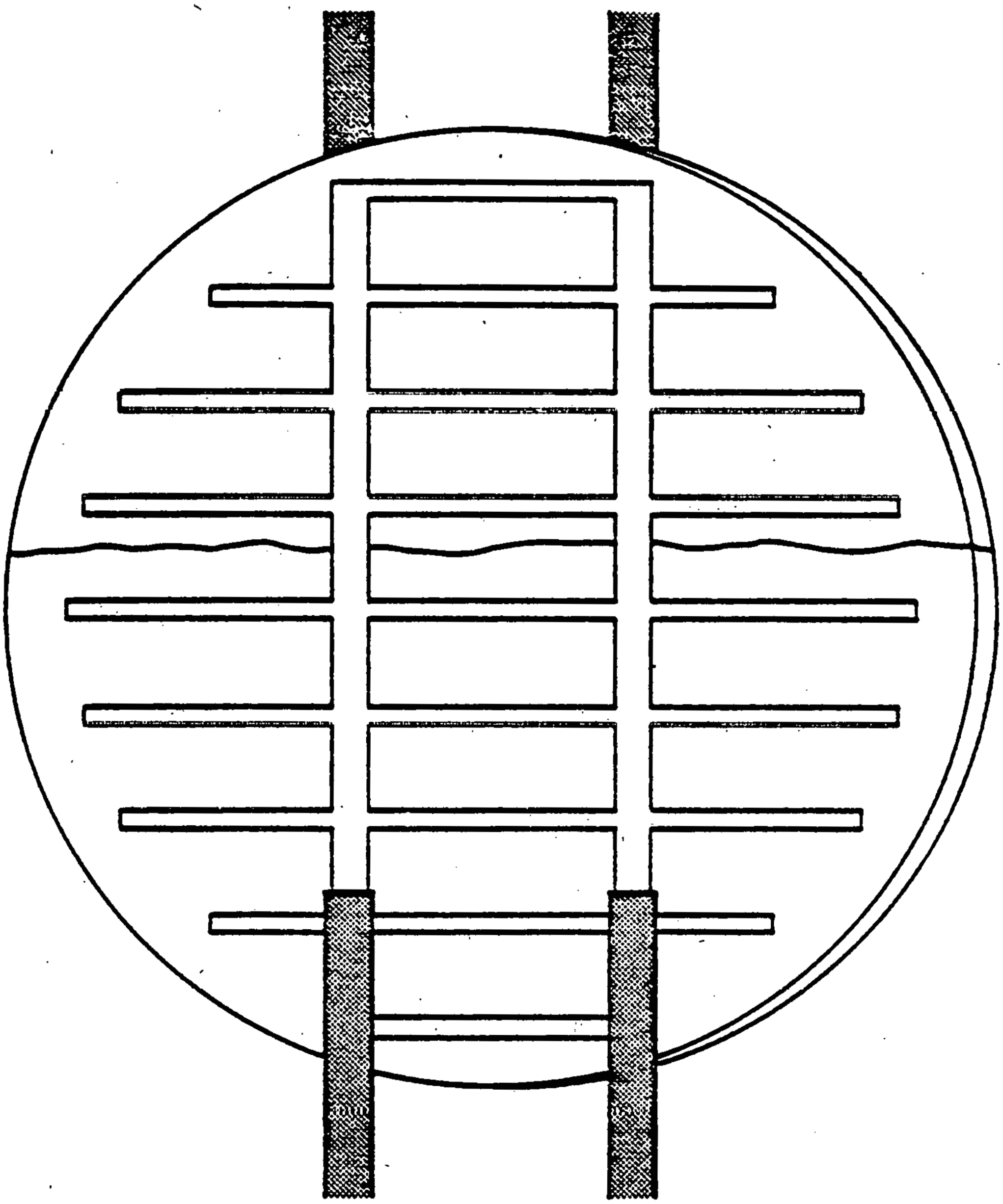


Figure 4. Rim to Rim Hairline Crack. Reject.

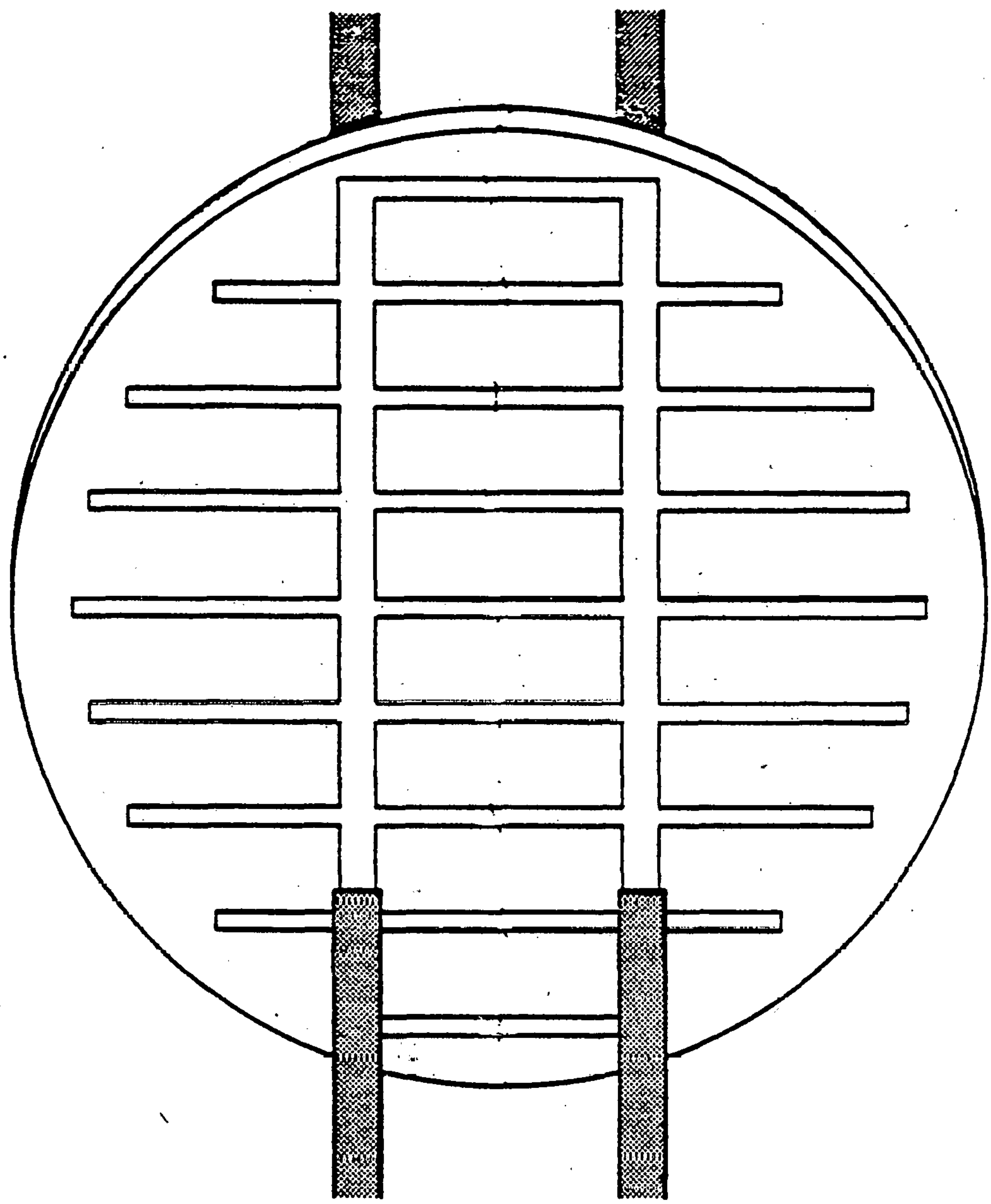


Figure 5a. Crack Between Collectors. Acceptable.

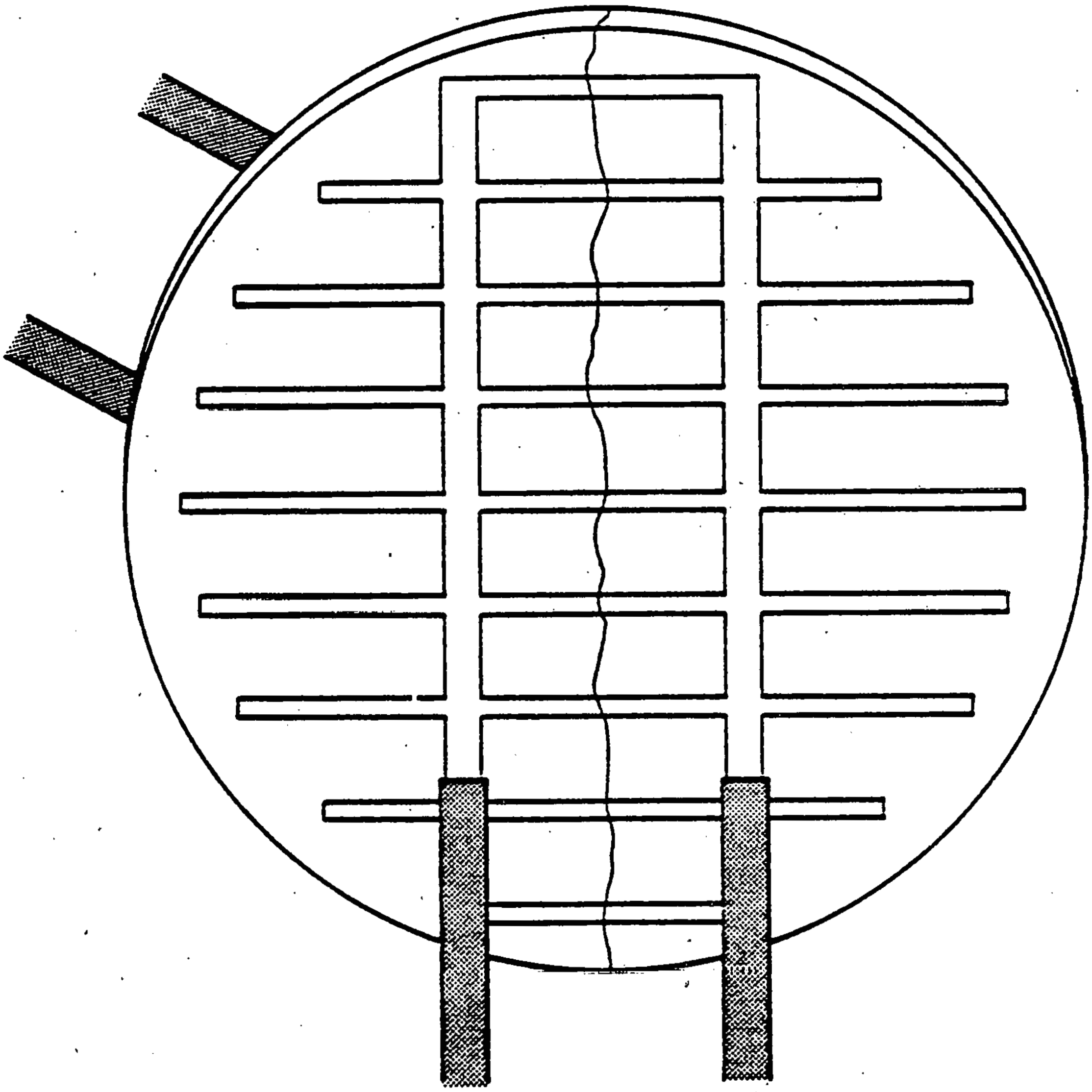


Figure 5b. Crack Isolating Offset Interconnects. Reject.

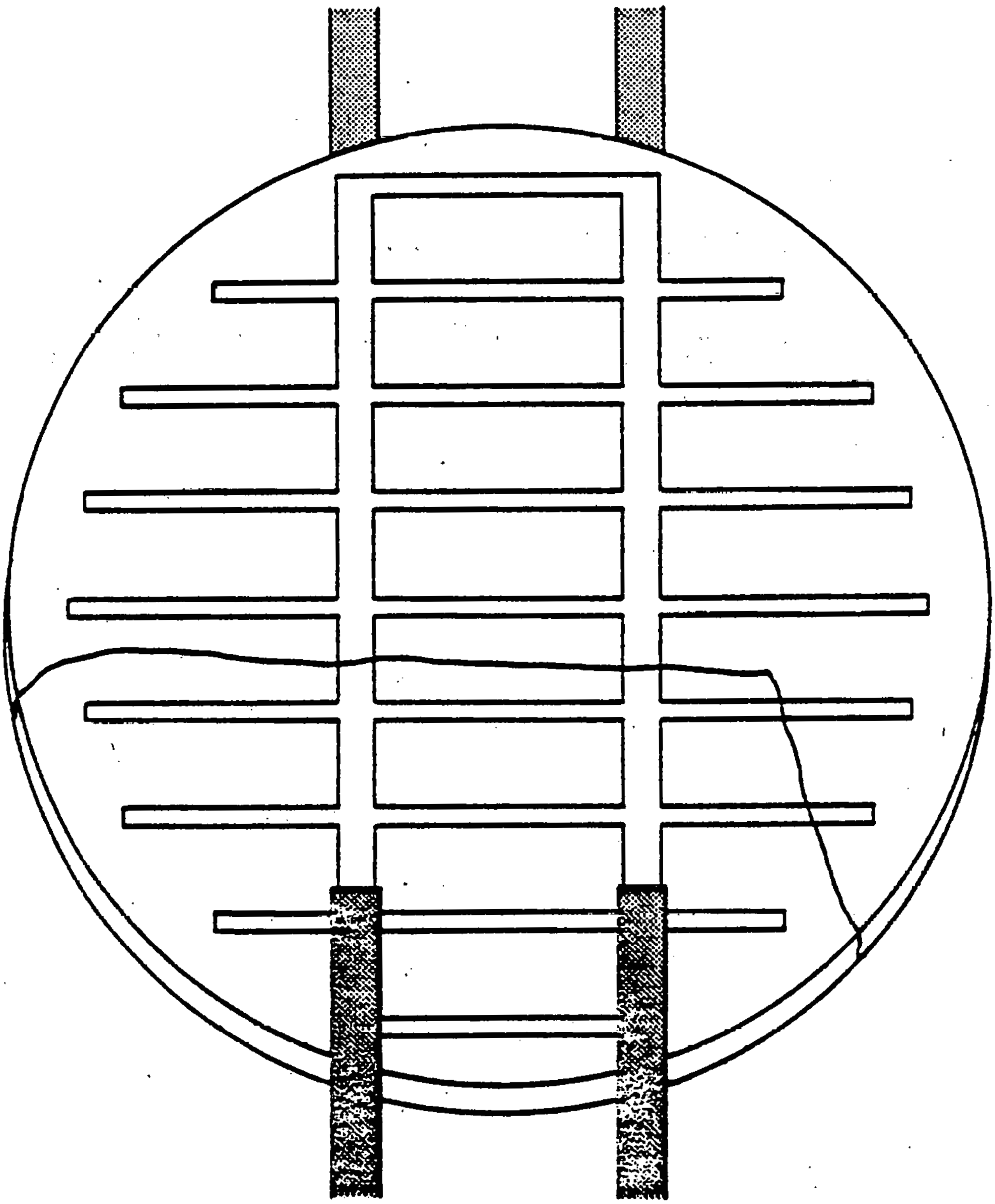


Figure 6. Irregular Hairline Crack Through Collector. Reject.

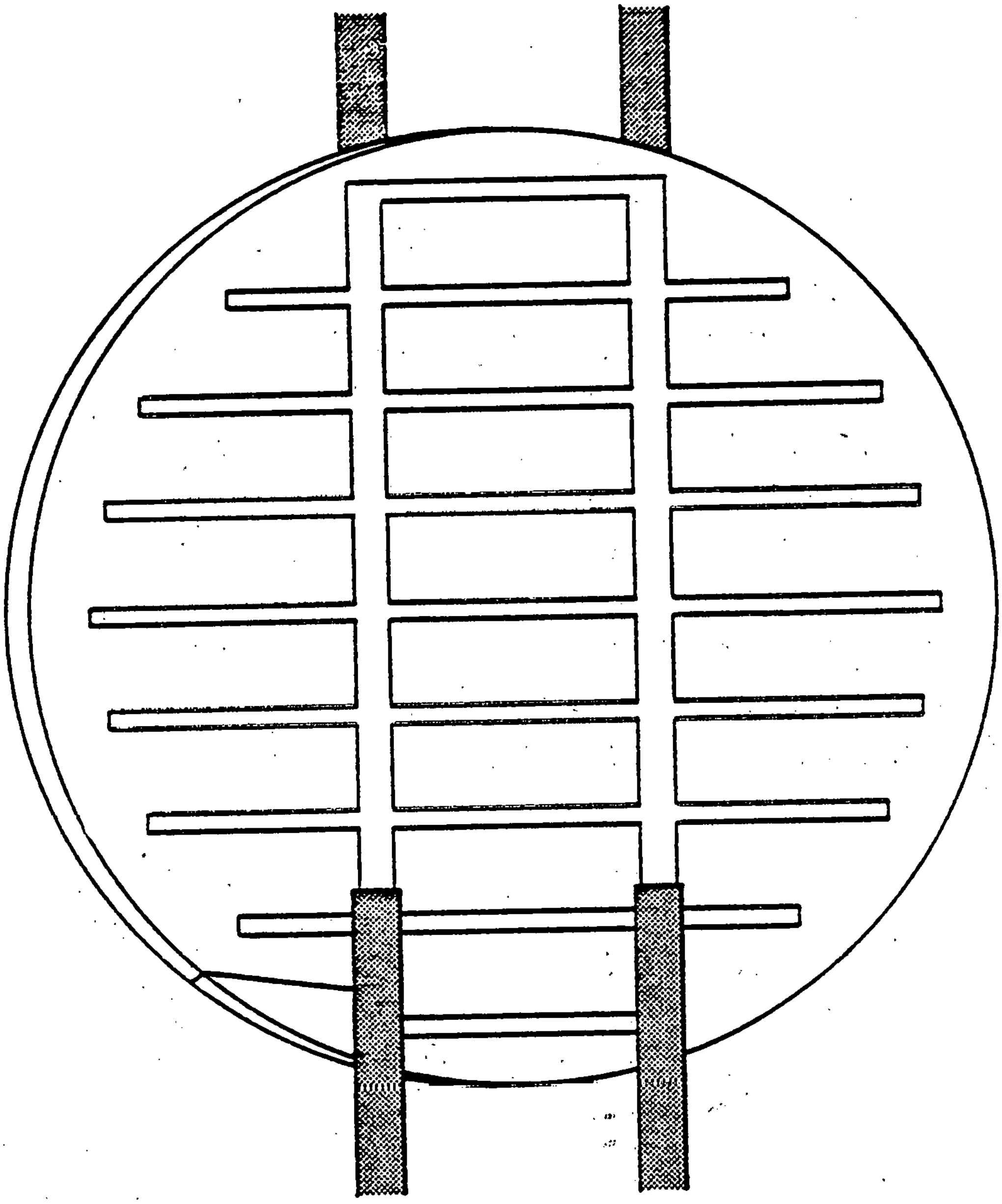


Figure 7. Edge Crack Terminated or Passing Through or Under Collector Solder Joint. Reject.

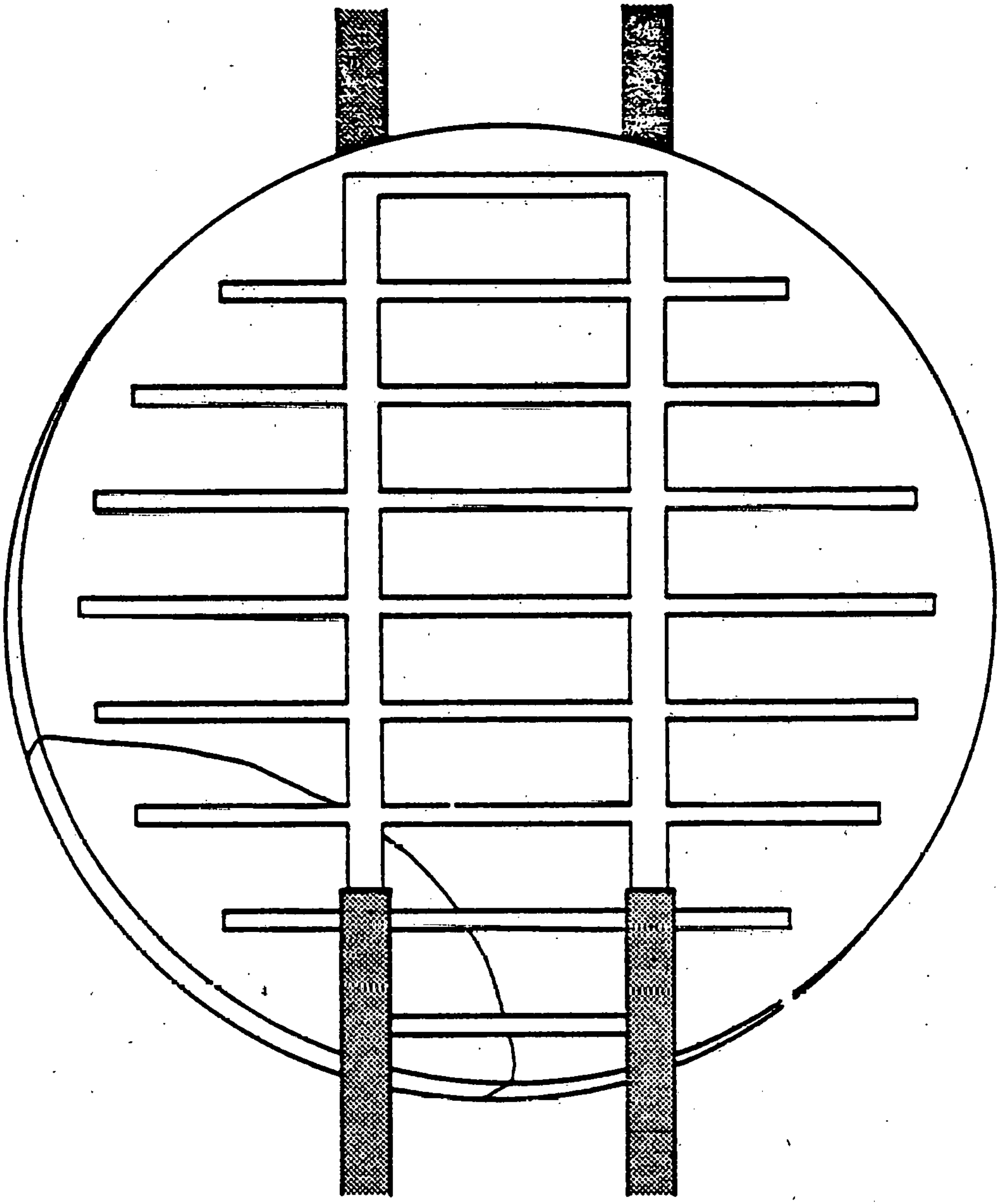


Figure 8. Broken Portion of Cell Intersecting Collector Strip. Reject.

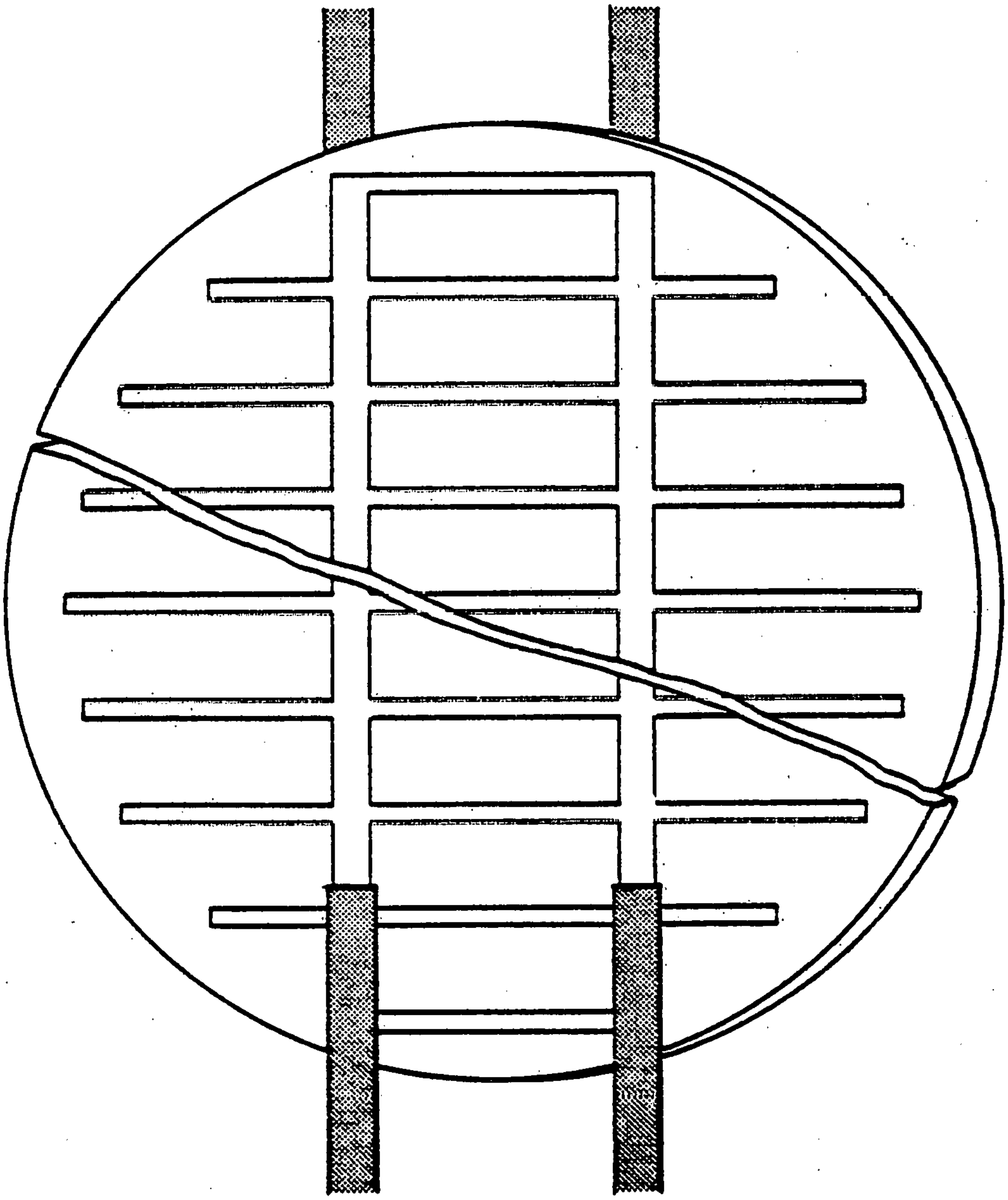


Figure 9. Crack Causing Total Separation. Reject.

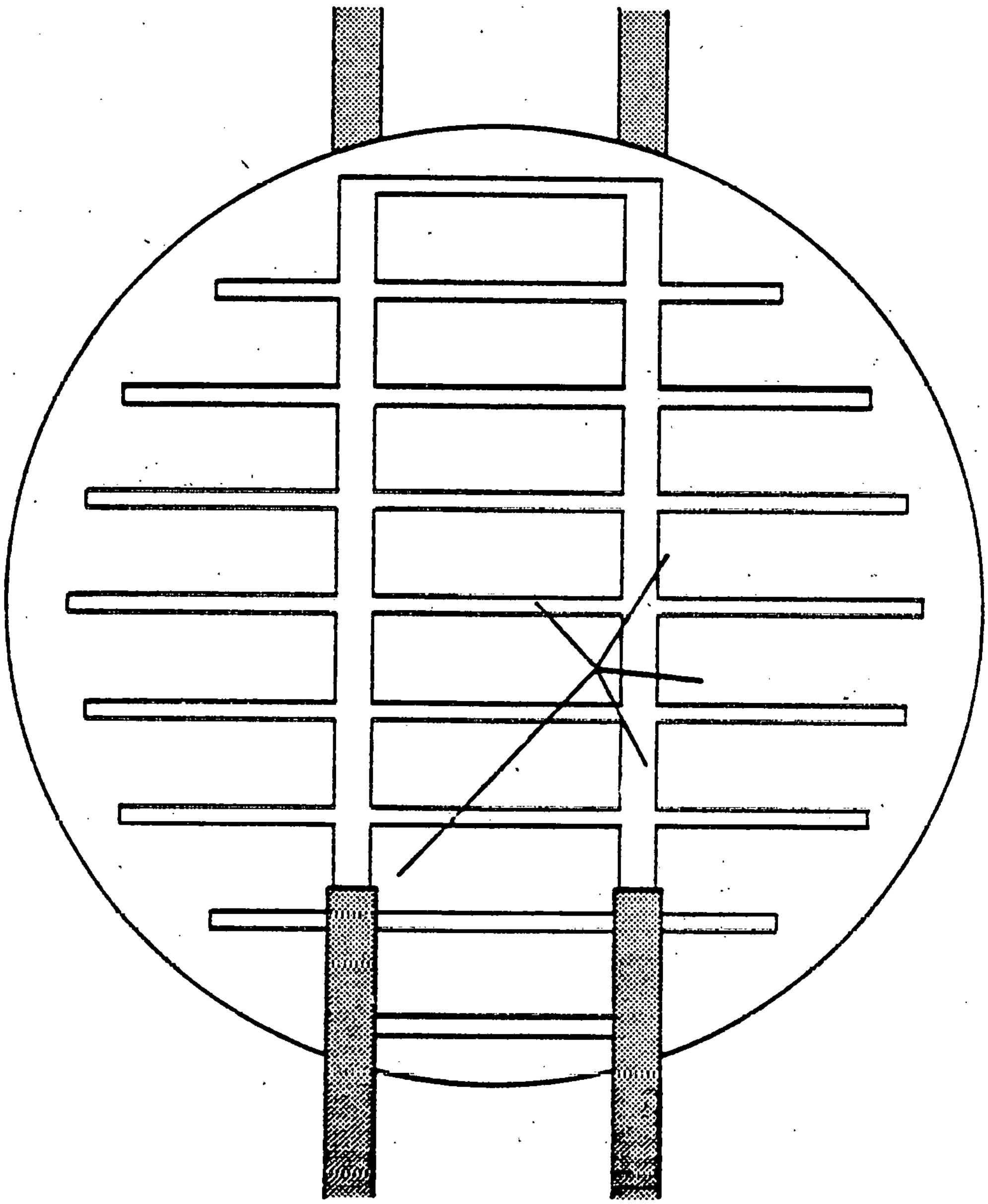


Figure 10. Cracks Caused by Point Impact. Reject.

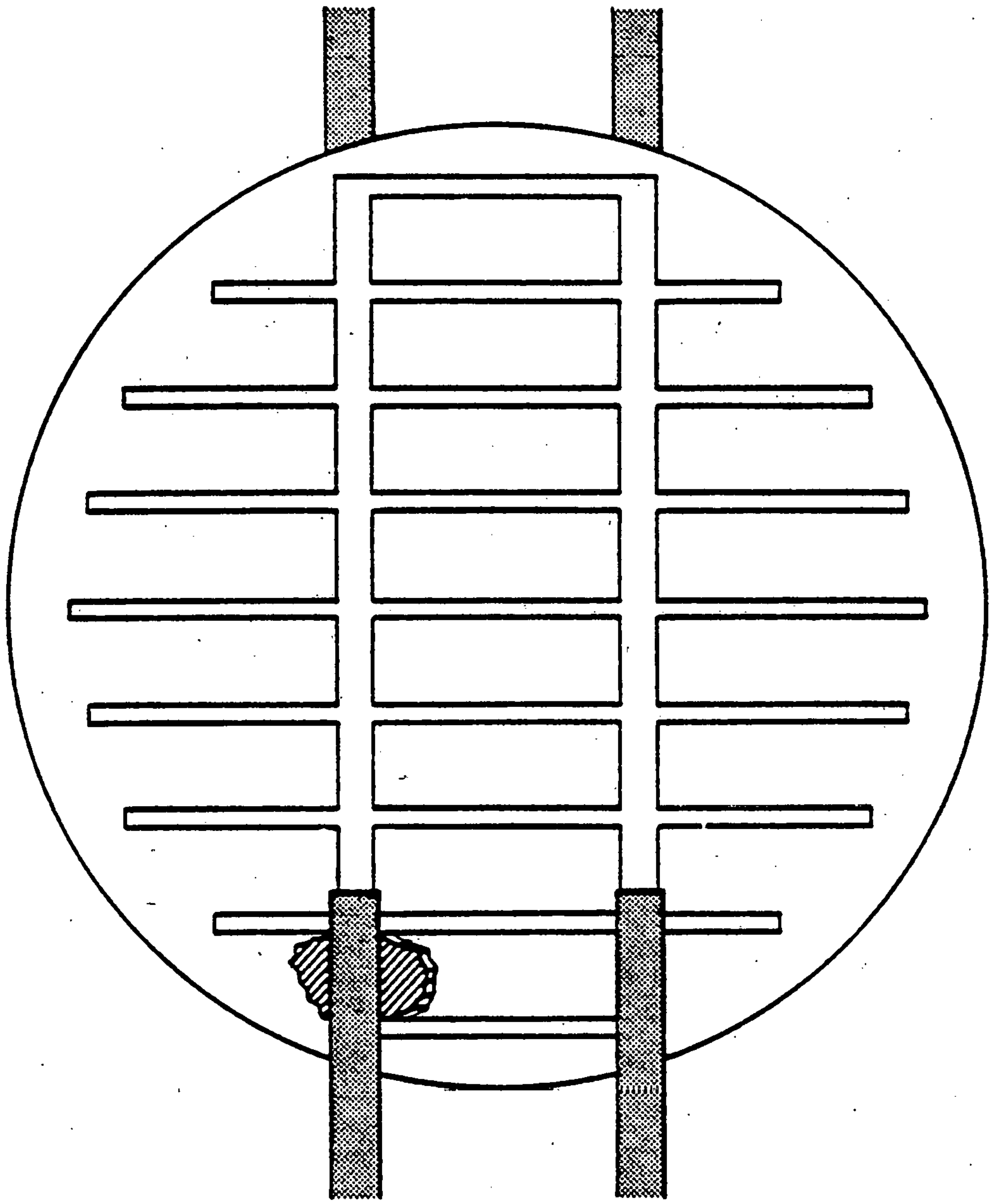


Figure 11. Spalling in Cell Surface Material at Collector. Reject.

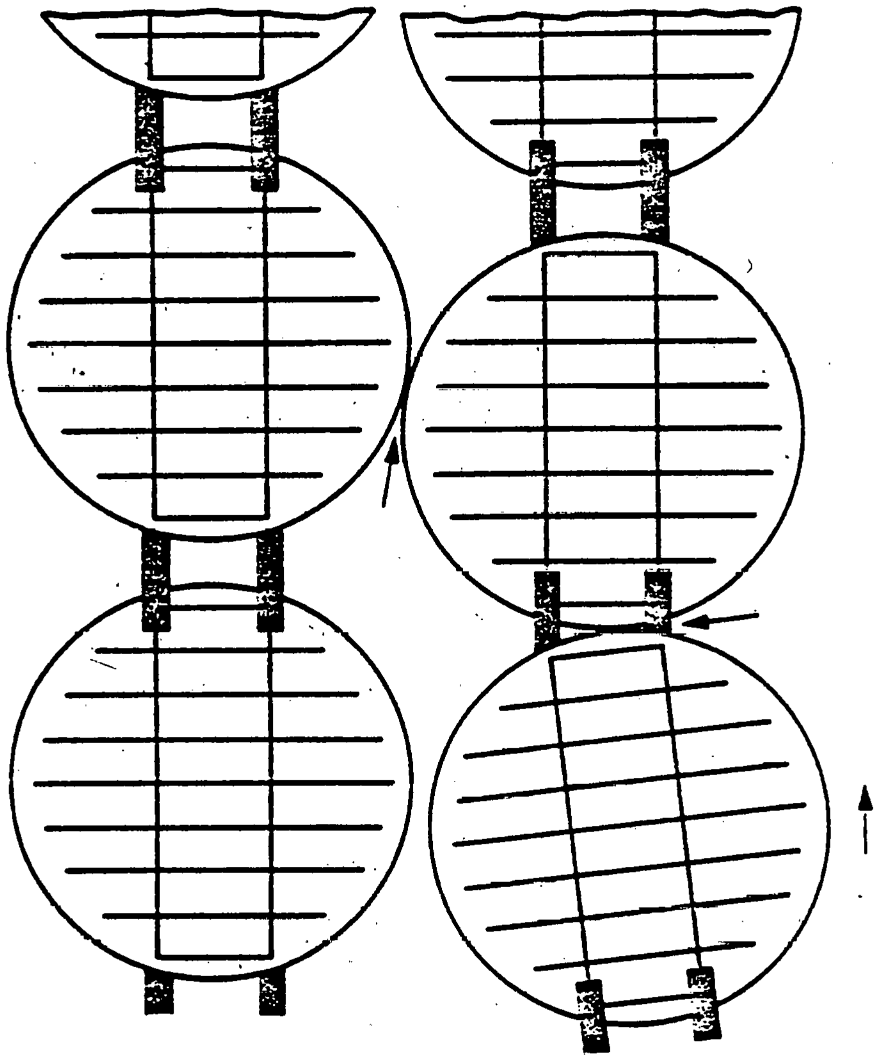


Figure 12. Cells in Edge-to-Edge Contact. Reject.

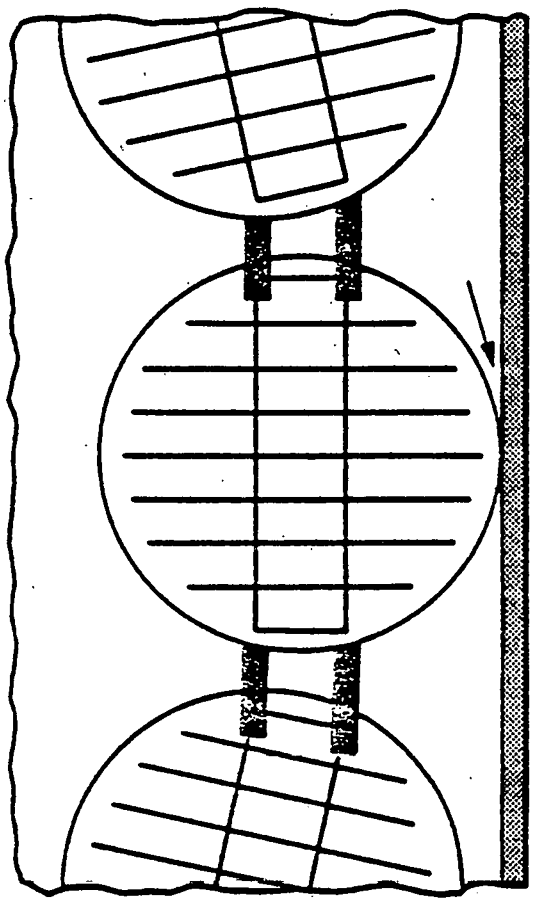


Figure 13. Cell in Edge Contact With Metal Module Substrate. Reject.

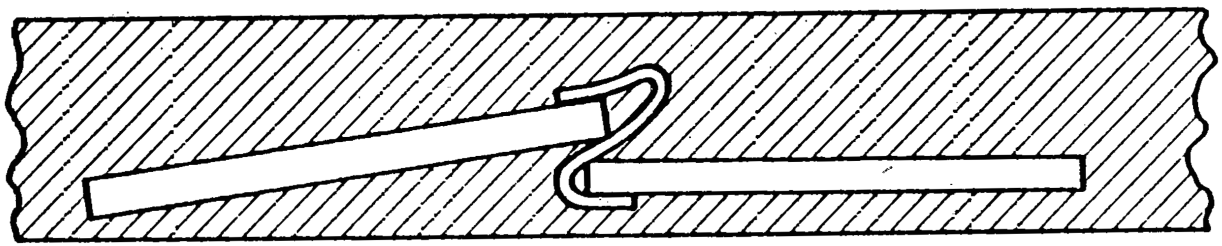


Figure 14. Overlapping Cells. Reject.

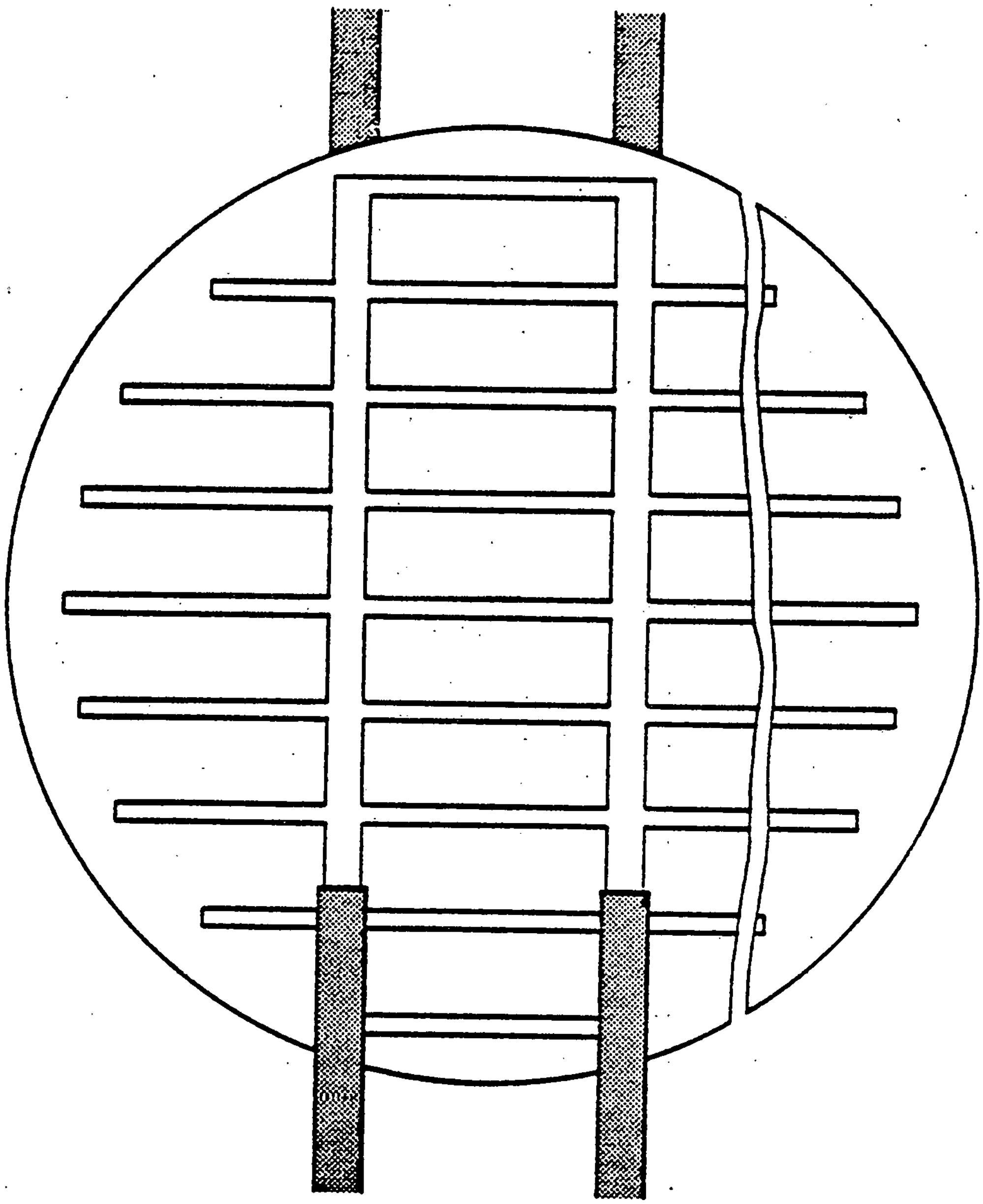


Figure 15. Break in Cell not Intersecting Collector. Acceptable.

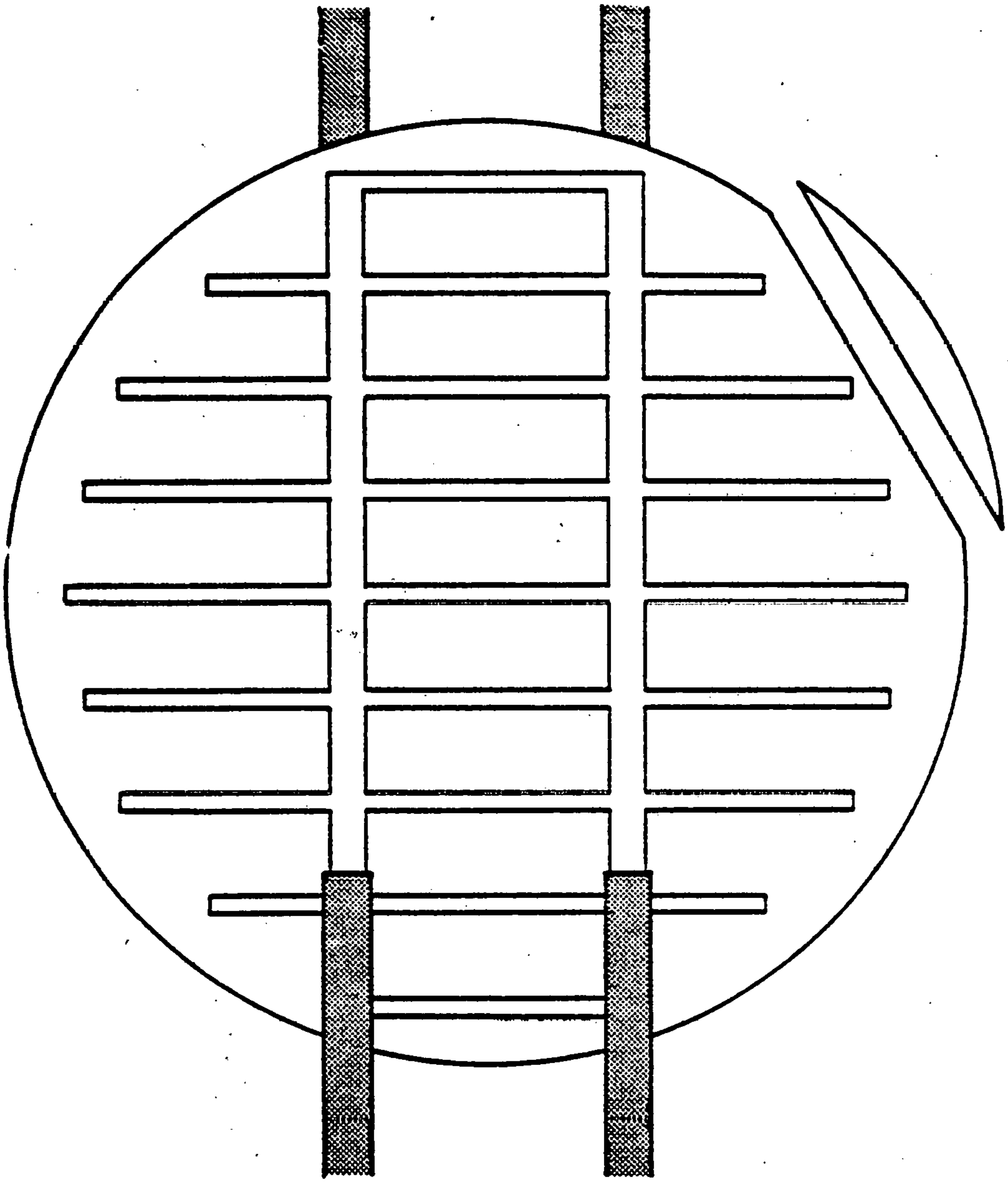


Figure 16. Part of Cell Broken Away Without Disturbing Cell Integrity. Acceptable.

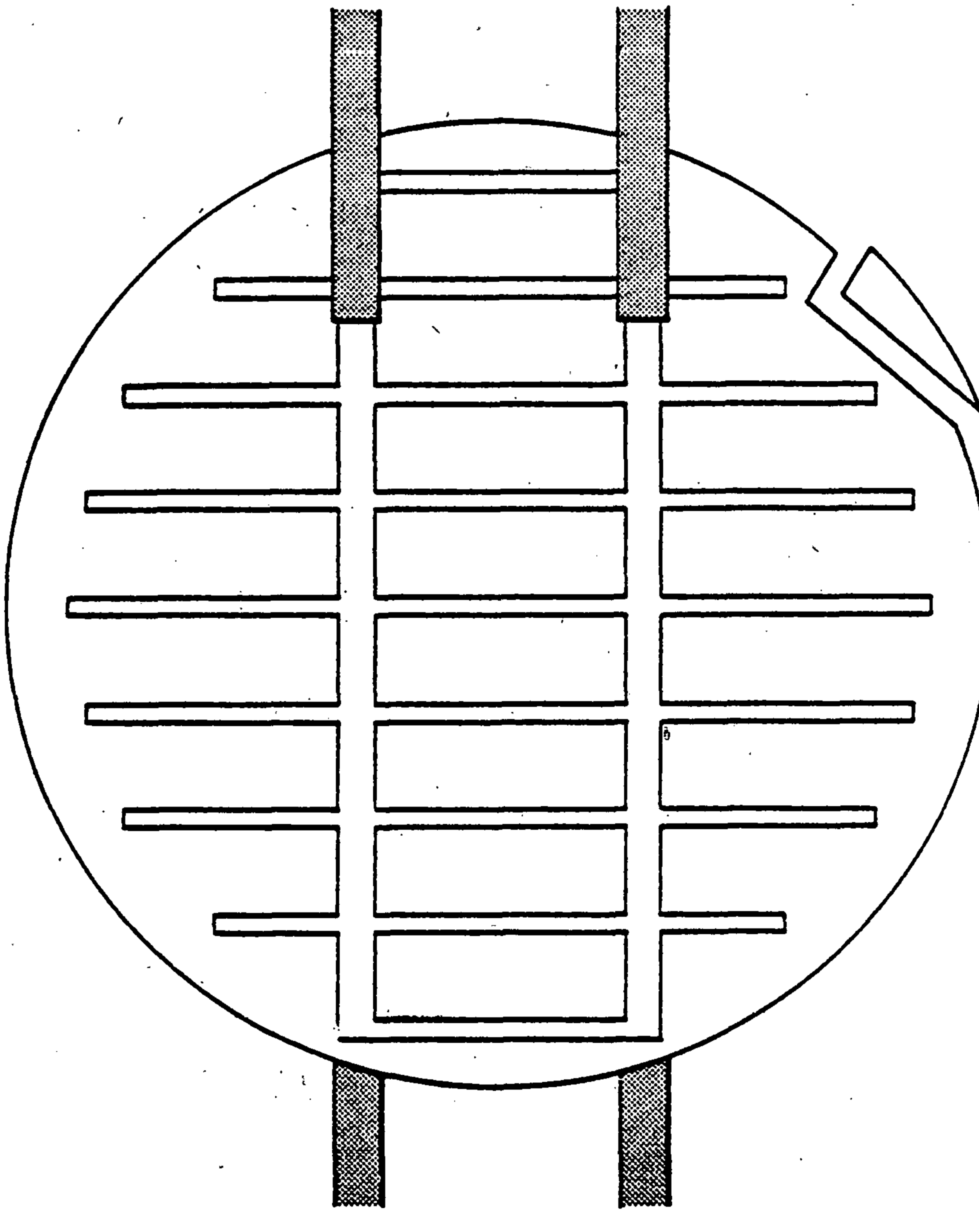


Figure 17. Chip Broken out of Cell Body at Edge. Acceptable.

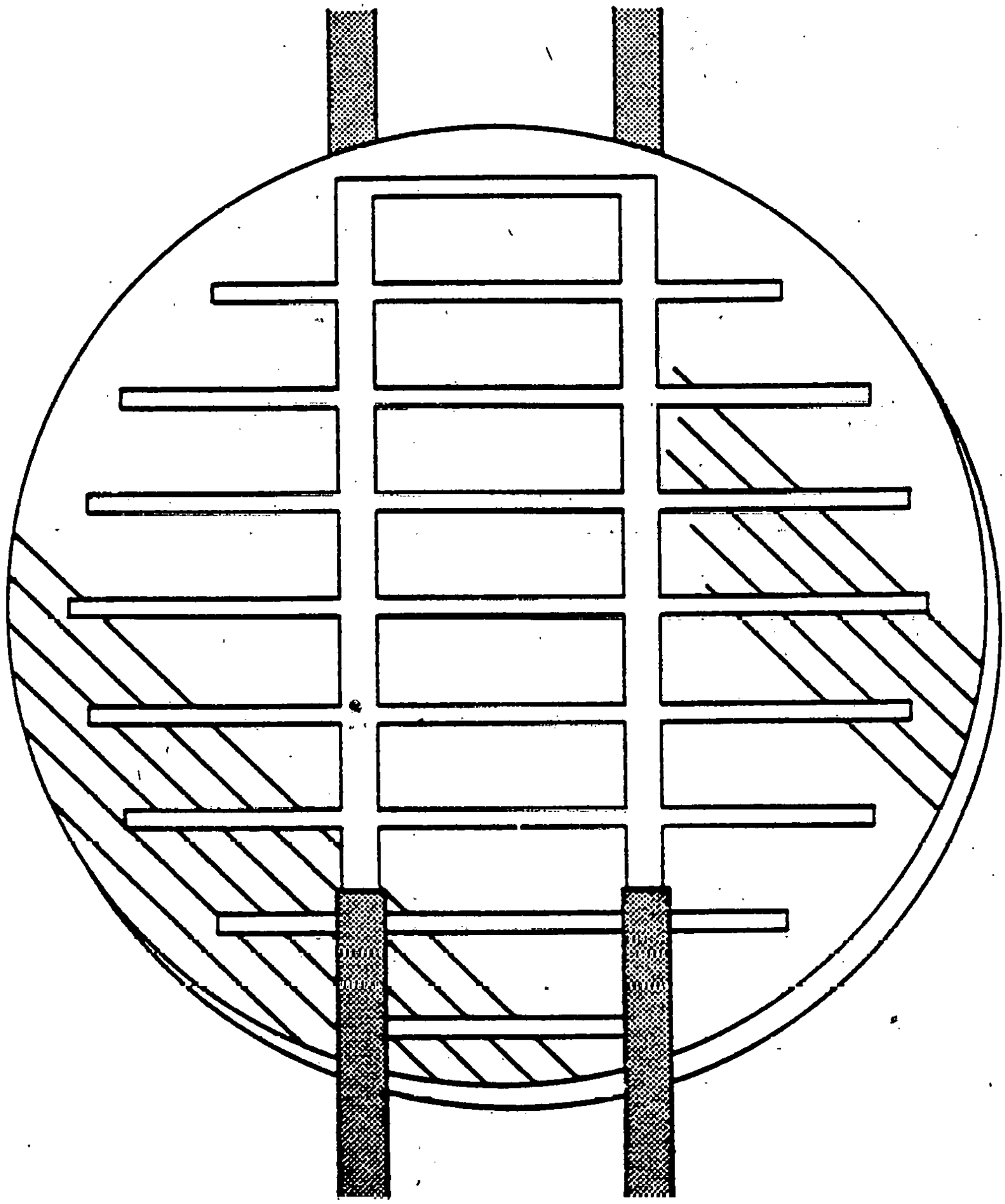


Figure 18. Parallel Saw Marks on Surface. Acceptable.

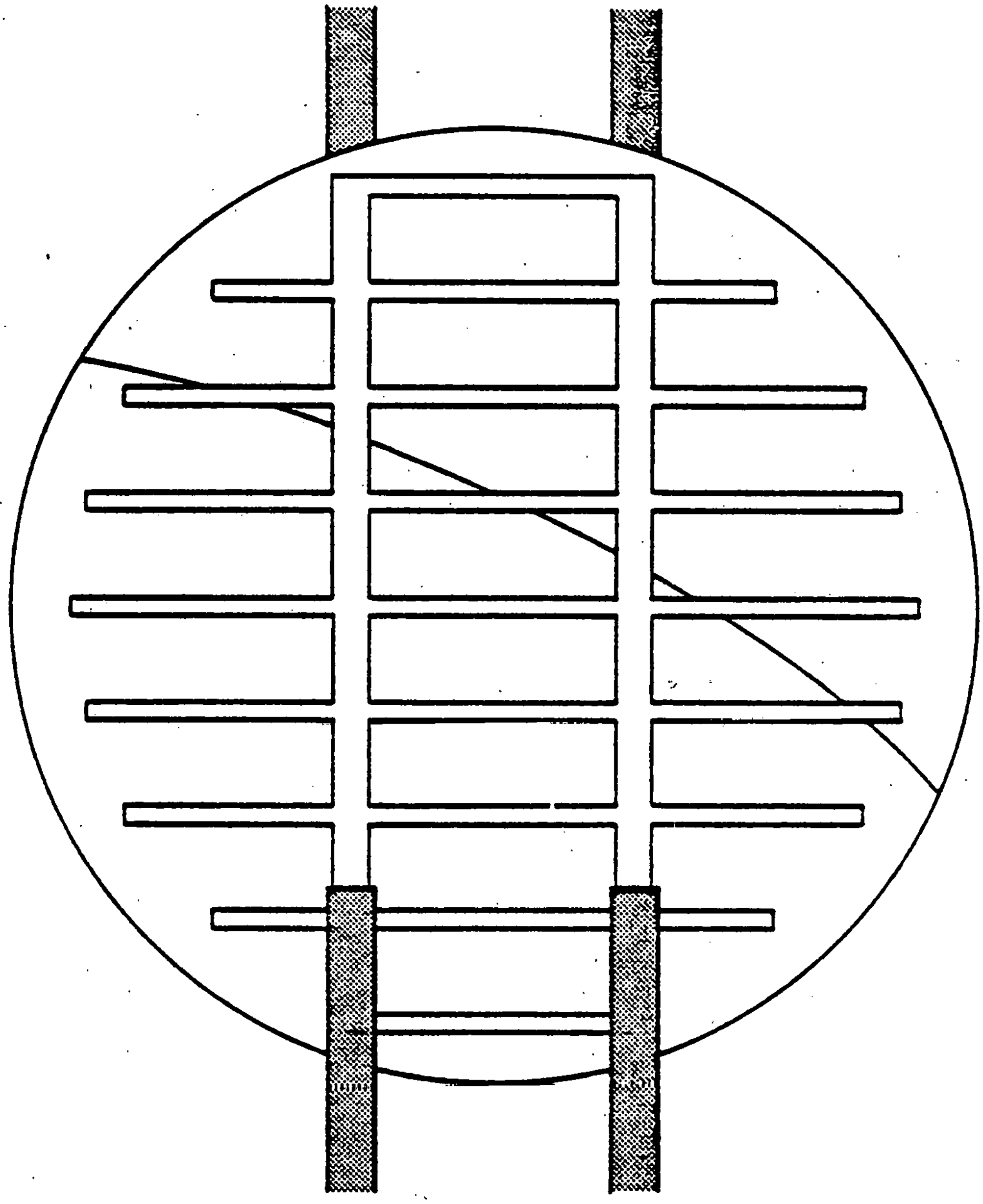


Figure 19. Saw Mark on Cell Surface Only. May be Straight Line or Curved. Acceptable.

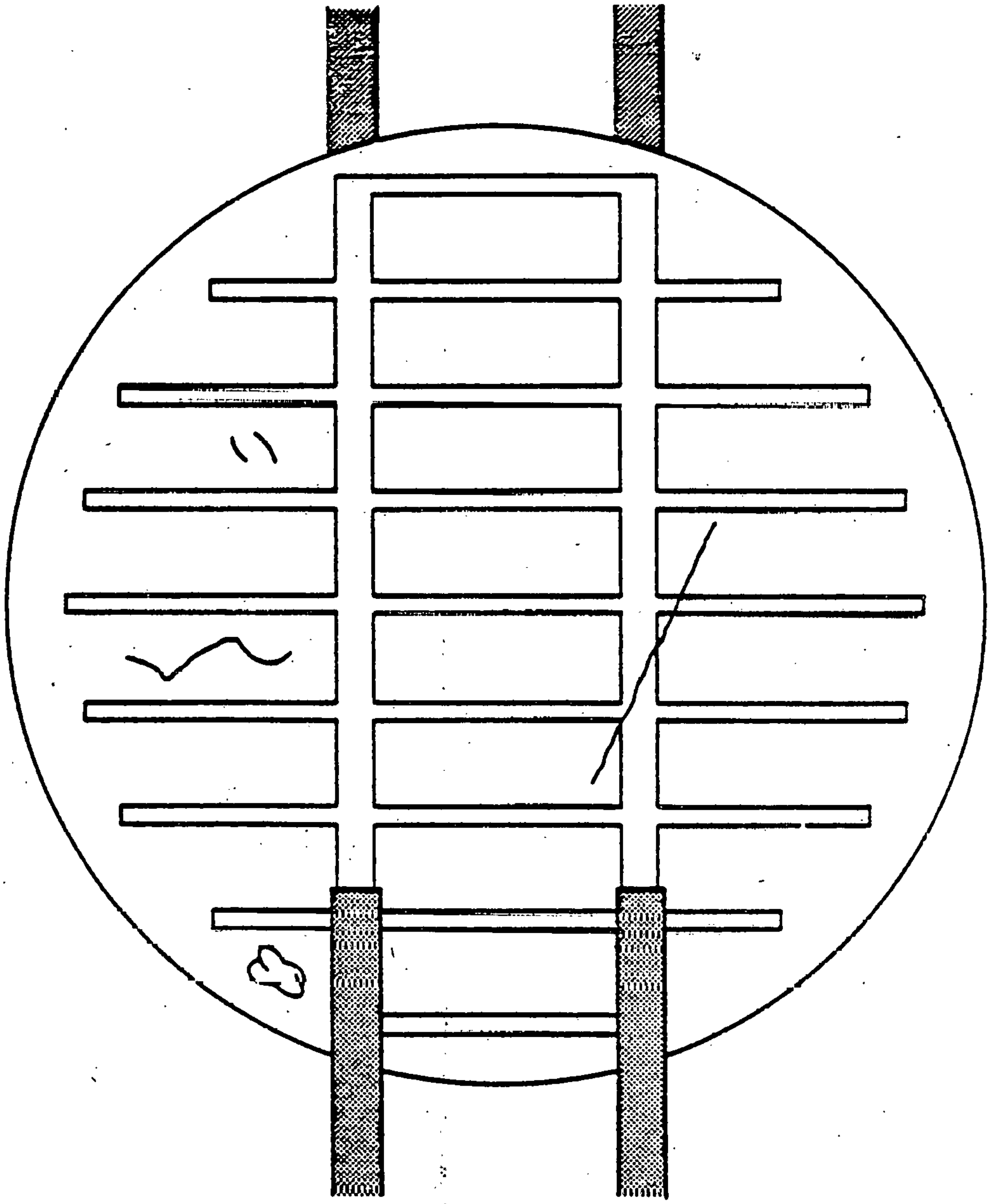


Figure 20. Surface Scars and Scratches. Acceptable.

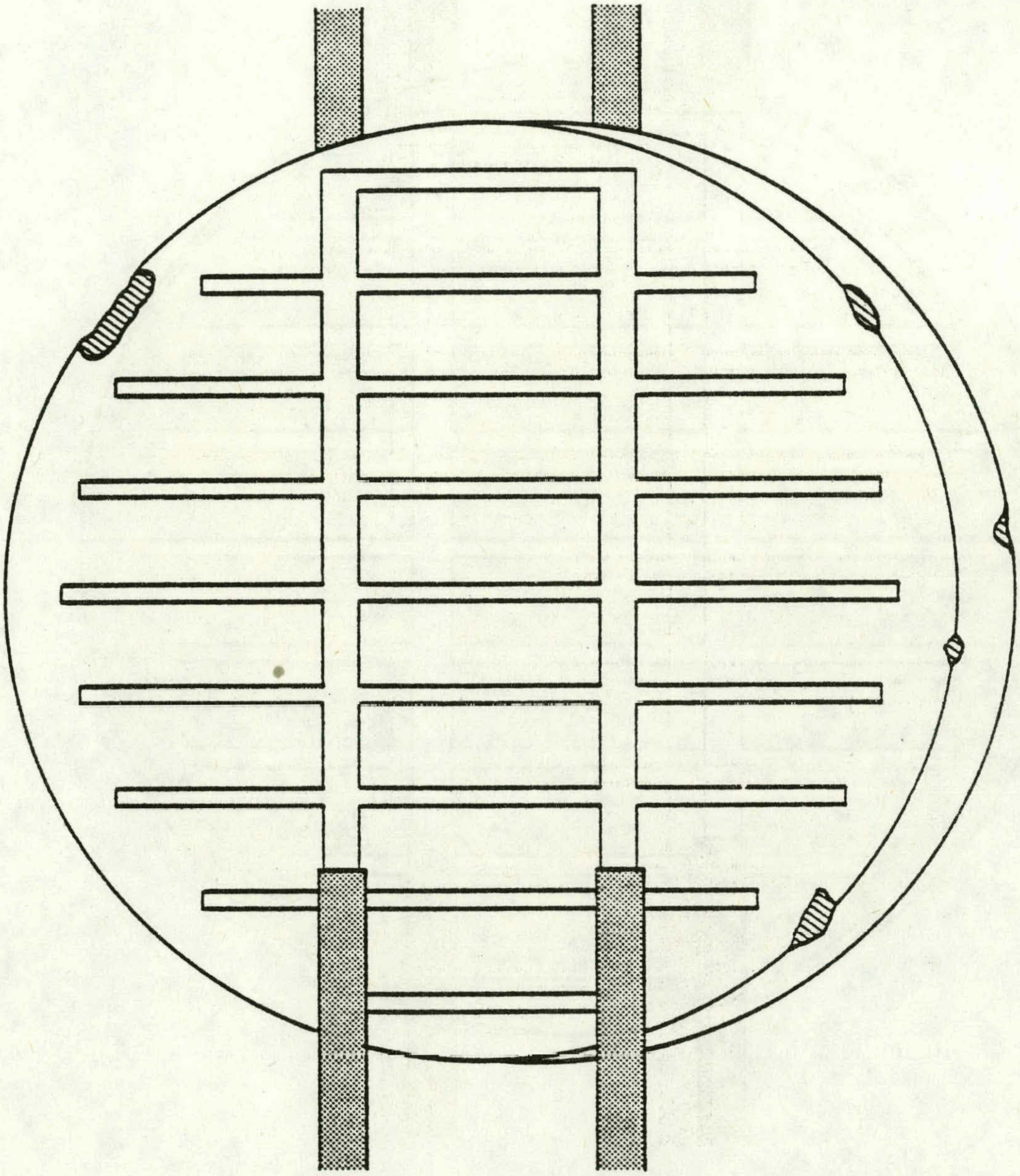


Figure 21. Edge Nicks. Acceptable.

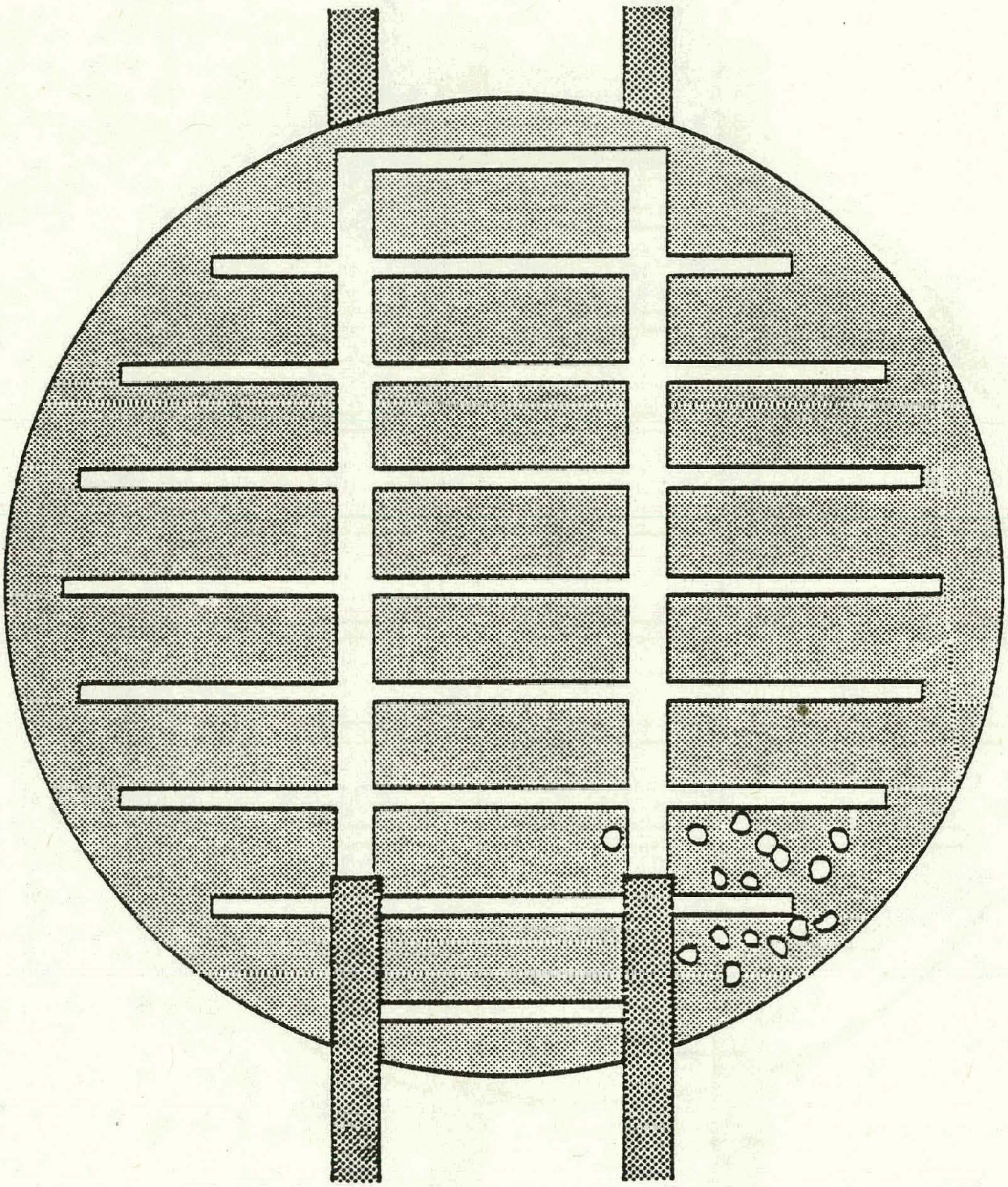


Figure 22. Excess Solder on Cell Surface.
Acceptable.

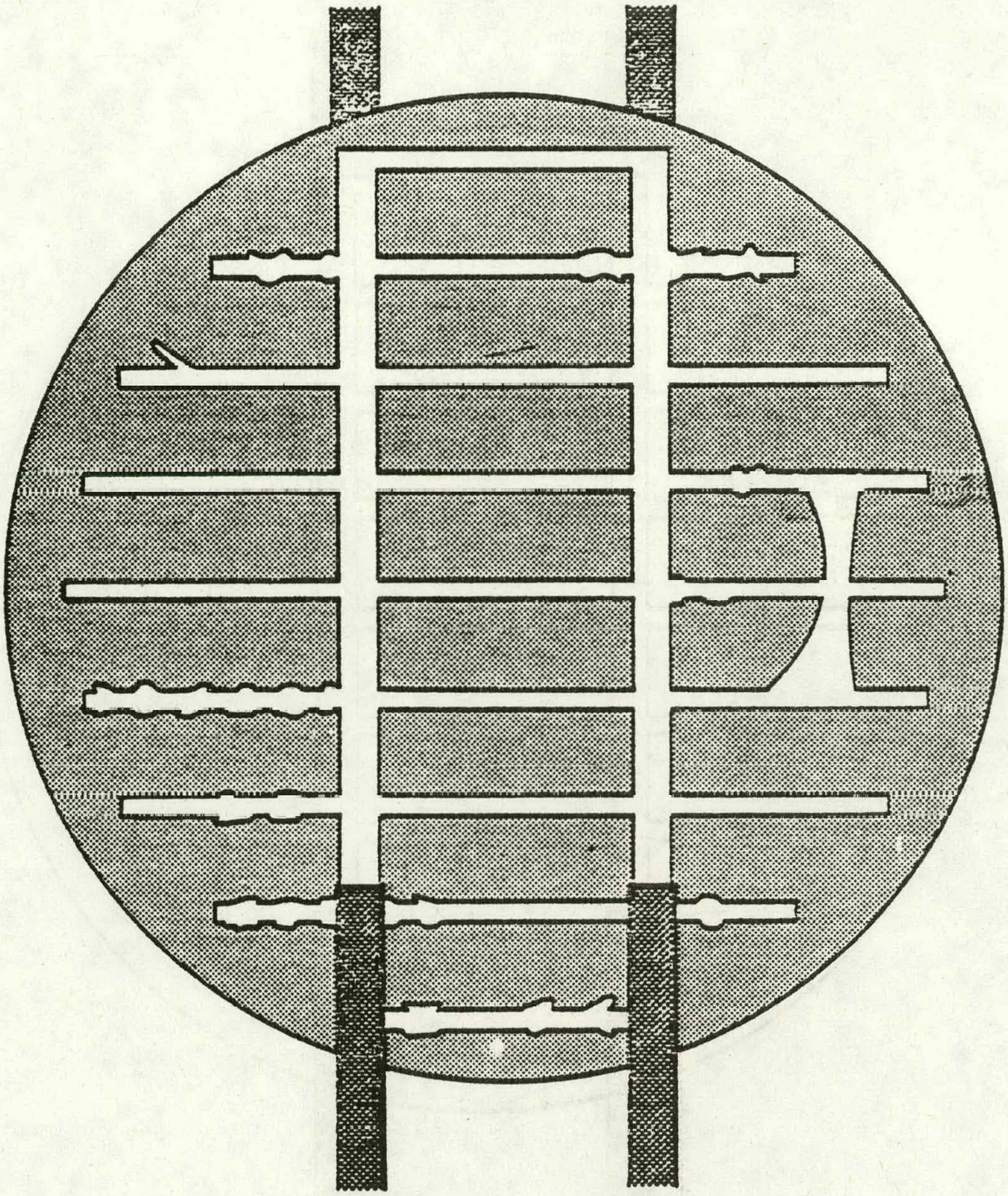


Figure 23. Excess Solder, and Solder Bridging Between Grid Lines. Acceptable.

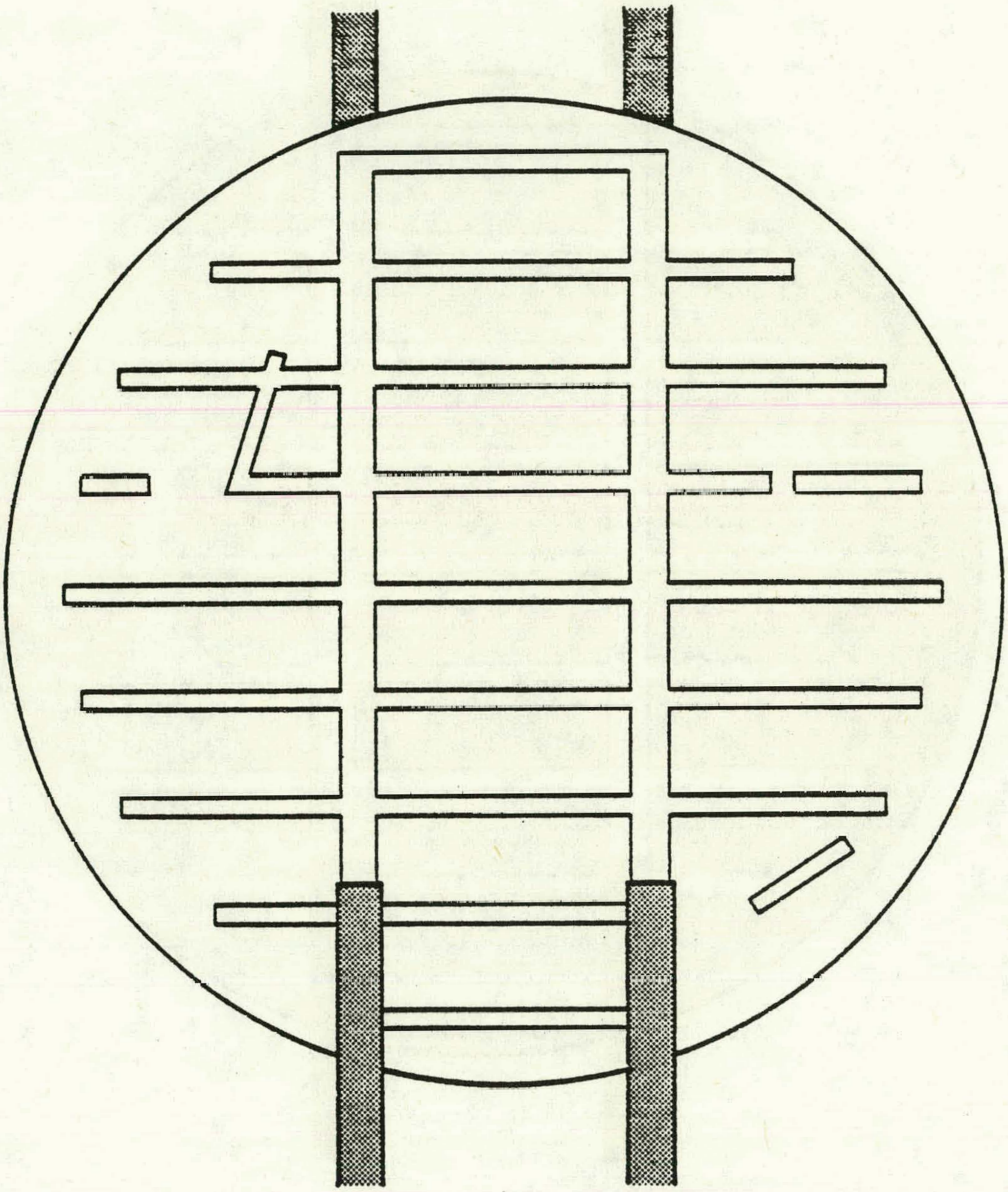


Figure 24. Broken or Missing Grid Lines With Loose Fragments of Grid Lines. Acceptable.

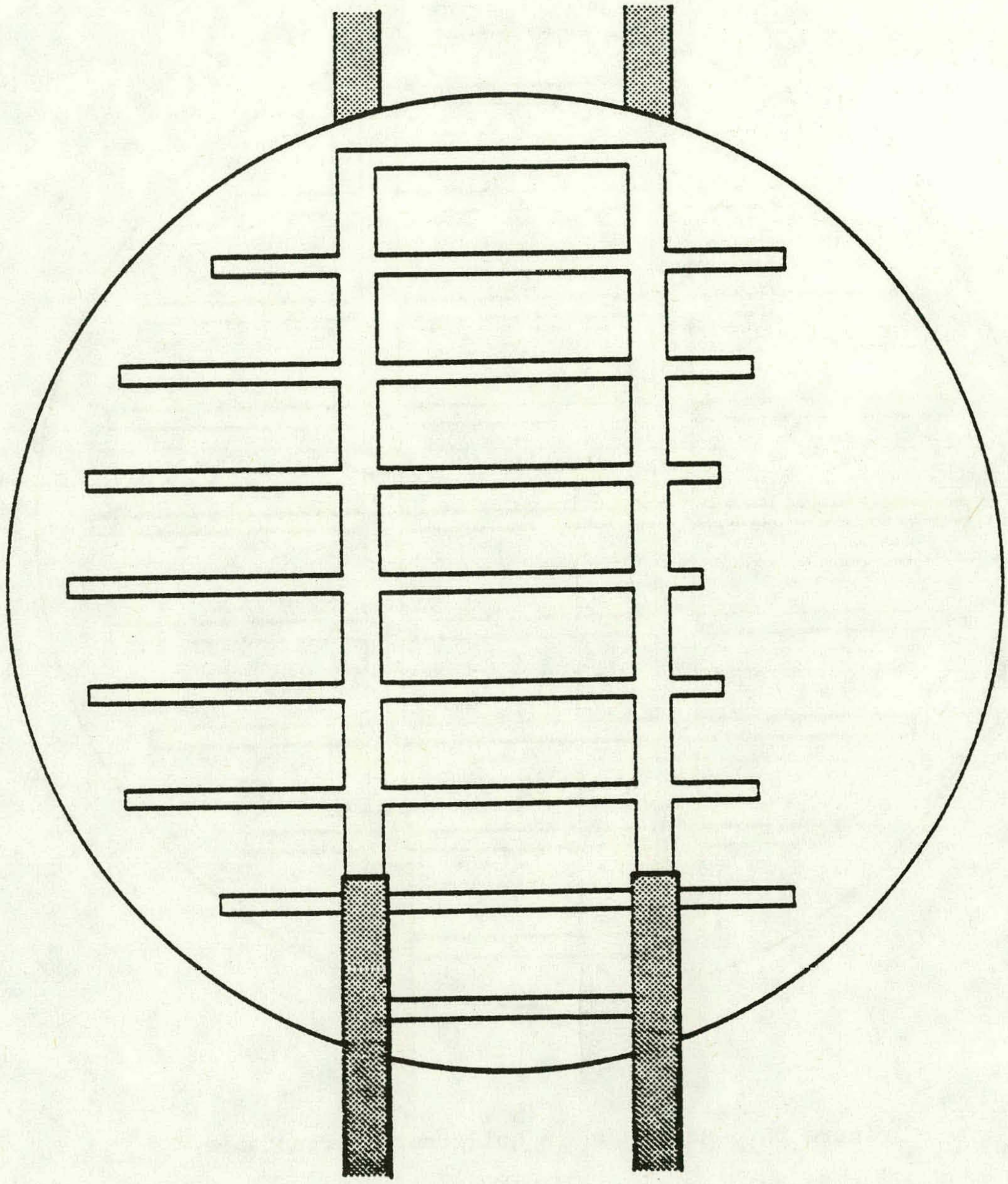


Figure 25. Missing Grid Lines. Acceptable.

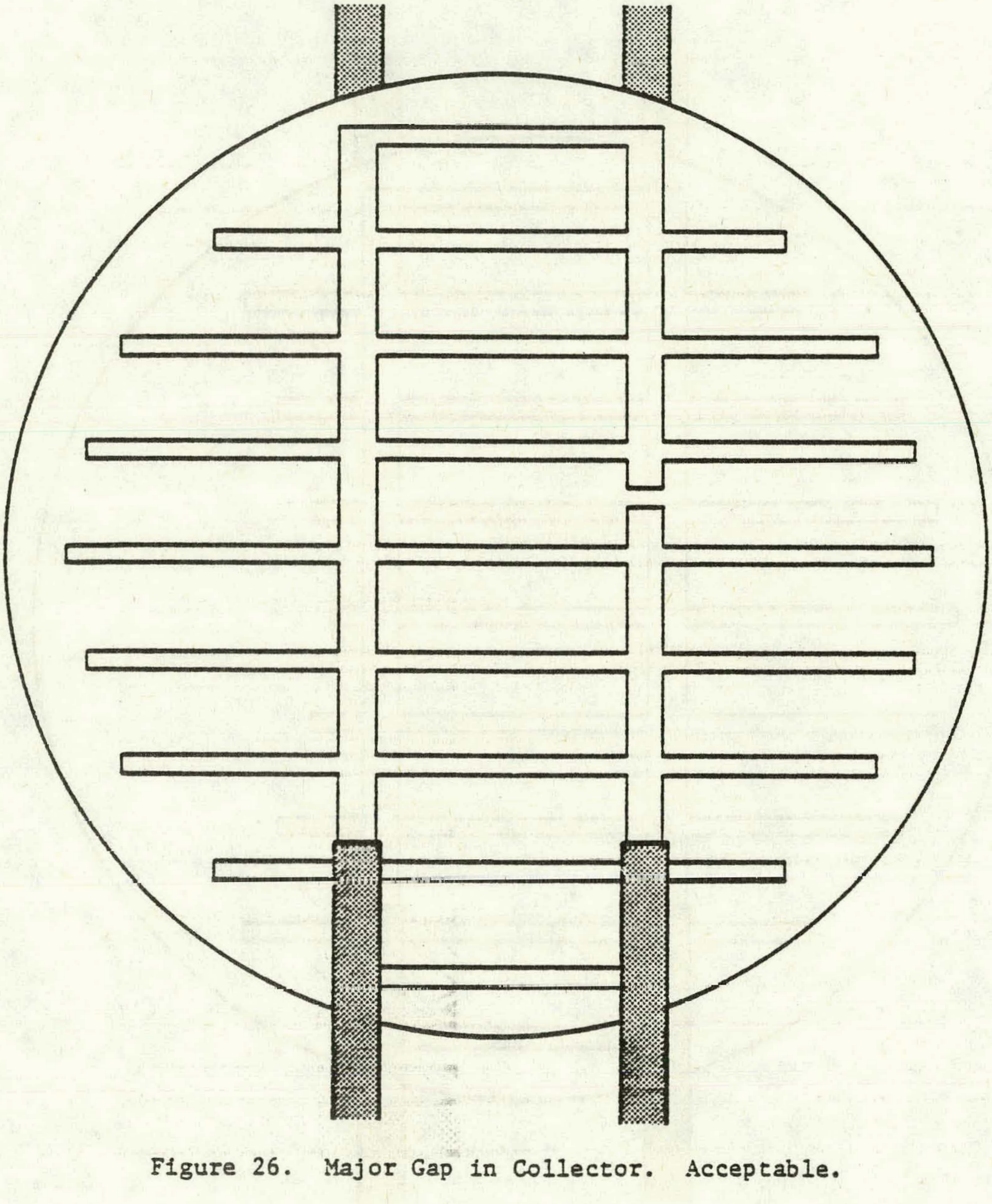


Figure 26. Major Gap in Collector. Acceptable.

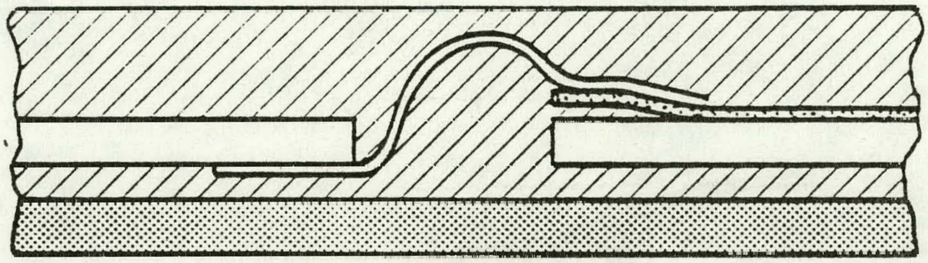


Figure 27a. Collector Delaminated at Interconnect Solder Joint. Reject.

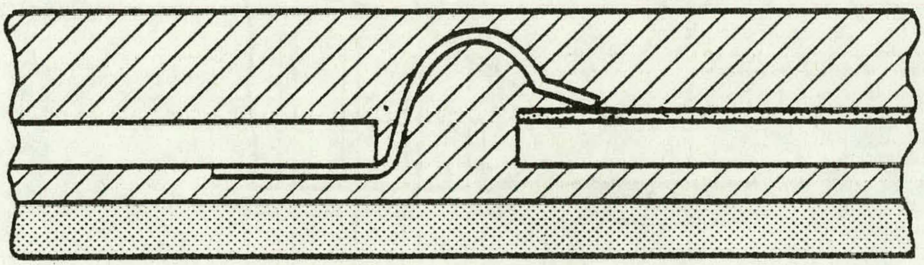


Figure 27b. Interconnect Delaminated at Solder Joint. Reject.

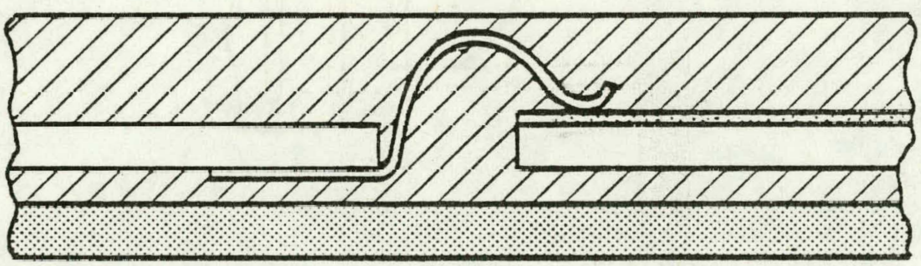


Figure 27c. Interconnect Delaminated at Solder Joint. Reject.

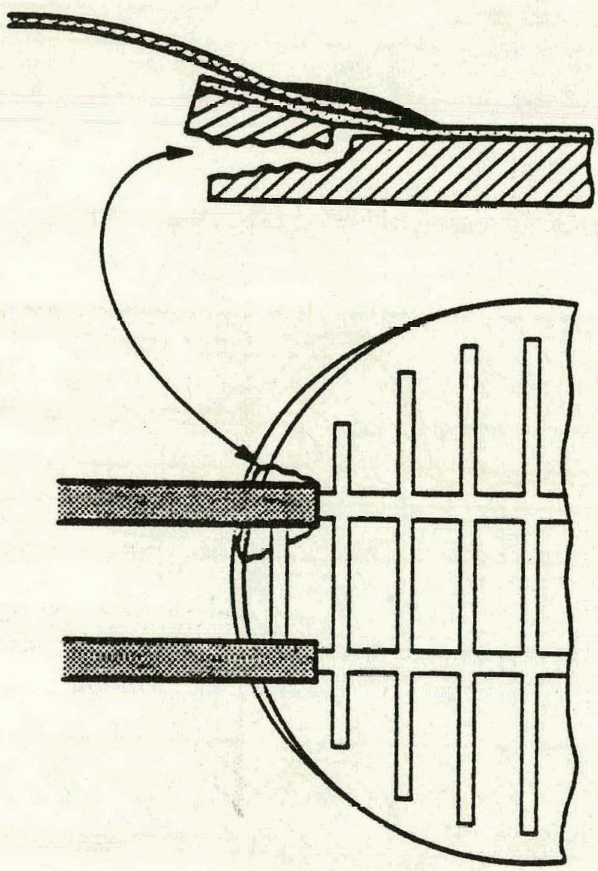


Figure 28. Alligatored Cell. Broken Material Under Collector Solder Joint Starting at Edge of Cell. Reject.

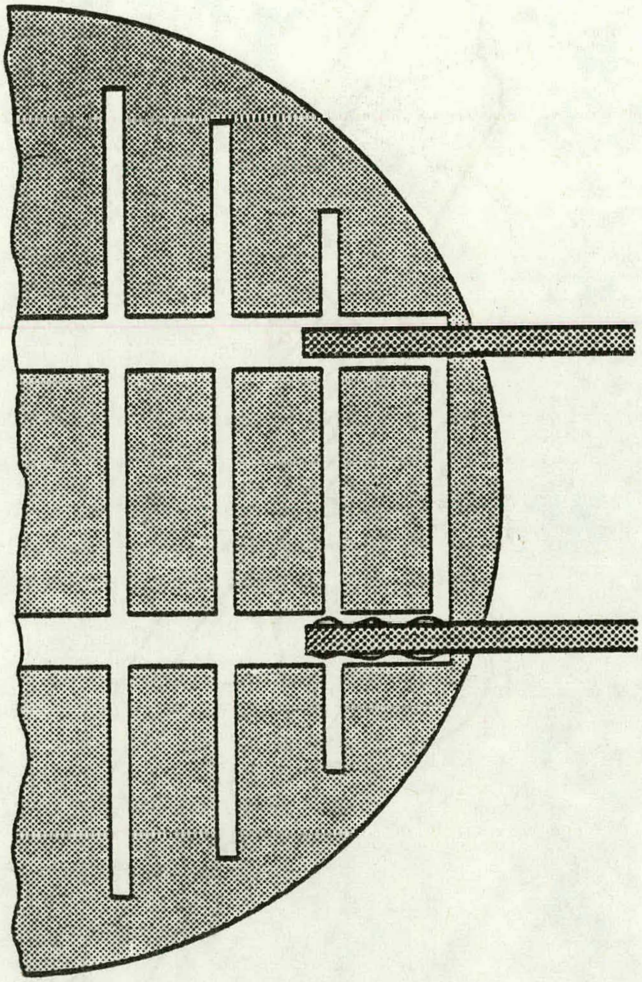


Figure 29. Interconnect Contact Solder Dewetting. Reject.

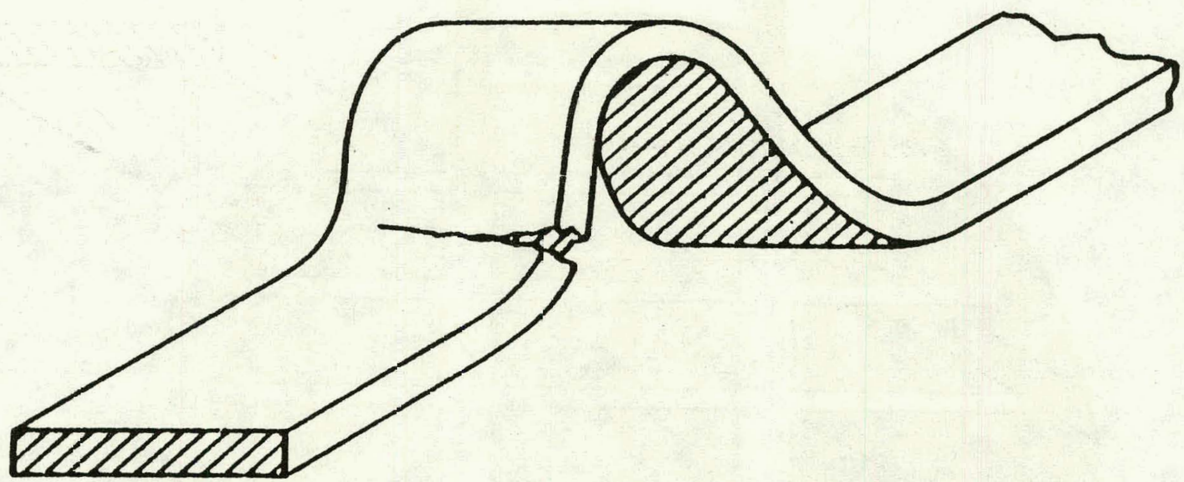


Figure 30. Solid Strip Interconnect Metal Fatigue Fracture. Reject.

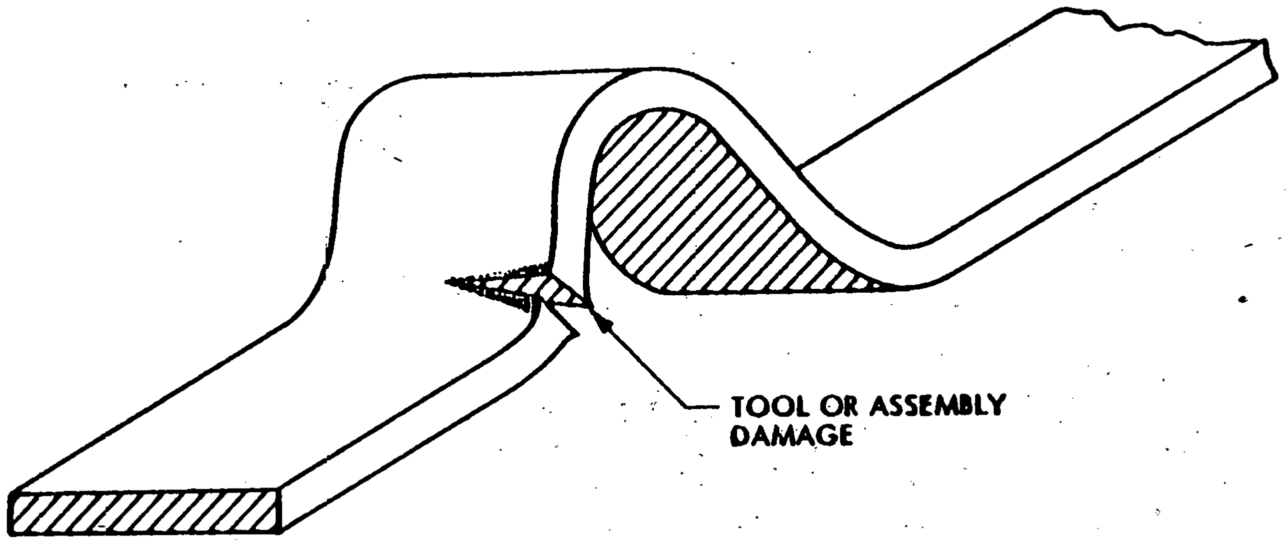


Figure 31. Solid Strip Interconnect Discrepancies If in Stress Relief Area. Reject if the Cross-Sectional Area of the Strip is Reduced by 25% or More.

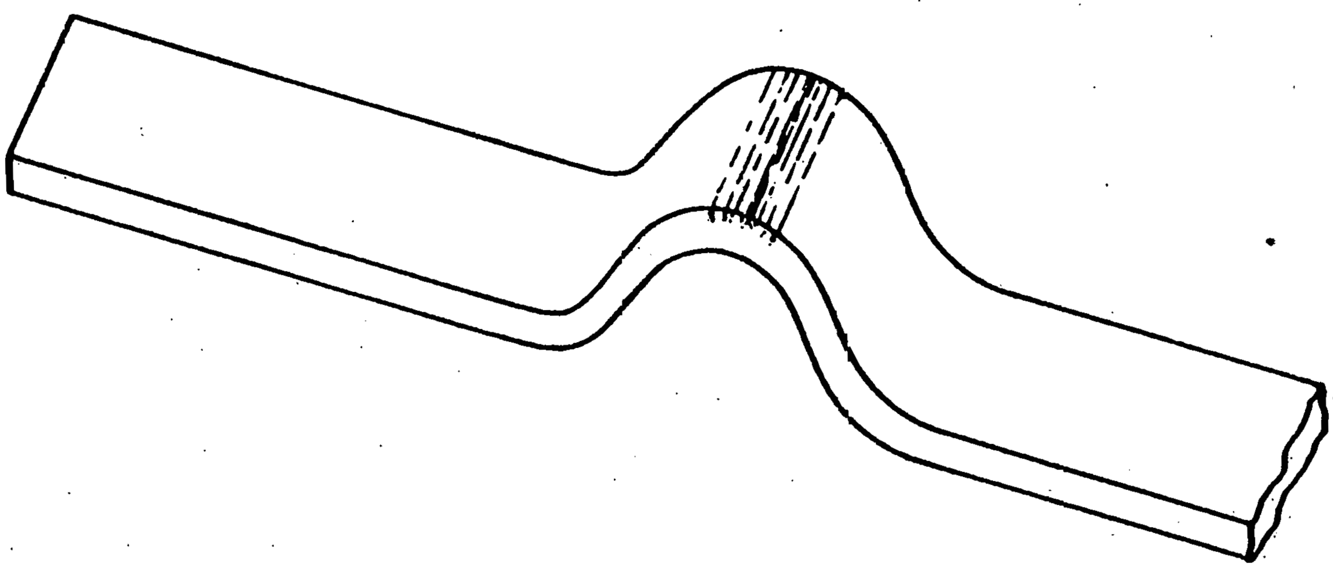


Figure 32. Interconnect Stress Damage. Reject.

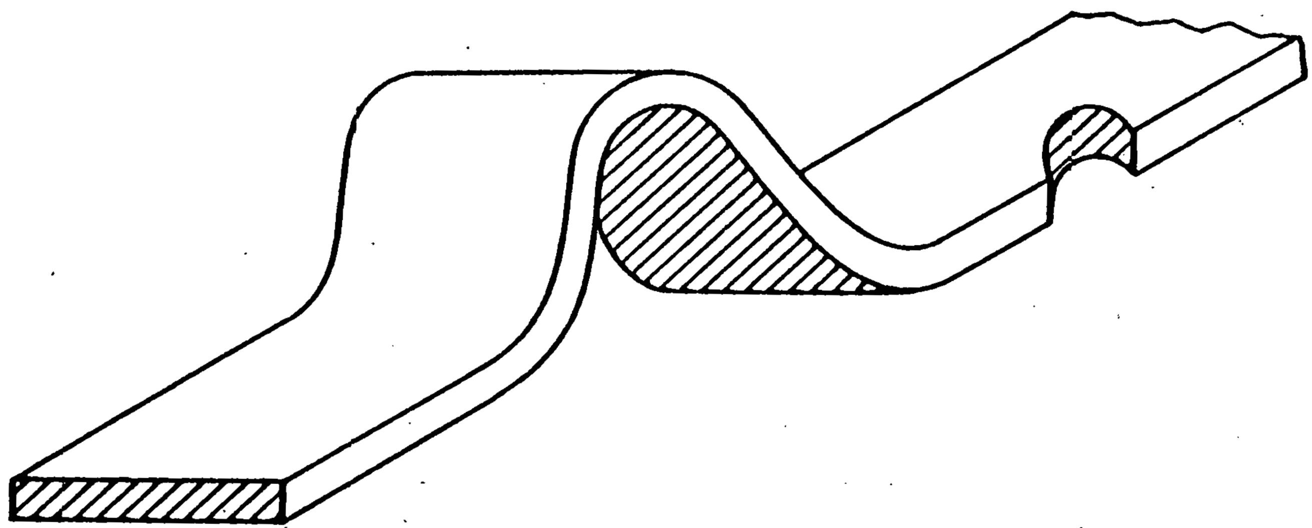


Figure 33. Solid Strip Interconnect Discrepancies. Reject if the Cross-Sectional Area of the Strip is Reduced by 25% or More.

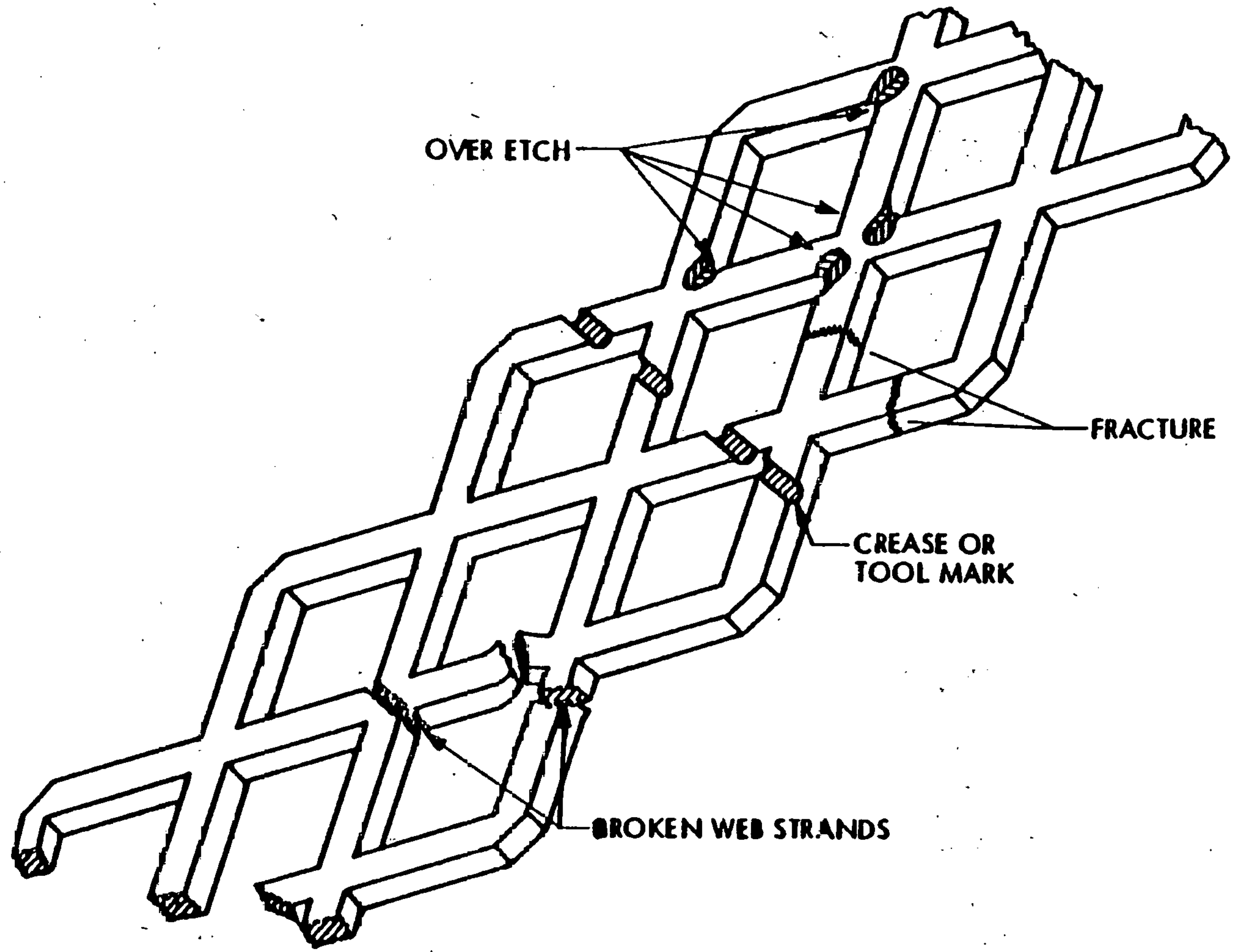


Figure 34. Web-Type Interconnect Defects. Defects Which Reduce the Cross-Sectional Area of the Web Material by 25% or More are Grounds for Rejection of the Unit.

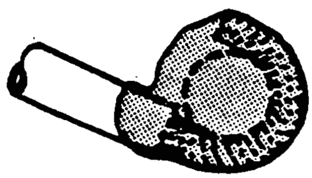


Figure 35. Insulation Buried Into the Solder. Reject.

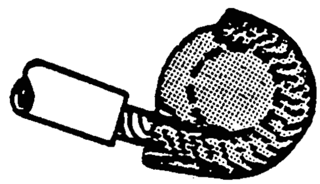


Figure 36. Poor Flow to Wire. Insufficient Heat or Contaminated Surfaces. Reject.

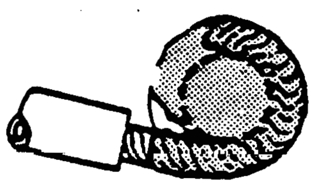


Figure 37. Cracked Solder. Reject.

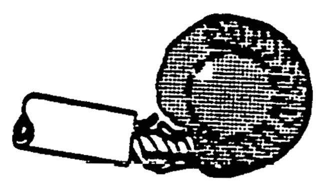


Figure 38. Splayed or Birdcaged Wire Strands at Solder Joint, With Strand Breakage. Usually Shows Exposed Copper in Breakage Area. Reject.

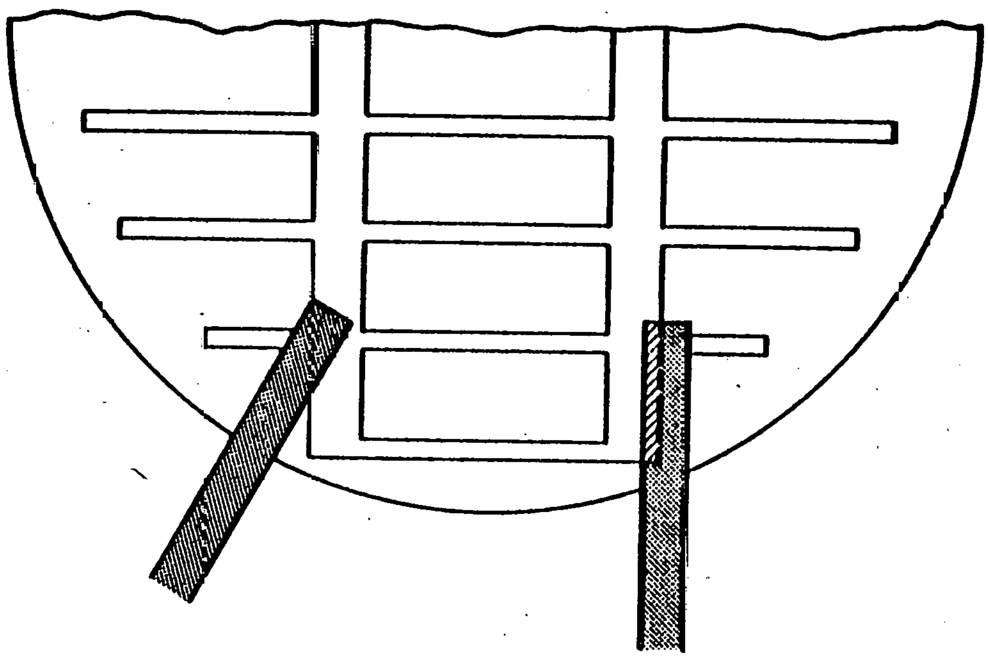


Figure 39. Any Interconnect Tab Misalignment With Less Than 50% Interconnect Contact With Collector. Reject.

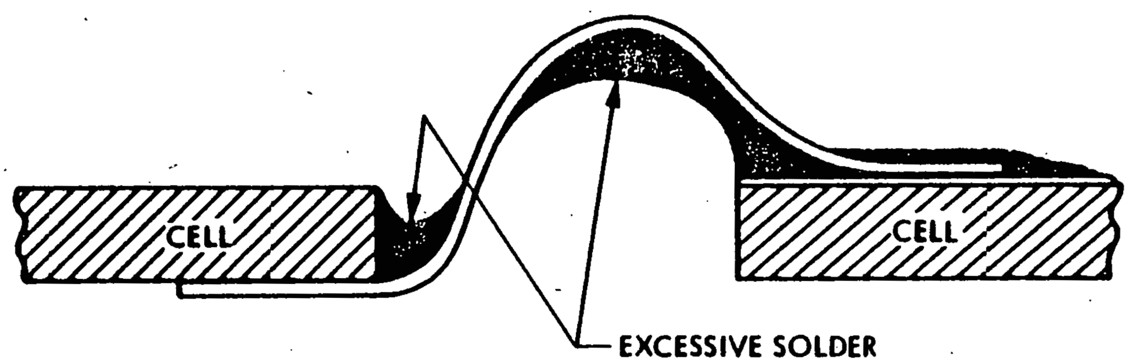


Figure 40. Stress Relief Loop Frozen by Solder. Reject.

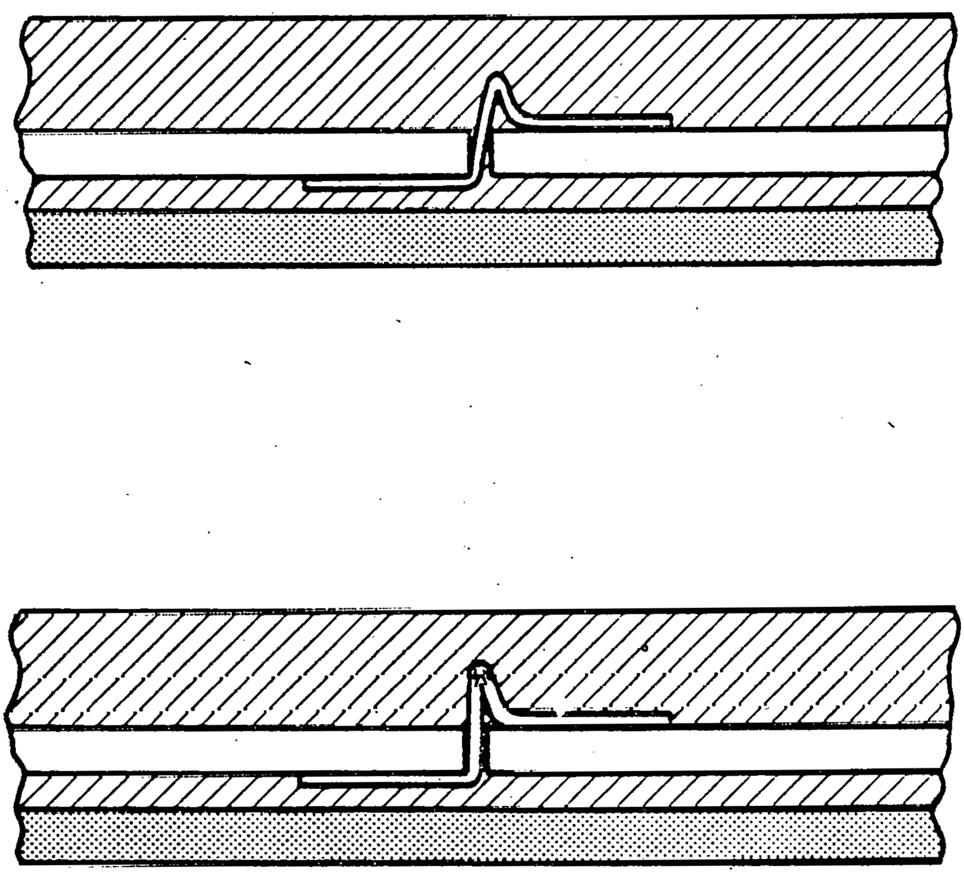


Figure 41. Interconnect Crushed Between Cell Edges and/or Distorted and Degrading Stress Relief. Reject.

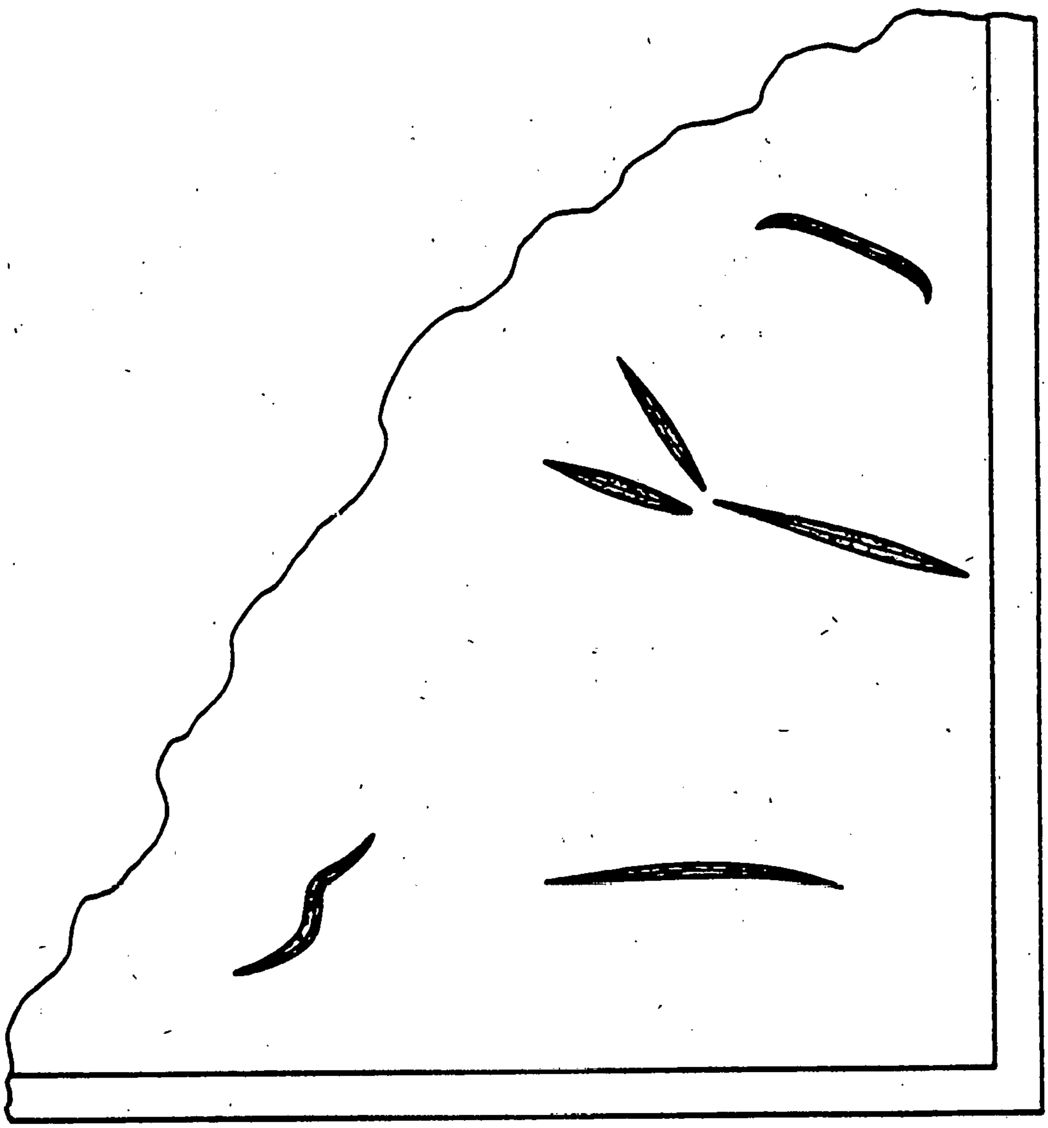


Figure 42. Encapsulant Surface Split. Reject.

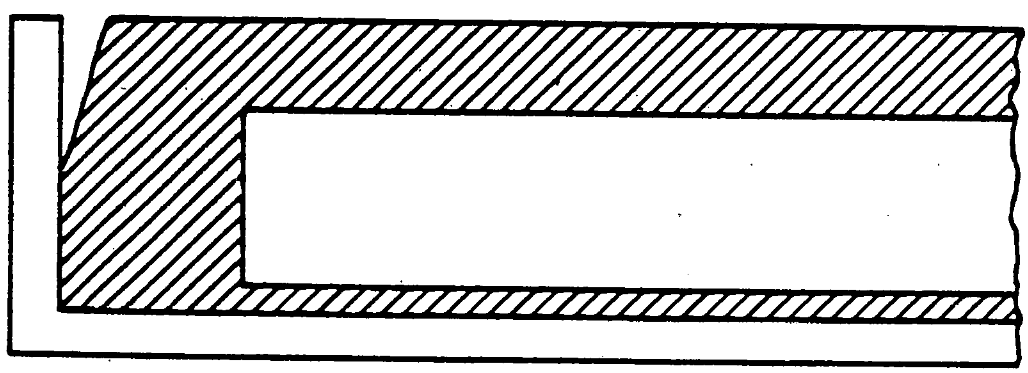


Figure 43. Edge Seal Void Between Substrate and Potting. (Side View) Reject.

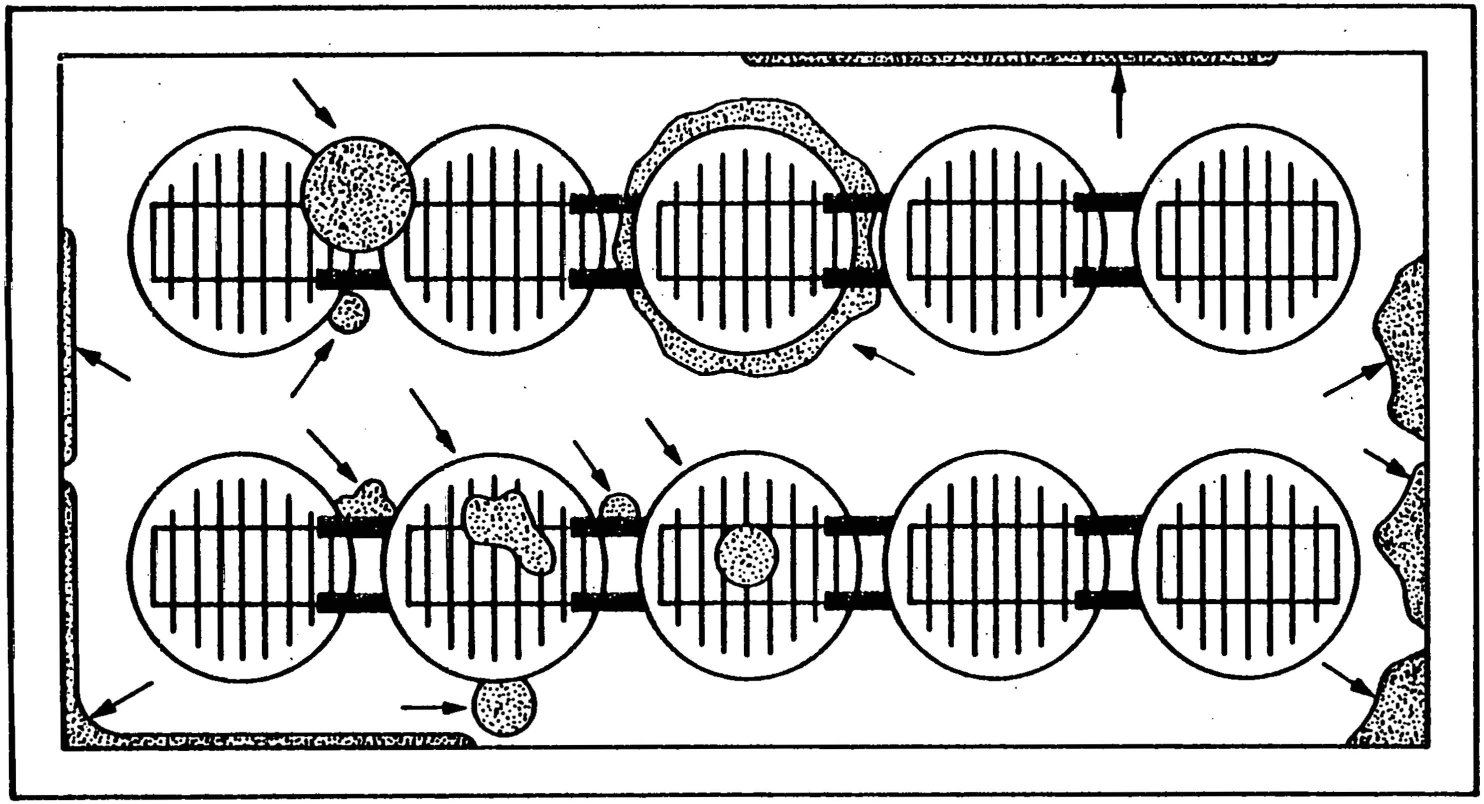


Figure 44. Any Delaminations or Bubbles Greater Than 3 mm. Reject.

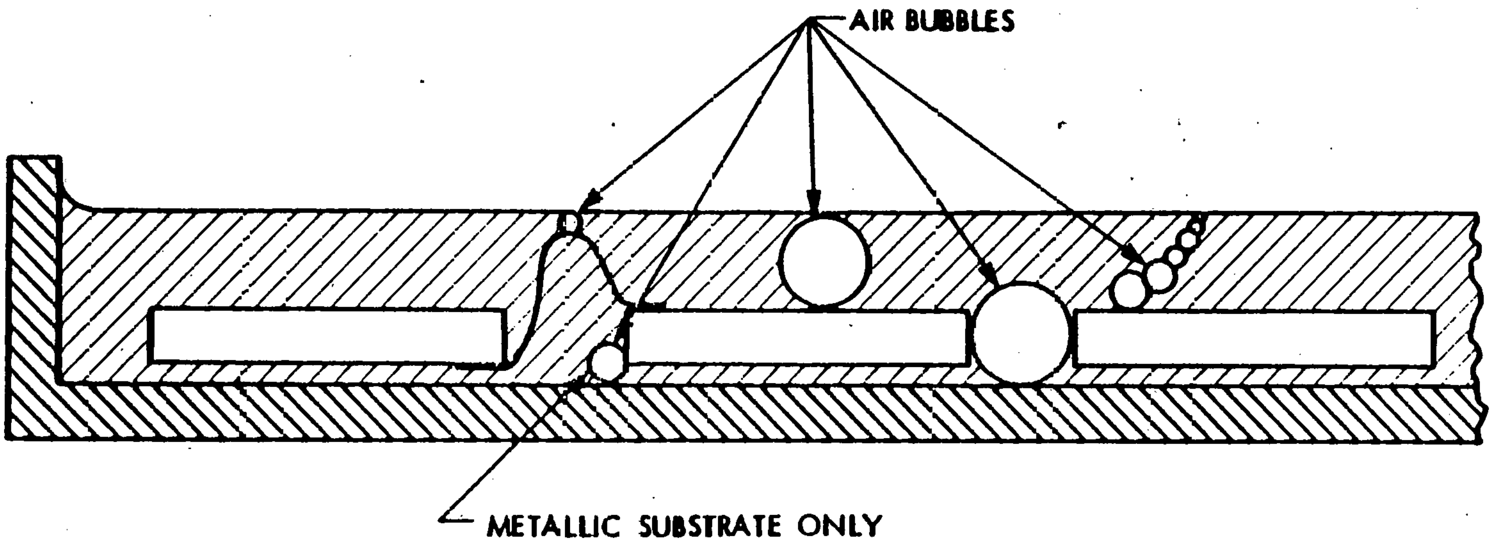


Figure 45. Air Bubble Discrepancies. Reject.

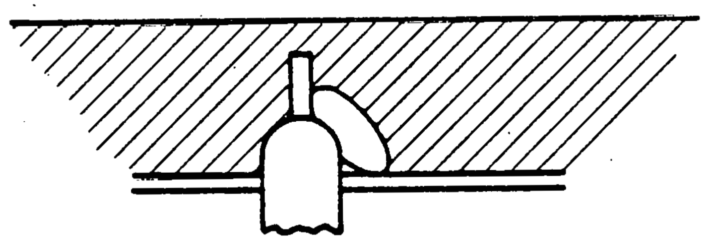


Figure 46. Void or Delamination from Output Terminal to Metal Substrate. Reject.

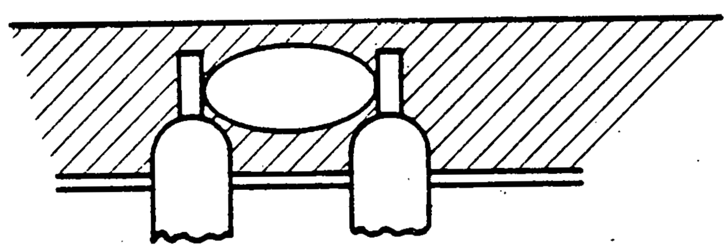


Figure 47. Void or Delamination Between Output Terminals. Reject.

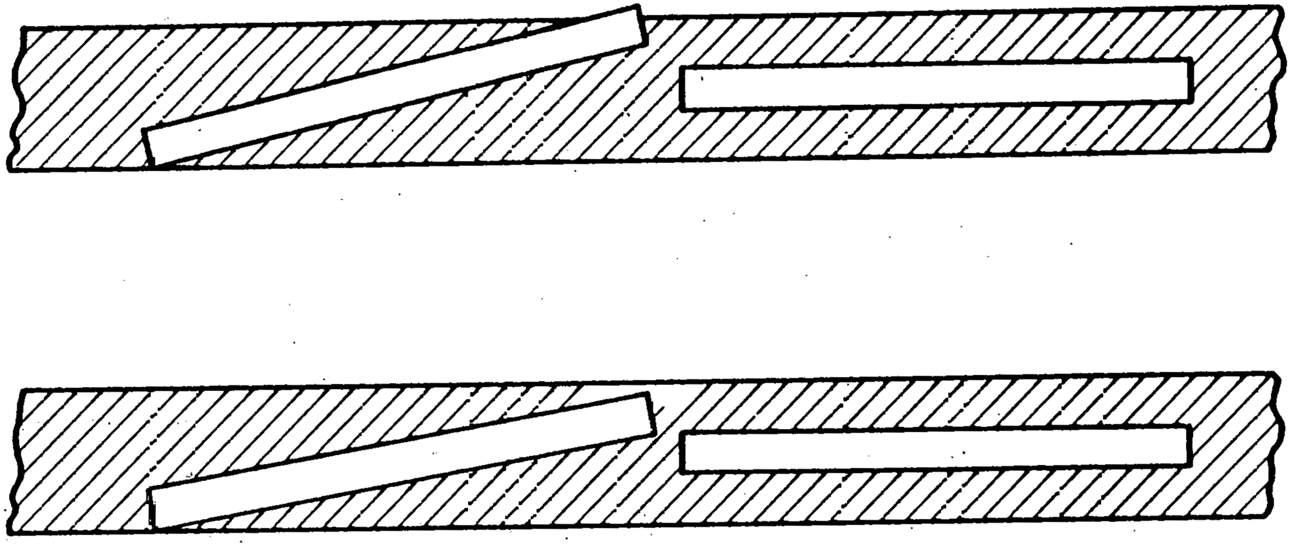


Figure 48. Cell Exposed or Less Than 1.5 mm Below Surface of Encapsulant. Reject.

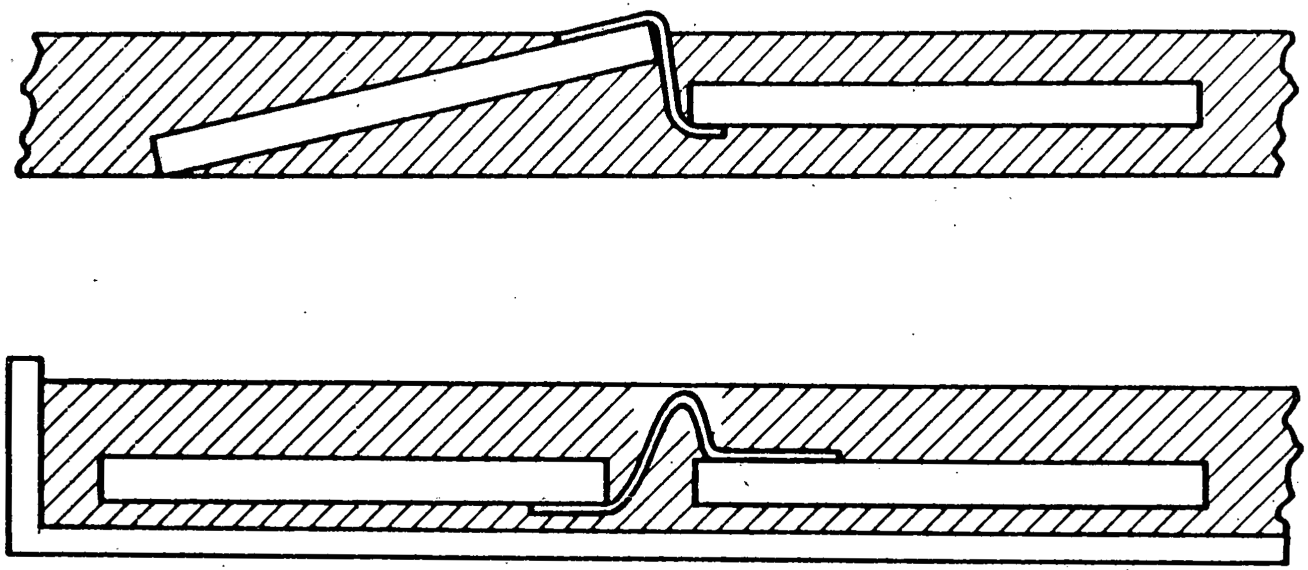


Figure 49. Interconnect Exposed or Less Than 1.5 mm Below Surface of Encapsulant. Reject.

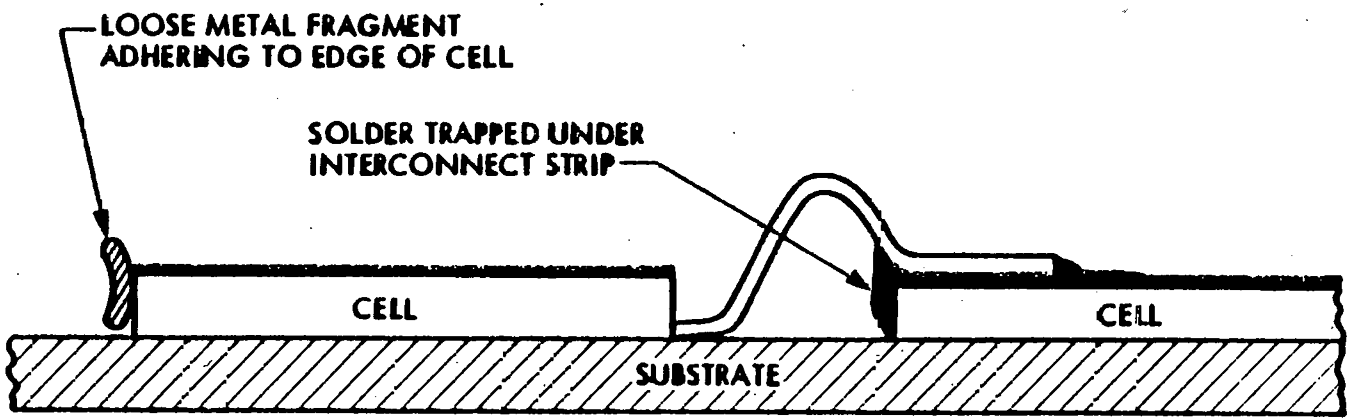


Figure 50. Possible Junction Shorts. Reject.