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# Photovoltaic Stand-Alone Systems

## Preliminary Engineering Design Handbook

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NOTE: Throughout this handbook, reference is made to Loss of Load Probability (LOLP) estimation procedures. According to the 1970 National Power Survey of the Federal Power Commission, these estimating procedures may be more correctly defined as Loss of Energy Probability (LOEP) procedures. This definitional difference in no way affects the accuracy or usefulness of these procedures.

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## ERRATA SHEET

o In Exhibit 11.2-4, "Listing of an HP-67 Insolation Computation Program", corrections shown parenthetically in the following tabulation of affected steps should be made:

| Step No. | Key Strokes | Key Code | | |
|---|---|---|---|---|
| 001 | f LBLA | (31) | 25 | 11 |
| 043 | g x (>) y | | 32 | 81 |
| 110 | f cos | | 31 | (63) |
| 138 | h $\pi$ | | (35) | 73 |
| 152 | h $\pi$ | | (35) | 73 |
| 200 | h RTN | | (35) | 22 |

o In Exhibit 11.2-3, paragraph 4 ("Example"), the tilt angle should be 30° instead of 20°. The paragraph which follows is also numbered "4" and should be changed to "5".

EXHIBITS

EXHIBITS (Continued)

EXHIBITS (Continued)

EXHIBITS (Continued)

# SECTION 1
# INTRODUCTION

The central component of any photovoltaic power system is the solar cell. It is the transducer that directly converts the sun's radiant energy into electricity. The technology for using solar cells to produce usable electrical energy is known and proven. The orbiting satellite Vanguard I, launched in March 1958, used solar cell panels to power its radio transmitter for about six years before radiation damage caused it to fail. The space program that continued after Vanguard I not only used photovoltaic systems, but fostered an industry for producing the spacecraft solar cells and arrays.

The production of photovoltaics associated with the space program reached about 50 kW per year and then leveled off. The 1973 oil embargo provided the stimulus for the government and the industry to begin to take serious steps to accelerate the normally very slow development process in order to seek significant expansion of the initial terrestrial markets. As of 1980, the annual production of solar cells is well in excess of 4 MW per year.

In 1973 a few pioneers of the photovoltaic industry began the terrestrial photovoltaic industry by shifting from the use of reject space solar cells to cells designed specifically for terrestrial use. This industry has installed thousands of photovoltaic systems representing a cumulative power of more than 6 MW since this beginning.

Since its initiation in 1975, the U.S. Department of Energy (DOE) National Photovoltaic Program has sponsored the design and implementation of nearly 40 system applications classed as "stand-alone" systems with less than 15 kW peak in power rating. In addition, through the DOE managed Federal Photovoltaic Utilization Program (FPUP), 3,118 applications of the small stand-alone class have been funded for installation in the first two of a five-cycle program.

Outside of DOE, the Department of Defense has funded the design and installation of nearly 150 stand-alone photovoltaic systems. A few scattered applications have also been sponsored by other government agencies such as the Indian Health Service of the U.S. Department of Health, Education, and Welfare and by the U.S. Department of State, Agency for International Development.

The purpose of this handbook is to enable a system design engineer to perform the preliminary system engineering of the stand-alone Photovoltaic Power System (PVPS). This preliminary system engineering includes the determination of overall system cost-effectiveness, the initial sizing of arrays and battery systems, and the considerations which must be specifically addressed in the subsequent detailed engineering stage of the project.

The scope of this handbook is limited to flat-plate, stand-alone PVPS for locations anywhere in the U.S. and in areas of the world which are located between the latitudes of $60^{o}$ South and $60^{o}$ North. As a stand-alone electrical system, the PVPS will be a self-sufficient system which includes an array field, power conditioning and control; battery storage, instrumentation and dc loads. While the intent of this handbook is for low-power applications, serving loads up to 15 kW in size, the theory and sizing methods are not dependent upon the generating capacity of the system or the peak demand of the loads, but only on the desired reliability criteria chosen.

## SECTION 2
## GUIDE TO HANDBOOK USAGE

This handbook is intended to aid a system design engineer in determining the suitability of stand-alone photovoltaic power systems for specific applications. It will be helpful in the preliminary engineering of the system in which the initial sizing of the major components of the power system are determined.

A flow chart is presented in Exhibit 2-1 which can be used to guide the reader in the use of this handbook. The flow chart expresses the relationships between the various sections of the handbook. The first three sections of the handbook contain introductory material and will not normally be referred to in the design process.

Section 4 enables the user to estimate loads in the PVPS, to estimate array performance, develop current-voltage curves for arrays with parallel and series connections, to estimate power output as a function of time, develop the conceptual design of the array for high reliability. This section of the handbook also shows the reader typical battery operations, battery current-voltage characteristics, and the procedures of estimating system performance with a battery, as well as the safety aspects of using lead-acid batteries in a stand-alone system. This section also describes the power handling portion of the PVPS which interfaces the arrays with the end-use loads. This includes dc power conditioning, control schemes, electrical wiring, and emergency back-up systems.

Section 5 contains two lists which will be useful in the assembly of data needed in the design processes. The first list contains the minimum data requirements to establish the feasibility of a photovoltaic power system (PVPS) in the preliminary design stage. The second is a more comprehensive list for the detailed design stage of the PVPS prior to construction which follows preliminary engineering.

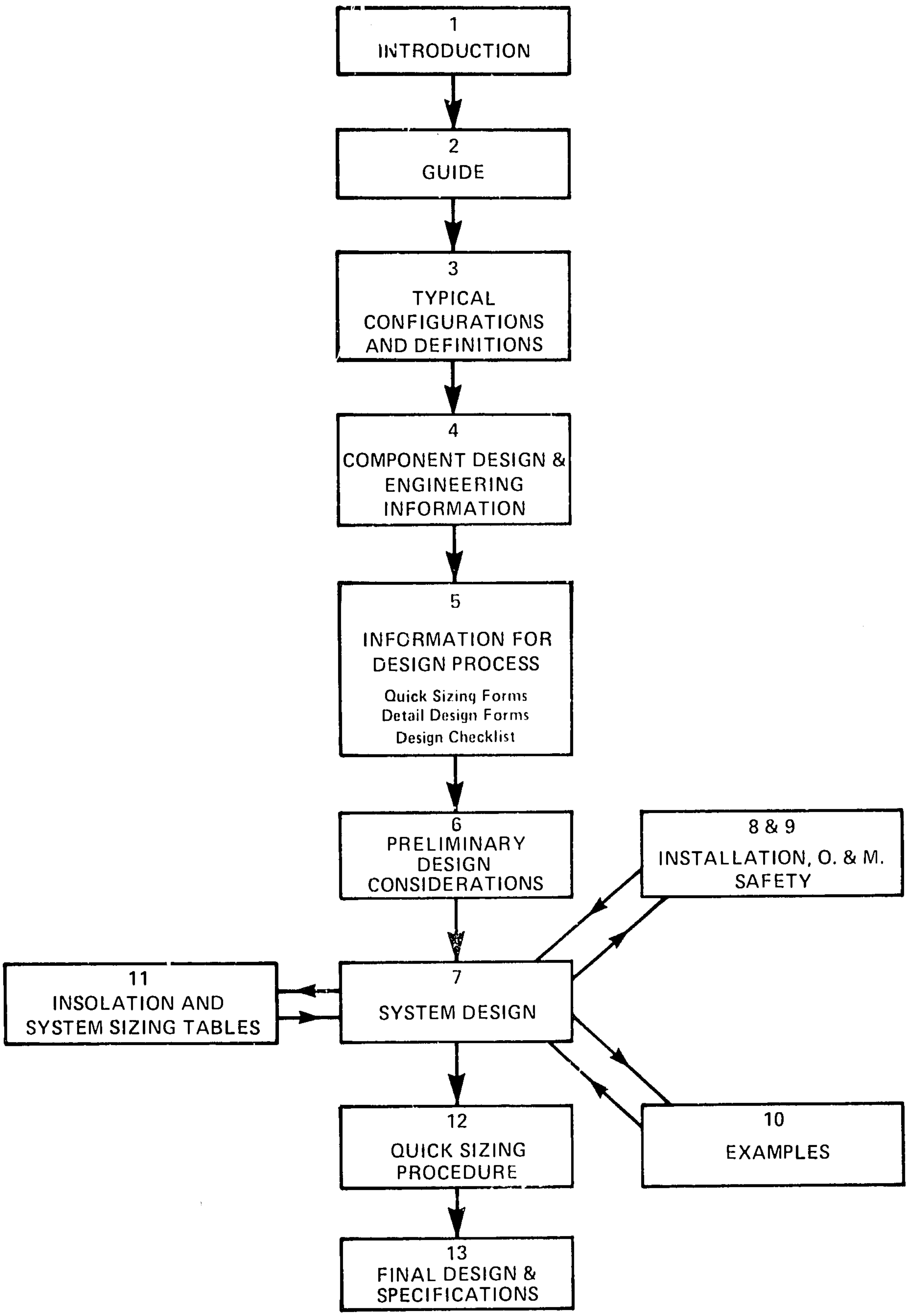


Exhibit 2-1

FLOW CHART
PHOTOVOLTAIC STAND-ALONE SYSTEMS
PRELIMINARY ENGINEERING DESIGN HANDBOOK

Section 6 presents the preliminary design considerations including insolation and siting, operation of the PVPS under varying loads, approaches to reliability engineering, the advantages and disadvantages of PV power systems, the elements of life-cycle costing and the quick-sizing of PV power systems. Section 7 presents the procedure for system design and the method for estimating the loss of load probability.

Sections 8 and 9 cover the installation, operations, maintenance and safety aspects of the PVPS. They set forth the basic design considerations which must be considered during detailed design of the system.

Section 10 presents an example of the quick-sizing procedure to determine the approximate size and cost of a photovoltaic system for any particular application. This quick-sizing is useful in evaluating photovoltaic feasibility without going through a detailed analysis.

Section 11 presents the calculational tools for the determination of the insolation on a tilted surface. Using the clearness index for a specific site (tabulated in Appendix A for a number of cities in the U.S. and throughout the world), the latitude angle of the site, the tilt angle of the site and the reflectance of the ground in front of the array, the average daily insolation for a given month can be determined.

For quick reference, Sections 12, 13, and 14 contain data on photovoltaic system components, a glossary of terms, and listings of equipment suppliers, respectively.

# SECTION 3
# TYPICAL STAND-ALONE PHOTOVOLTAIC SYSTEM CONFIGURATIONS

A photovoltaic power system using today's technologies and designed for a stand-alone (non utility-grid connected) application in today's markets includes a solar array using flat plate or concentrating type collectors, and may include such electrical system components as a system controller, a lead acid battery, a voltage regulator, an instrumentation system and an on-site standby generator for emergency back-up. Exhibit 3-1 is a generalized stand-alone direct current photovoltaic power system block diagram showing the elements of the generating and load portions of the overall system.

A flat plate array or concentrator array functions as the solar collector for the photovoltaic system. At present, flat plate arrays are the principle collectors used in the installed photovoltaic power systems in the world. Some concentrator applications exist. The methodology of sizing the arrays in this handbook applies to either fixed-tilt or seasonally adjusted tilted, flat plate arrays.

The power conditioning subsystem provides the interface between the arrays and the power system's loads. The function of a power conditioning subsystem is to render the variable dc output of the array suitable to meet the power requirements of the loads. For dc systems, the power conditioning subsystem typically includes voltage regulation, energy storage, and possibly a dc/dc converter interface with the loads.

The lead-acid battery provides the energy storage for the photovoltaic system. It increases the reliability level of providing power to the loads and also improves the array efficiency by keeping the solar cell voltage within prescribed limits. The operation of the arrays is presented in Section 4.

A regulator is required when electrochemical storage is employed. The regulator controls the current and voltage inputs to the batteries to protect them from damage at either end of the charging cycle. At the beginning of the cycle,

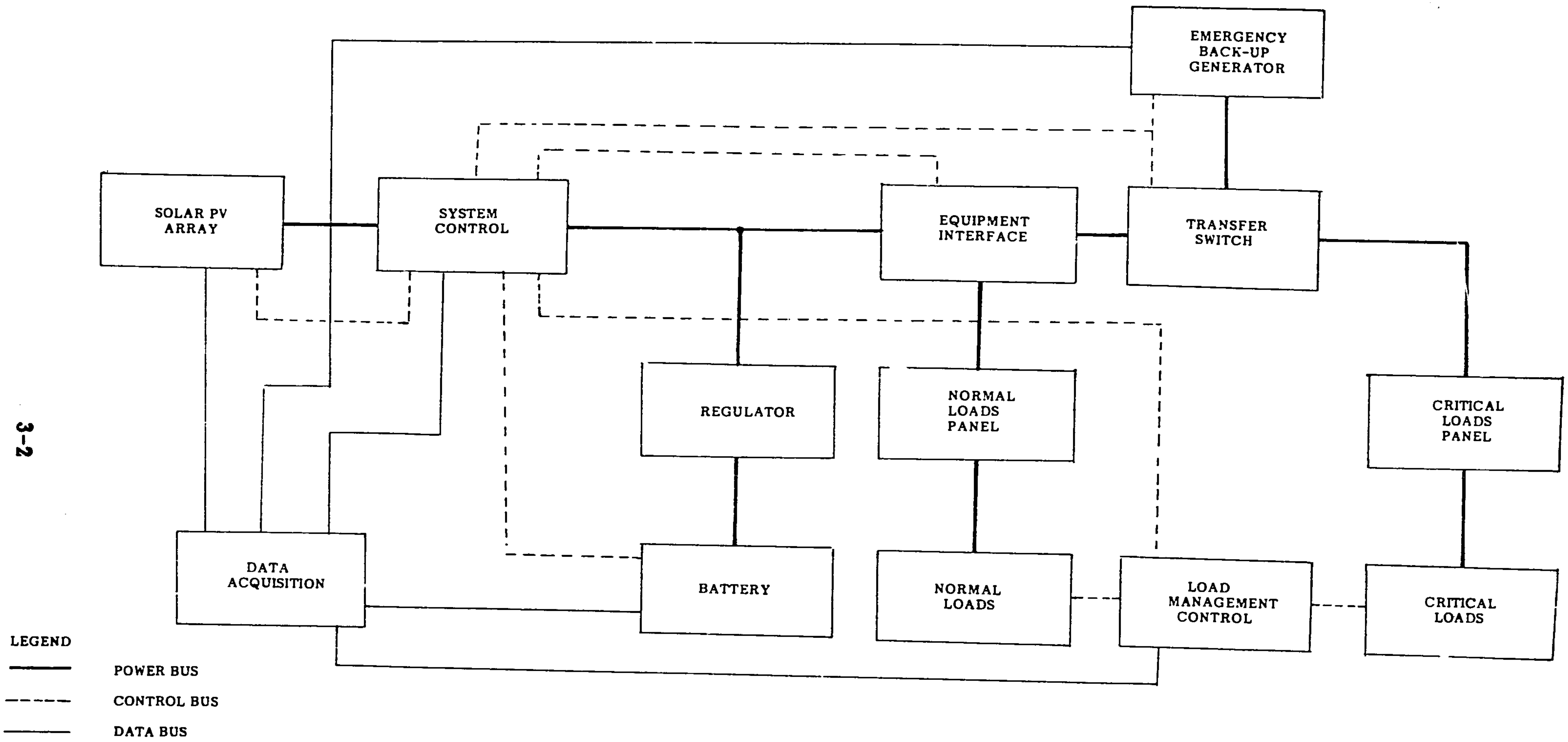


Exhibit 3-1

GENERALIZED STAND-ALONE DIRECT CURRENT
PHOTOVOLTAIC POWER SYSTEM BLOCK DIAGRAM

the discharged batteries would draw a large current from an unregulated photovoltaic array which would cause overheating of the batteries and shorten their lives. At the end of the charging cycle, the voltage across an unregulated battery would be too large and further charging would generate hydrogen gas and dehydrate the batteries.

In order to provide a higher degree of reliability of electric service to the power system's loads than the combination of the photovoltaic arrays and storage batteries might be capable of in a cost effective manner, an emergency back-up generating unit may be connected into the system. When emergency back-up is incorporated, it is advantageous to be able to feed just those loads which are deemed to be of an emergency or critical nature. An automatic transfer switch may thus be incorporated to "throw" these loads over to the emergency back-up system upon the complete discharge of the storage batteries during periods of low insolation.

A load management control system may also be included in some systems to reduce the peak aggregate of the loads and thus reduce somewhat the required capacity of both the photovoltaic arrays and that of the energy storage system. It is also possible to control the loads in such a way as to reduce not only the peak diversified demand but also the system's average daily energy requirements by means of duty cyclers and load schedules which limit electricity use according to preset patterns. Such a strategy would also help reduce the size of arrays and the energy storage system.

The sections which follow present details of various components for photovoltaic power systems and tradeoff considerations in the preliminary sizing of those systems.

# SECTION 4
# COMPONENT DESIGN AND ENGINEERING INFORMATION

## 4.1 ELECTRICAL LOADS

The size and cost of a photovoltaic system is strongly dependent upon the energy requirements of the loads which are to be served. The peak demand and energy requirements must be estimated as well as possible, to avoid unnecessarily oversizing the power system and adding to cost. This is especially apparent when the relative component costs are compared in the capital cost estimate for the life-cycle cost computation based on current-day (1980) levels. It is seen in such a comparison that the unit cost of array capacity is typically appreciably higher than for any other part of the power system. This sub-section reviews load estimations, load reduction strategies and considerations of using dc rather than ac for the distribution system and loads.

### 4.1.1 Estimating the Load

Individual loads are characterized by their power requirements as determined by both voltage and current ratings and duty cycle, which will determine their energy requirements. Dc loads may be made of either resistive elements, drawing constant power for given applied voltages, or may be composed of motors which are dependent upon the mechanical torque requirements of the driven loads to determine voltage and current inputs. A third category of energy tranformation utilizing induction coupling applies to ac load categories and includes examples such as fluoresent lamps, power supplies with tranformers, and high frequency converters such as microwave oven supplies. For systems up to 15 kW in size, the load might be comprised of a single device, e.g. a single 15 hp motor, or a multiple combination of lesser-sized motors and resistive loads.



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The first aspect of the load analysis is to define energy requirements of the combination of loads to be operated by the power system. The power requirement represents the maximum demand at any one time. Since some of the equipment is operated on a cyclic basis, the average demand or the energy requirement is considerably less than would be obtained by assuming a full-time operation, and multiplying rated power requirements by 24 hours a day.

Cyclic operation of a large number of components permits the under-sizing of equipment on the basis of load diversity. The odds are that if there are enough components drawing power from the system, not all components will draw current simultaneously. Large electric utilities make constant use of the low odds associated with their enormous systems in capacity sizing of generating units and distribution circuits. As an example, suppose there are four components on the line, drawing 1, 2, 3, and 5 kilowatts peak power randomly with duty cycles of 50 percent, 40 percent, 30 percent, and 20 percent, respectively. The probability that all four loads will operate simultaneously is 1.2 percent, as shown on Exhibit 4.1-1.

The 1.2 percent figure can be translated into 0.012 times 365 days, or 4 days per year that the aggregate load on the system will equal 10 kW. The probability of other load combinations are shown in the exhibit along with the expected energy demand of 72 kWh/day. The daily load factor for this system is 30% (72 kWh / (10 kW x 24 hr)), which is equivalent to having an average 3 kW load running 24 hours/day. The full 10 kW of generating capacity must be installed to meet the peak loads unless either a load management scheme is installed or a 1.2% probability of overload is acceptable.

The probability of any other load can be estimated from the data on Exhibit 4.1-1. For example, the probability that the load will be 2 kW is equal to the probability that the 2 kW load will be on (0.40), multiplied by the probability that the three loads will be off (0.5 x 0.7 x 0.8), giving a probablity of 0.112 that the load will be 2 kW. Similar computations can be executed for the other load sizes, so a curve of load size versus probability can be generated.

Exhibit 4.1-1

LOAD DIVERSITY

| Load | Operating Time |
|---|---|
| 1 kW | 50% |
| 2 kW | 40% |
| 3 kW | 30% |
| 4 kW | 20% |

Probability of simultaneous operation = 0.5 x 0.4 x 0.3 x 0.2 = 0.012 = 1.2%

Probability of all combinations:

| kW | Probability | | | Expected kWh/day |
|---|---|---|---|---|
| 0 | (1-0.5) x (1-0.4) x (1-0.3) x (1-0.2) | = | 0.168 | 0 |
| 1 | 0.5 x (1-0.4) x (1-0.3) x (1-0.2) | = | 0.168 | 4.0 |
| 2 | 0.4 x (1-0.5) x (1-0.3) x (1-0.2) | = | 0.112 | 5.4 |
| 3 | 0.3 x (1-0.5) x (1-0.4) x (1-0.2) + 0.5 x 0.4 x (1-0.3) x (1-0.2) | = | 0.184 | 13.3 |
| 4 | 0.5 x 0.3 x (1-0.4) x (1-0.2) + 0.2 x (1-0.5) x (1-0.4) x (1-0.3) | = | 0.114 | 10.9 |
| 5 | 0.3 x 0.4 x (1-0.5) x (1-0.2) + 0.5 x 0.2 x (1-0.4) x (1-0.3) | = | 0.090 | 10.8 |
| 6 | 0.5 x 0.4 x 0.3 x (1-0.2) + 0.2 x 0.4 x (1-0.5) x (1-0.3) | = | 0.076 | 10.9 |
| 7 | 0.2 x 0.3 x (1-0.5) x (1-0.4) + 0.2 x 0.4 x 0.5 x (1-0.3) | = | 0.046 | 7.7 |
| 8 | 0.2 x 0.3 x 0.5 x (1-0.4) | = | 0.018 | 3.5 |
| 9 | 0.2 x 0.3 x 0.4 x (1-0.5) | = | 0.012 | 2.9 |
| 10 | 0.2 x 0.3 x 0.4 x 0.5 | = | 0.012 | 2.9 |
| | | | Total daily load | 72.0 |

### 4.1.2 Load Reduction Strategies

The foregoing discussion brings us to the logical concept of load shedding. If the probability of simultaneous operation is low, or if some functions are not critical, the peak demand can be limited by a controller that senses the total demand and supplies power to the low-priority components only when the demand on the power system is low. Reducing the peak load has an indirect effect on the reduction in energy demand, although it is difficult to estimate the energy impact without a detailed, sophisticated computer program that tracks system performance on an hourly basis.

When the energy demand of a potential photovoltaic application is analyzed, methods for reducing the requirements frequently are discovered. Exhibit 4.1-2 lists the most frequent methods of reduction. First, components can be operated cyclically. When one load is operating at peak demand, a second load can be shut off, thereby reducing peak power demand and, consequently, the sizes of the equipment such as motors. Smaller sized motors operating at higher loadings will result in higher system efficiency during off peak operation, and, therefore, 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 generally be cost-effective only if the peak power under simultaneous 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.

Exhibit 4.1-2

LOAD-REDUCTION STRATEGIES

- Cyclic operation of components
  - Manual
  - Automatic
- Diversity
- Load Shedding



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### 4.1.3 Merits and Disavantages of Both Ac and Dc Power

For a remote stand-alone photovoltaic power system, the advantage of utilizing direct current loads is that the frequency inverter is not required, thus saving both the costs of the inverter equipment and of the added array capacity which would be required to supply the power lost from inverter inefficiency. A disadvantage of using dc is that there is very little flexibility to choose a higher distribution system voltage than that of the load in order to minimize the losses in the distribution system.

In making an assessment of whether or not to utilize an ac distribution system, the question of regulation should be considered. Although the inversion of dc to ac carries with it a nominal penalty of 12 percent inefficiency, relatively good ac output regulation can be achieved with the inverter within nominal limits of $\pm 5$ percent. Regulating dc from an unregulated dc source (of which the array/battery combination is typical with a voltage range of $\pm 30$ percent) also involves an inefficiency penalty of about 12 percent. Thus, power economy benefits would only result by using unregulated dc. Exhibit 4.1-3 lists some of the disadvantages of dc and ac for selected items.

Exhibit 4.1-3

DISADVANTAGES OF DC AND AC

| Interaction | Waveform dc | Waveform ac |
|---|---|---|
| Motor Drive | Brushes wear | |
| Universal/Induction | More expensive than ac equipment | |
| Lights | | Fluorescent less efficient at low frequency operation |
| | Loss of incandescent and fluorescent reliability | |
| Electronics | Requires regulation | Requires regulation/ rectification |
| PV Output | | Requires inverter |
| Battery Charging | | Requires rectification |
| Controls | Contact wear | Requires rectification |
| Multiple Voltages | Not easily accommodated | |



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## 4.2 PHOTOVOLTAIC ARRAYS

The intent of this sub-section is to (1) develop the current-voltage curve for arrays of solar cells consisting of parallel and series connections; (2) estimate the power output as a function of time, indicating the decrease that occurs due to cell failure, dirt accumulation, and maintenance routines; and (3) develop the conceptual design of the ıy for high reliability.

### 4.2.1 Photovoltaic Terminology

The terminology associated with the photovoltaic power systems, as used in this handbook, is that adopted from U.S. Department of Energy (DOE) projects. The power output from most solar cells currently in use is approximately 0.5 watts for a single cell; therefore, most systems require groups of cells to produce sufficient power. Cells are normally grouped into "modules"*, which are encapsulated with various materials to protect the cells and electrical connectors from the environment. A current typical module is two feet by two feet by two inches, with a glass cover through which the cells are exposed to the sunlight.

The modules are frequently combined into panels of, perhaps, four modules each. These panels are pre-wired and attached to a light structure for erection in the field as a unit. If the power output from a module is 30 watts, then power from a panel containing four modules is 120 watts. The panels are often attached to a field-erected structure to form an array (see Exhibit 4.2-1). Logical groups of arrays form an array subfield, which may feed a single power control system. The subarrays can be combined to form the entire array field. For small systems, the module, panel, array, subarray field, and array field may be identical, with only one module being used.

*In order to be consistent with much of the current literature which results from DOE-funded studies this Handbook uses the DOE definition of "module" viz., the smallest, independent, encapsulated unit consisting of two or more solar cells in series or parallel. It should be noted, however, that the photovoltaic industry often refers to the same item as a "panel".

**SOLAR CELL** – The basic photovoltaic device which generates electricity when exposed to sunlight.

**MODULE** – The smallest complete, environmentally protected assembly of solar cells and other components (including electrical connectors) designed to generate dc power when under unconcentrated terrestrial sunlight.

**PANEL** – A collection of one or more modules fastened together, factory preassembled and wired, forming a field installable unit.

**ARRAY** – A mechanically integrated assembly of panels together with support structure (including foundations) and other components, as required, to form a free-standing field installed unit that produces dc power.

**BRANCH CIRCUIT** – A group of modules or paralleled modules connected in series to provide dc power at the dc voltage level of the power conditioning unit (PCU). A branch circuit may involve the interconnection of modules located in several arrays.

**ARRAY SUBFIELD** – A group of solar photovoltaic arrays associated by the collection of branch circuits that achieves the rated dc power level of the power conditioning unit.

**ARRAY FIELD** – The aggregate of all array subfields that generate power within the photovoltaic central power station.

**PHOTOVOLTAIC CENTRAL POWER STATION** – The array field together with auxiliary systems (power conditioning, wiring, switchyard, protection, control) and facilities required to convert terrestrial sunlight into ac electrical energy suitable for connection to an electric power grid.

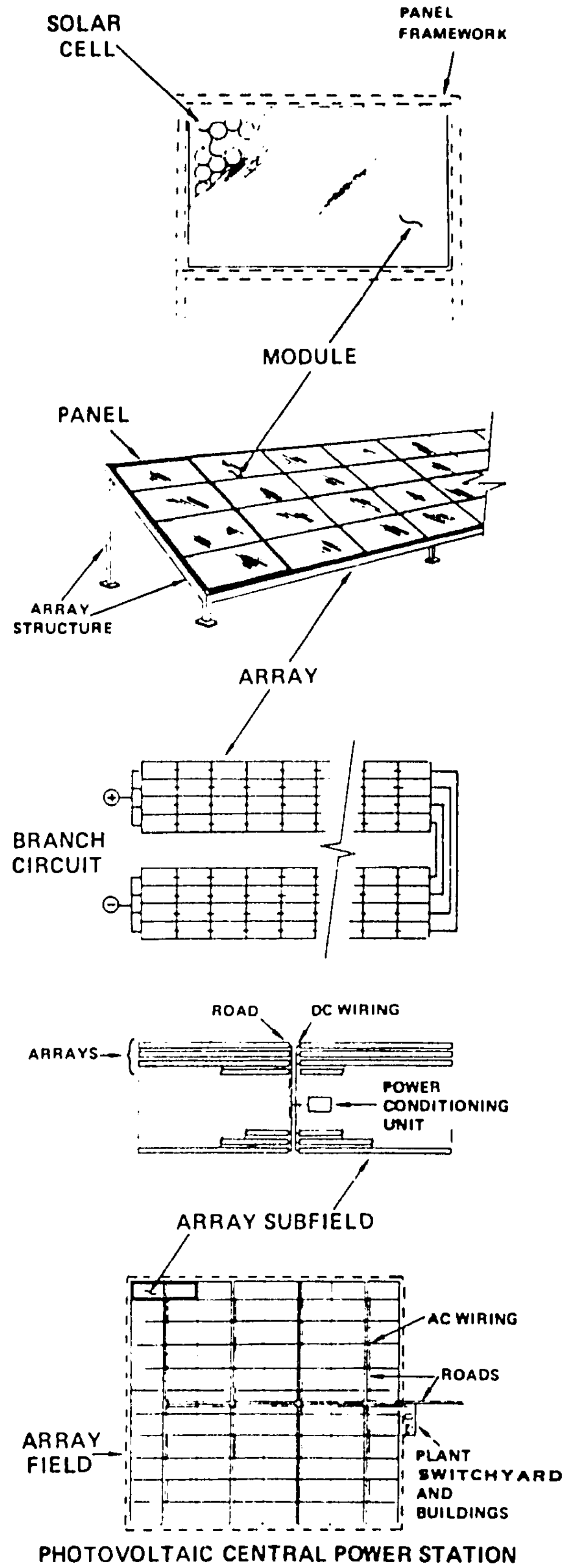


Exhibit 4.2-1

TERMINOLOGY FOR LARGE-SCALE PHOTOVOLTAIC INSTALLATIONS

(Source: Reference 4-1)

The nomenclature for the electrical circuits associated with the array is shown in Exhibit 4.2-2. Groups of cells arranged in series are called substrings; substrings arranged in parallel are called series blocks; series blocks connected in series are called branch circuits; and branch circuits are connected in parallel to form the array circuit. Blocking diodes are used to prevent the reverse flow of electricity from the load through the solar cells during times when part or all of the array is shadowed, although one blocking diode might be used for the entire array, rather than for each branch circuit as shown in Exhibit 4.2-2. Bypass diodes are frequently used to permit the current to pass through the branch circuit even when one or more of the series blocks has totally failed in the open-circuit condition.

The terminology pertaining to module output and efficiencies is presented in Exhibit 4.2-3. The overall efficiency is partitioned into efficiencies that identify each of the loss mechanisms. The ratio of the cell area to the module area is called the module packing efficiency, $n_p$. The cell active area is the product of the module area, the module packing efficiency and the cell nesting efficiency. The cell efficiency, $n_c$, is usually measured by a flash technique in which the cell temperature does not rise because the flash duration is so short. The efficiency so measured, at an insolation of 1.0 $kW/m^2$ and a cell temperature of $28^oC$, is called the bare cell efficiency. If the cell is encapsulated such as with a glass cover, the efficiency measured by this technique is called the encapsulated-cell efficiency.

The NOCT efficiency (Nominal Operating-Cell Temperature) corrects for the temperature at which a cell would operate in the field. The NOCT efficiency is measured at 1.0 $kW/m^2$ insolation and an outdoor-air temperature of $20^oC$, with a wind speed of one meter per second. The efficiency is measured at the cell temperature realized when the circuit is open, so no power is being extracted. The effect of power extraction is small, but the open-circuit temperature is used for purposes of standardization. The NOCT corrects for the losses associated with increased cell temperature.

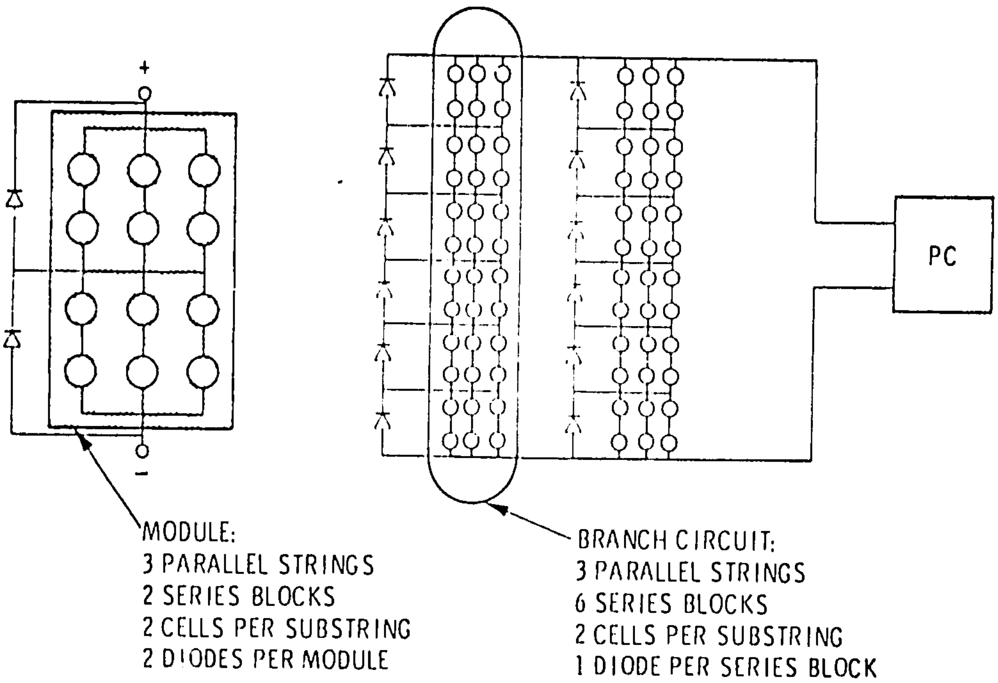


Exhibit 4.2-2

SERIES/PARALLEL CIRCUIT NOMENCLATURE

Exhibit 4.2-3

MODULE OUTPUT AND INTERMEDIATE LOSS MECHANISMS

| Definitions | | Typical Values |
|---|---|---|
| Overall Module Efficiency* at 1,000 $W/m^2$ and NOCT (Nominal Operating Cell Temperature) is: | | |
| $n_m$ = | $n_p \times n_{NOCT} \times n_{EC} \times n_{IM}$ | 10% |
| where: $n_p$ = | Module Packing Efficiency = $n_{BR} \times n_N$ | 81% |
| $n_{BR}$ = | $1 - \left(\frac{\text{Module Border + Bus Area + Interconnect Area}}{\text{Module Area}}\right)$ | 90% |
| $n_N$ = | Cell Nesting Efficiency | 100% |
| = | $\frac{\text{total cell area}}{\text{Module area - (Border area + Bus area + IC area)}}$ | |
| $n_{NOCT}$ = | Nominal Operating Cell Temperature Efficiency | 90% |
| $n_{EC}$ = | Encapsulated Cell Efficiency at 1,000$W/m^2$, 28°C | 13.5% |
| $n_c$ = | Bare Cell Efficiency (1,000$W/m^2$, 28°C) | 15% |
| $n_T$ = | Optical Transmission Efficiency | 95% |
| $n_{MIS}$ = | Electric Mismatch/Series Resistance Efficiency | 95% |
| $n_{IM}$ = | Illumination Mismatch Efficiency | 98% |

Therefore, module output is:

$m_O$ = Insolation x $n_M$

= Insolation x $(n_{BR} \times n_N) \times (n_{NOCT}) \times (n_c \times n_T \times n_{MIS}) \times (n_{IM})$

*(Reference 4-2, 4-3)



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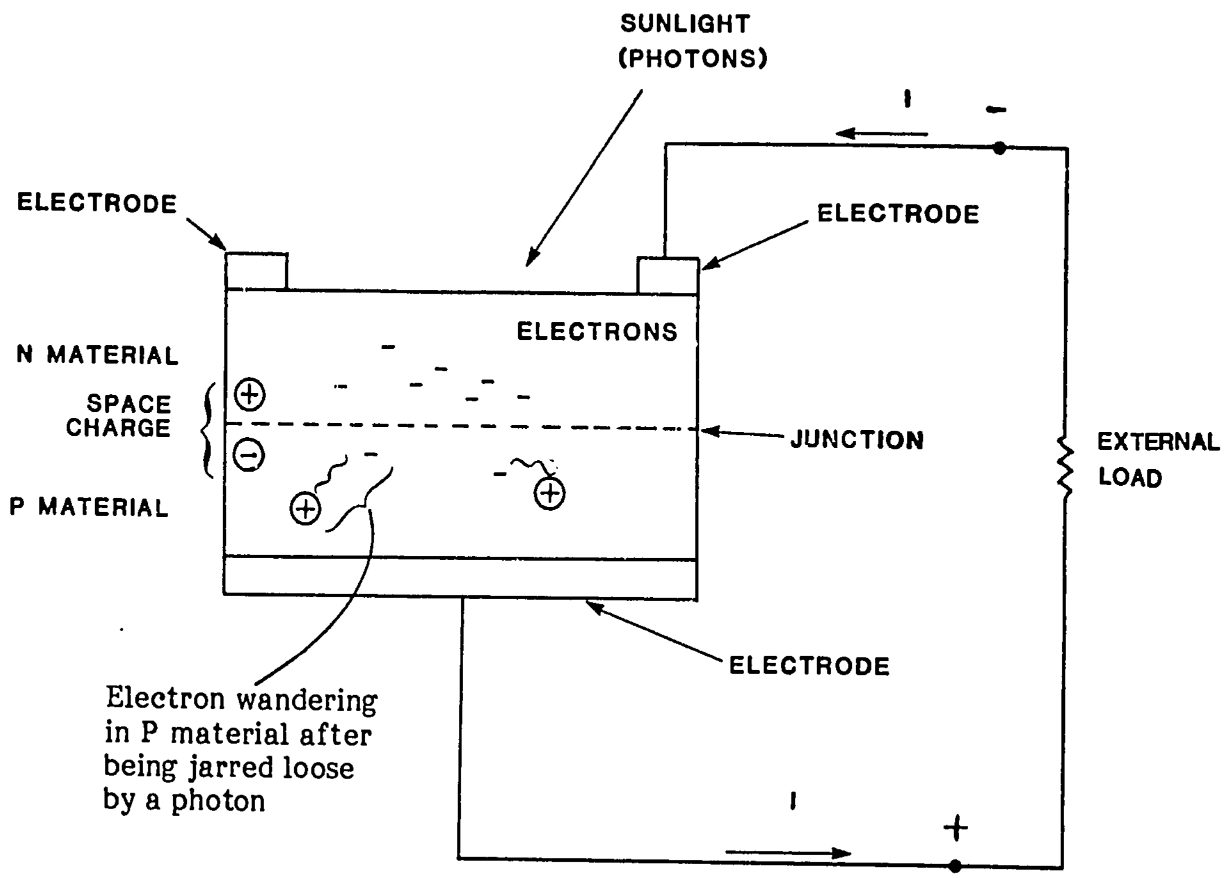
If the cells do not have identical current/voltage characteristics, there will be an additional loss, characterized by the electrical mismatch efficiency. If the cells are not all illuminated uniformly, perhaps due to partial shading by other panels, there is an additional loss which is characterized by the illumination-mismatch efficiency.

The overall panel output is the product of the insolation and the following efficiencies: module packing, encapsulated cell, NOCT and illumination mismatch. Some of these efficiencies are obtainable directly from the manufacturer. Others must be calculated, based on the techniques to be presented in this section.

### 4.2.2 Ideal Solar-Cell Current-Voltage Characteristics

Although the mathematical description of the processes occurring in a solar cell are quite complicated, the physical description is simple. Photons from the sunlight pass through the upper layer (the "n" material) into the thicker "p" material, where they strike the atoms, jarring electrons loose. The electrons wander throughout the "p" material until they are either recaptured by a positively charged ion (an atom that lost an electron) or until they are captured in the "n" material. The electrostatic charge near the junction between the "n" and "p" materials is such that, once in the vicinity of the junction, an electron is drawn across the junction and is held in the "n" material. As a consequence, the "n" material becomes negatively charged and the "p" material, which loses the electrons, becomes positively charged. If the electrons are gathered by the electrodes on the top surface of the cell and connected to an electrode on the bottom surface, the electrons will flow through the external connection, providing electricity through the external circuit. (Exhibit 4.2-4).

The junction in the solar cell is the same as the junction in a diode that might be used to pass electricity in one direction but not in the other. Approximately 0.4 volts is all that is required to drive the electrons from the "n" to the "p" region, across the electrostatic charge at the junction. This internal flow limits the voltage that can be attained with a solar cell. The resistance to electron flow from the "p" to the "n" material is much greater, being on the order of 50




(a) Some are recaptured by the positive charge (hole)

(b) Some wander across the junction and get trapped by the space-charge barrier across the junction.

P region becomes +

N region becomes -

Exhibit 4.2-4

OPERATION OF A SOLAR CELL

volts. Only because the photons jar the electrons loose is there a flow in this direction under normal solar cell operation.

An equivalent circuit for a solar cell can be devised that incorporates its diode nature (Exhibit 4.2-5). The photon bombardment acts as a current source, driving the electrical current from the "n" to the "p" material. The diode tends to short this current directly back to the "n" material. An additional shunt resistance, characterizing primarily the losses near the edges and corners of the cell, adds to this shunting, although the shunt resistance is usually too small to be considered in most analyses. A series resistor characterizes the resistance of the cell material itself, the electrode resistance, and the constriction resistance encountered when the electrons travel along the sheet of "n" material into the small electrodes on the top surface.

The equation that describes the equivalent circuit and the corresponding current/voltage relationship consists of the following terms (Exhibit 4.2-5):

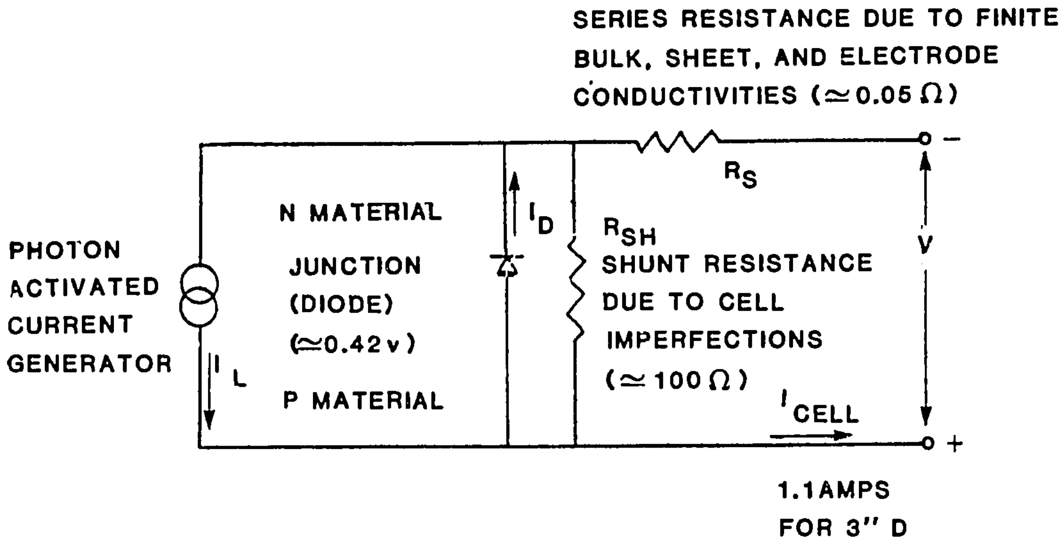
a. the current source, called the light current, which is proportional to the illumination;

b. the diode current, given by the Shockley equation; and

c. the current through the shunt resistor.

With slight adjustment of the constants in the equation, excellent agreement can be obtained between the theoretical current/voltage relationship and the actual relationship. Notice that the relationship between the current and voltage is nonlinear, so the computations will be difficult and the relationships somewhat obscure.

Some insight into the importance of the various terms in the current/voltage relationship can be obtained by re-examining the typical performance curves for solar cells (Exhibit 4.2-6). The current is proportional to the illumination, whereas the open-curcuit voltage changes little with illumination. Notice also that temperature has little effect on the short-circuit current, but that increasing temperatures decrease the open-circuit voltage -- an important effect when solar cells are used to charge batteries. When the voltage is zero, there is no flow of current throught the diode. For small increases in the voltage, there is still



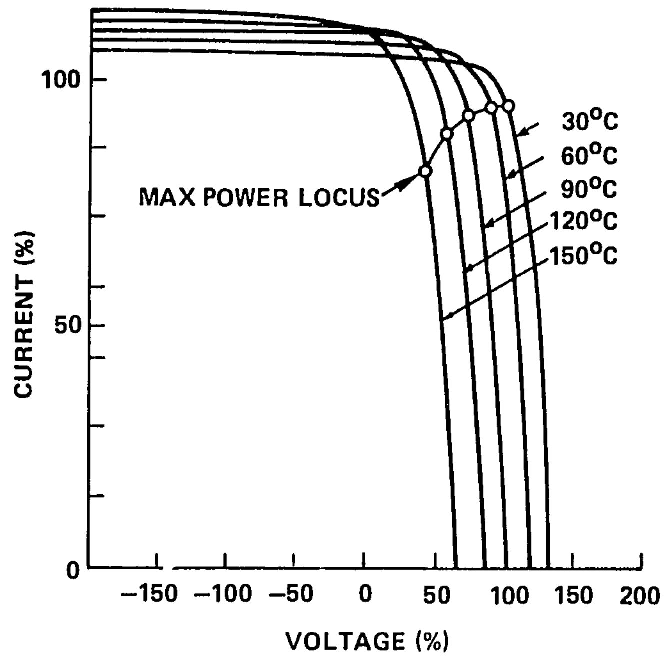

Current density output of solar cell:

$$I_{Cell}/A = \underbrace{S\ s}_{I_L/A} + \overbrace{K_{dev}\, A_o T^3\, e^{-E_{GO}/KT}\left[1 - e^{\frac{}{KT}(V + R_s I_{Cell})}\right]}^{\text{Diode Current}} - \overbrace{\frac{V + R_S I_{Cell}}{R_{SH}}}^{\text{Shunt Current}}$$

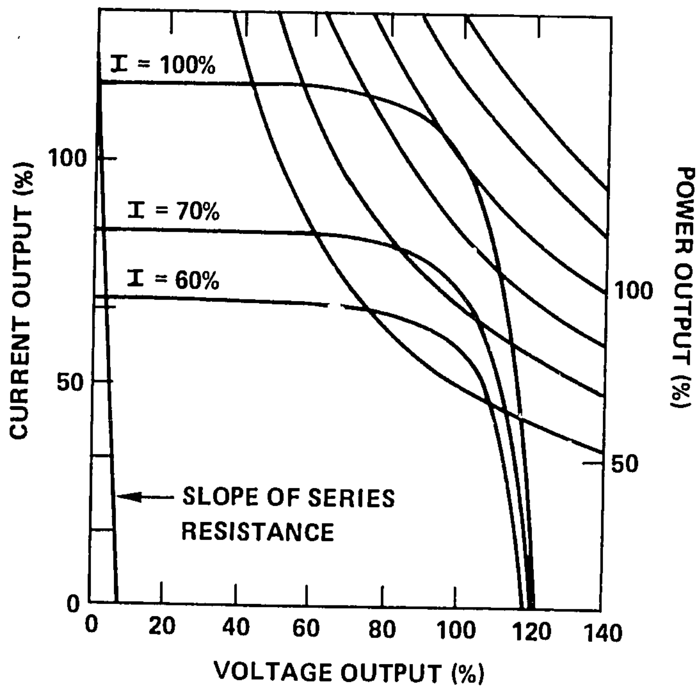
- $KT$ (in the exponent $\frac{}{KT}$): Electronic charge ($q/K = 11600^\circ K$)
- $K$ (in $-E_{GO}/KT$): Boltzman constant
- $E_{GO}$: Band gap at $0^\circ K$ ($E_{GO}/K = 14000^\circ K$ for silicon)
- $T$: Cell temperature ($^\circ K$)
- $A_o$: Material constant ($1.54 \times 10^{45}$ carriers$^2$/m$^6$/$^\circ K^3$ for silicon)
- $K_{dev}$: Device constant ($1.55 \times 10^{-39}$ Amps m$^4$/carrier$^2$ for typical cells)
- $s$: Current sensitivity (Amps/kW)
- $S$: Insolation (kW/ m$^2$)

Exhibit 4.2-5

EQUIVALENT CIRCUIT OF A SOLAR CELL




OUTPUT CHARACTERISTIC VERSUS TEMPERATURE




TYPICAL I-V CURVES OF A SOLAR ARRAY AT THREE DIFFERENT ILLUMINATION LEVELS (Constant Spectral Distribution and Temperature, Illustrative Example)

Exhibit 4.2-6

TYPICAL ARRAY CHARACTERISTICS

no flow through the diode, which requires approximately 0.4 volts for significant current flow. Therefore, the slope of the I-V curve at low voltage depends only on the shunt resistance. The curve would be horizontal if the resistance were infinite.

As the cell output voltage increases, the diode current becomes important, so the output current from the cell begins to decrease rapidly. At approximately 0.55 volts, the photon-generated current is passed totally by the diode. At this near-constant-voltage condition, changes in the current have little effect on the diode and shunt current, so the current/voltage relationship is governed by the series resistance. The slope of the cell's I-V curve at zero current is equal to (the negative of) the series resistance. For best performance, the series resistance should be high, so better cells have steeper slopes at zero current.

The power output of a cell falls to zero at both zero voltage and zero current. Somewhere in between the power will be at a maximum. The maximum will occur near the knee of the curve, typically at 0.42 V and 1.1 A. The ratio of the peak power to the product of the open-circuit voltage and short-circuit current is called the fill factor.

The characteristics of the individual cells can be combined to obtain the characteristics of strings of cells connected in series or in parallel (Exhibit 4.2-7). For example, the current passing through two cells in series is the same, so the current-voltage curve of the pair of cells is constructed from that of the individual cells by adding the voltages for each current. For example, in Exhibit 4.2-7, the voltage of one cell is 0.4 when the current is 1.0 A. For two cells operating at 1.0 A, the output would be at 0.4 + 0.4 = 0.8V. If the two cells were connected in parallel, rather than in series, the voltage across each of the cells would be the same, but the currents would add. Thus, at 0.4 V, the output current of two cells in parallel would be twice the 1.0 A, or 2.0 A. The same procedures would be used for more cells in parallel or series or for entire modules in parallel or series.

If one cell is only 15% illuminated (dotted I-V curve in Exhibit 4.2-7), it will seriously alter the performance of the pair of cells. For example, if the cells are in series and an output current of 0.4 A is to be obtained, the output voltage would be 0.49 - 25 = -24.5 V, as read from the Exhibit. The negative implies that an external voltage source would be required to drive the current in the forward

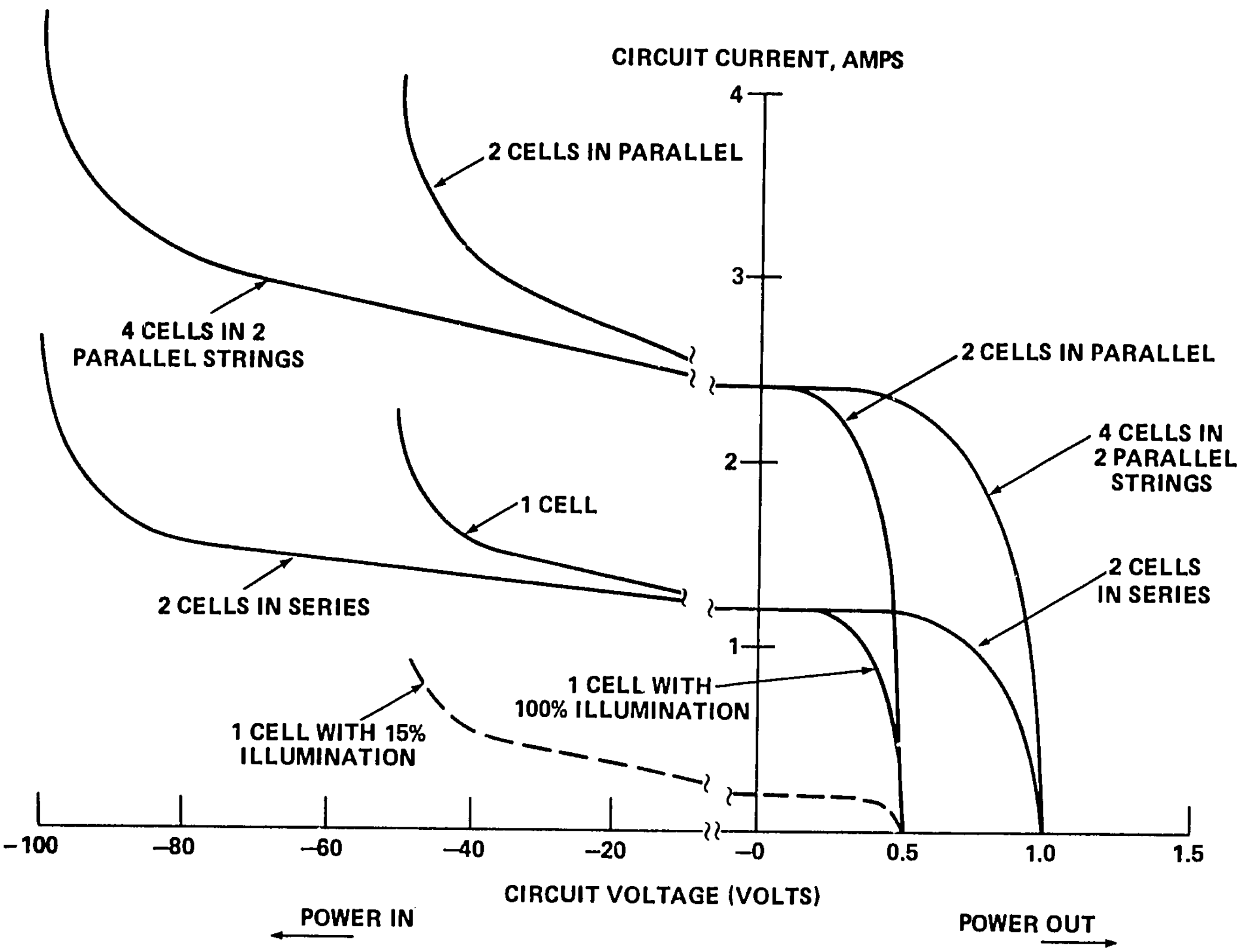



Exhibit 4.2-7

CURRENT-VOLTAGE CHARACTERISTICS
OF CELLS IN SERIES AND PARALLES



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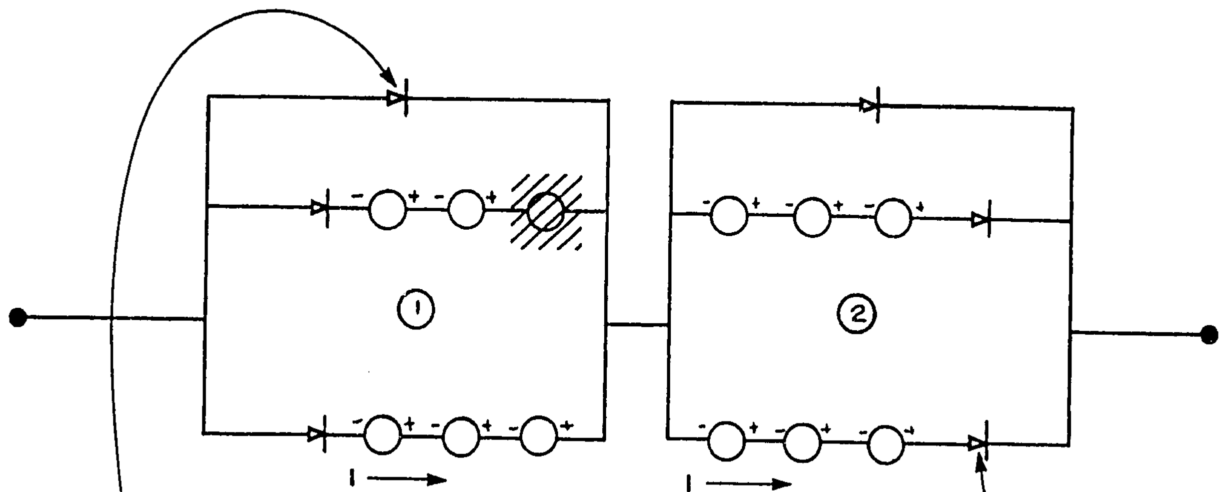
direction. Only if the output current were decreased from 0.4 to 0.18 A would a positive voltage be obtained. The 0.18 A represents the short-circuit current of the shaded cell. The current through cells in series is limited by the current of the cell with the lowest illumination. If two cells are in parallel and one is only 15% illuminated, the output voltage would be only slightly reduced. At 0.4 V, the current would be 1.0 + 0.15 = 1.15 A (Exhibit 4.2-7), down from the 2.0 V realized with 100% illumination on both cells. The voltage across cells in parallel is limited by the voltage of the cell with the lowest illumination, but, as was seen in Exhibit 4.2-7, this is only slightly less than the voltage of the cell with full illumination.

In the usual photovoltaic system with many cells, diodes can be used beneficially to offset the effects of broken and partially illuminated cells (Exhibit 4.2-8). Series blocks can use bypass diodes, so the branch circuit is not totally lost when the series block is shaded or has too many cell failures. The bypass diode also prevents overheating of a partially shaded cell. For example, in the shaded cell in the previous paragraph, a current of 0.4 A would result in a voltage drop of 25 V, so 10 W must be dissipated in the cell. A hot spot would develop that could further damage the cell, its encapsulation, or neighboring cells. Most systems use both blocking and bypass diodes. The optimal arrangement depends on the number of cells in series and parallel and the maintenance costs. Blocking diodes can be used to prevent a reverse current from being forced through the branch circuit either by other branch circuits or by the batteries.

The system current-voltage characteristics are determined by the interaction among the photovoltaic array, the battery and the load. The methods for determining the system voltage, as described in conjunction with Exhibit 4.2-6, apply as well for the entire array. The effects of cell failures and partial shading can be examined upon construction of the I-V curves using the series/parallel analyses just described, superimposed upon the I-V characteristics of the battery and load.




(a) Bypass diode prevents Series Block 2 from driving too much current through unfailed substring in Series Block 1 (overheats) but carries loss of entire Series Block 1 upon partial shading.

(b) Bypass diode prevents loss of array upon total shading of Series Block 1

(a) Blocking diode prevents reverse current -- but gives a constant $\Delta$ v loss ($\simeq$0.4 v) (Use several in parallel to minimize loss)

(b) Blocking diode required for array to prevent battery discharge through array

(c) Bypass diode can prevent overheating of shaded cell (module) under reverse bias — if many cells in series

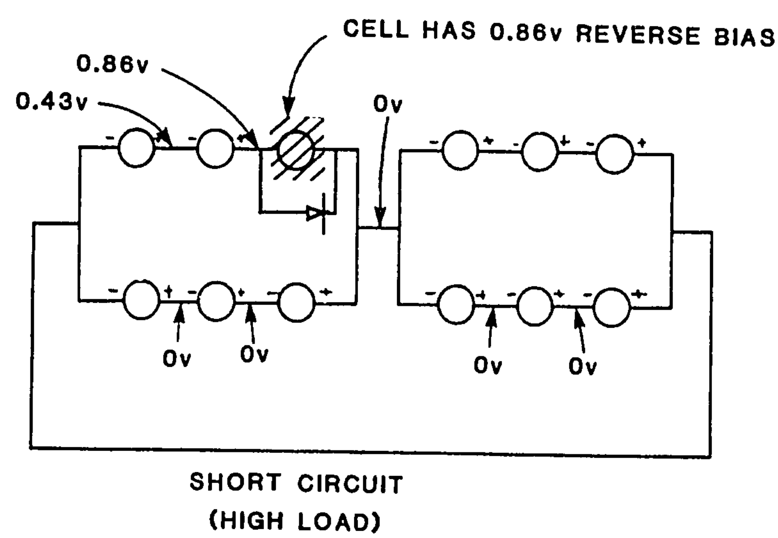



Exhibit 4.2-8

PROTECTION FROM OPEN-CIRCUIT FAILURES



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### 4.2.3 Current-Voltage Characteristics of Arrays in the Field

The manufacturer's reported I-V curves, as considered in the previous section, must be modified for field operation by considering the effects of cell mismatch, dirt, cell failures and maintenance strategies. Cell-to-cell I-V differences result in a decrease in array output as compared to the output that would be calculated if all of the cells had the average maximum-power current/voltage combination. For N cells in series in each of P substrings, forming S series blocks and B branch circuits, the decrease in power output due to mismatch is given by the equation

$$\frac{\Delta P}{\bar{P}_{MP}} = 5.06 \left[ \sigma_I^2 \left(1 - \frac{1}{N}\right) + \frac{\sigma_V^2}{N} \left(1 - \frac{1}{P}\right) + \frac{\sigma_I^2}{NP} \left(1 - \frac{1}{S}\right) + \frac{\sigma_V^2}{NPS} \left(1 - \frac{1}{B}\right) \right]$$

where $\sigma_I$ is the standard deviation of the maximum-power current and $\sigma_V$ is the standard deviation of the maximum-power voltage. Typcially $\sigma_I$ is 0.07; no typical value has been reported for $\sigma_V$. For this $\sigma_I$ and for $\sigma_V$ equal to zero, the power loss is only 2% for N = 10.

Dirt accumulation can be severe for arrays tilted only slightly and for arrays in areas with much air pollution. The dirt will continually accumulate on soft surfaces, such as silicon rubber, so almost all manufacturers now use glass coverplates. Frequent rains help keep the glass clean. After months of operation without cleaning, dirt caused losses of 4% in Chicago; 3% in Lexington, MA; 3% in Cambridge, MA; 1% at Mount Washington, NH; and 12% in New York City (Ref. 4-4).

The effects of failures of individual cells, primarily due to cracking, is important but difficult to compute. The computational difficulties arise from the number of combinations of failed cells. For example, if all of the cell failures occur in one substring of a series block, the effect on the entire array field is much less than if one cell fails in each branch circuit. Some cases already have been analyzed at NASA's Jet Propulsion Laboratory; typical results are presented in Exhibit 4.2-9. The probability of any given configuration of failed cells can be estimated using the binomial and multinomial distributions. Although long and



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tedious, the computations are straightforward. However, the computation of the I-V curve for the system for each of these configurations is a major difficulty. There are many non-linear equations to be solved, with a different set for each combination of failures. The substring failure density is computed for N cells per substring by the formula

expression:

$$F_{ss} = 1 - P_c^{\,N}$$

where Pc is the probability of survival of one cell within the time period of interest. For example, the mean time between failures of cells is approximately 200 years, so the probability of survival for one year is

$$Pc = \exp(-t/200) = \exp(-1/200) = 0.995$$

If 20 cells were connected in series to make a substring, the failure density, $F_{ss}$, after one year would be 0.095.

The abscissa of Exhibit 4.2-9 would be determined by this value. If there were 8 parallel strings in each of 50 series blocks, the branch-circuit power loss fraction would be 0.29, as read from Exhibit 4.2-9. The power output for this number of cells (20 x 8 x 50 = 8000) would be approximately 4 kW when new; the power output after one year, if none of the modules were replaced, would be 0.71 x 4 = 2.84 kW. In addition, other curves must be used if a simple voltage regulator is used instead of a peak-power tracker. Eventually, there should be enough design charts to cover all practical possibilities.

Although Exhibit 4.2-9 seems to imply that the greater the number of series blocks, the greater the power loss, the opposite is the case. For the 8000 cells, if there were 500 series blocks, there would be only 2 cells per block, so the failure density would be only 0.01. For this failure density, the power loss fraction would be only 0.08 and the output after one year, 3.68 kW. Therefore, the more series blocks (the more cross ties between parallel substrings), the lower the power-loss fraction.

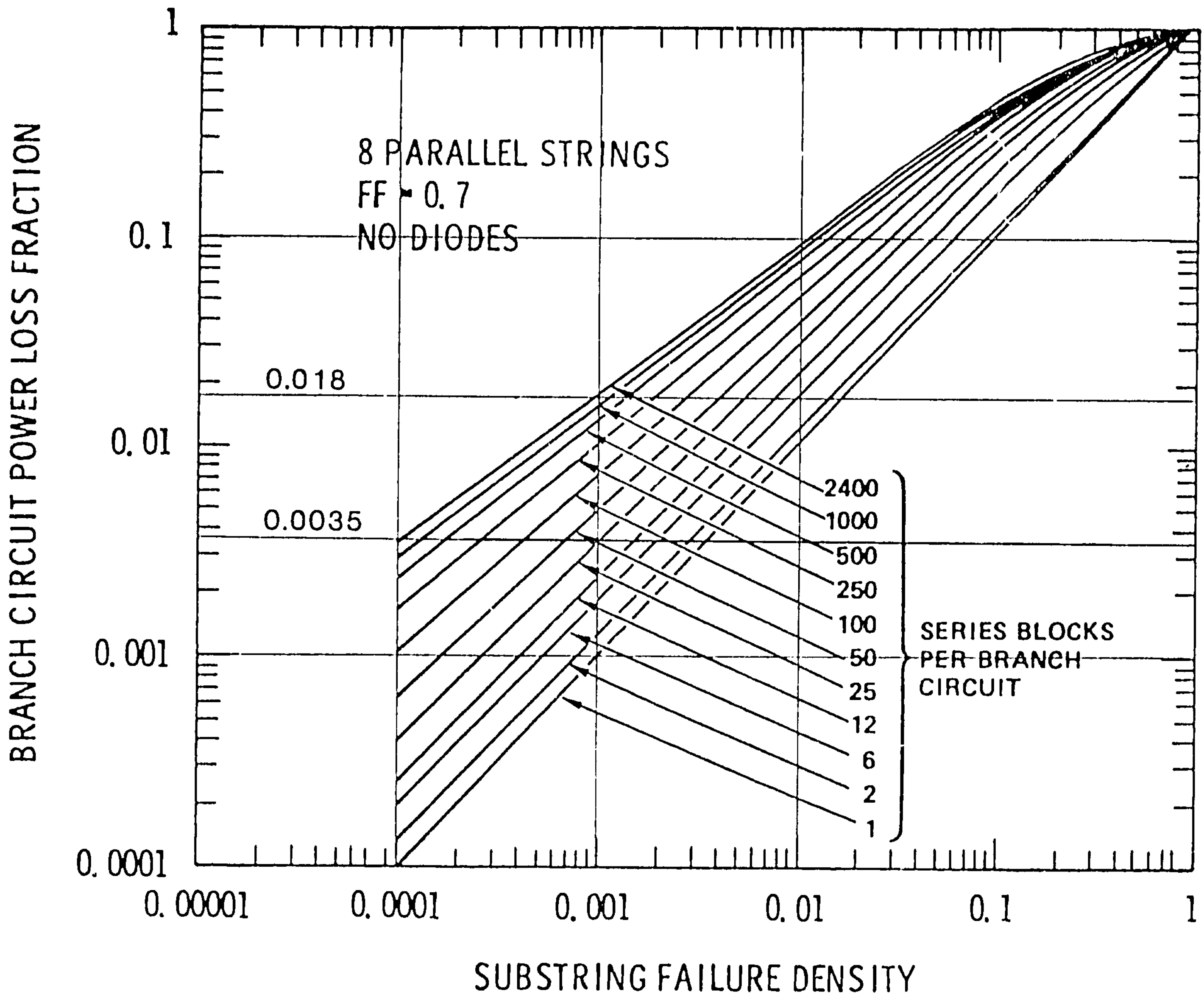


Exhibit 4.2-9

ARRAY POWER LOSS FRACTION
VERSUS SUBSTRING FAILURE DENSITY

(Source: Reference 4-5)

Much of the loss due to cell failures can be avoided if failed modules are replaced during routine maintenance. There is a tradeoff, however, between the cost of the replacement module and oversizing the array initially to compensate for expected failures. Locating failures also presents a maintenance problem. Monitoring the output from subsections of the array can reduce the area requiring inspection. Visual inspection will frequently be sufficient to discover the broken cells; detecting the higher temperatures of broken cells can also help. (See Section 8 for additional information on maintenance).

### 4.2.4 Available Modules

Modules are available in almost any combination of operating voltage and current (Exhibit 4.2-10). The unit costs are relatively insensitive to module size, at least for sizes above 2' by 4' (Exhibit 4.2-11). The reliability of the larger modules can be kept sufficiently high by using enough cross ties (series blocks) within the module.



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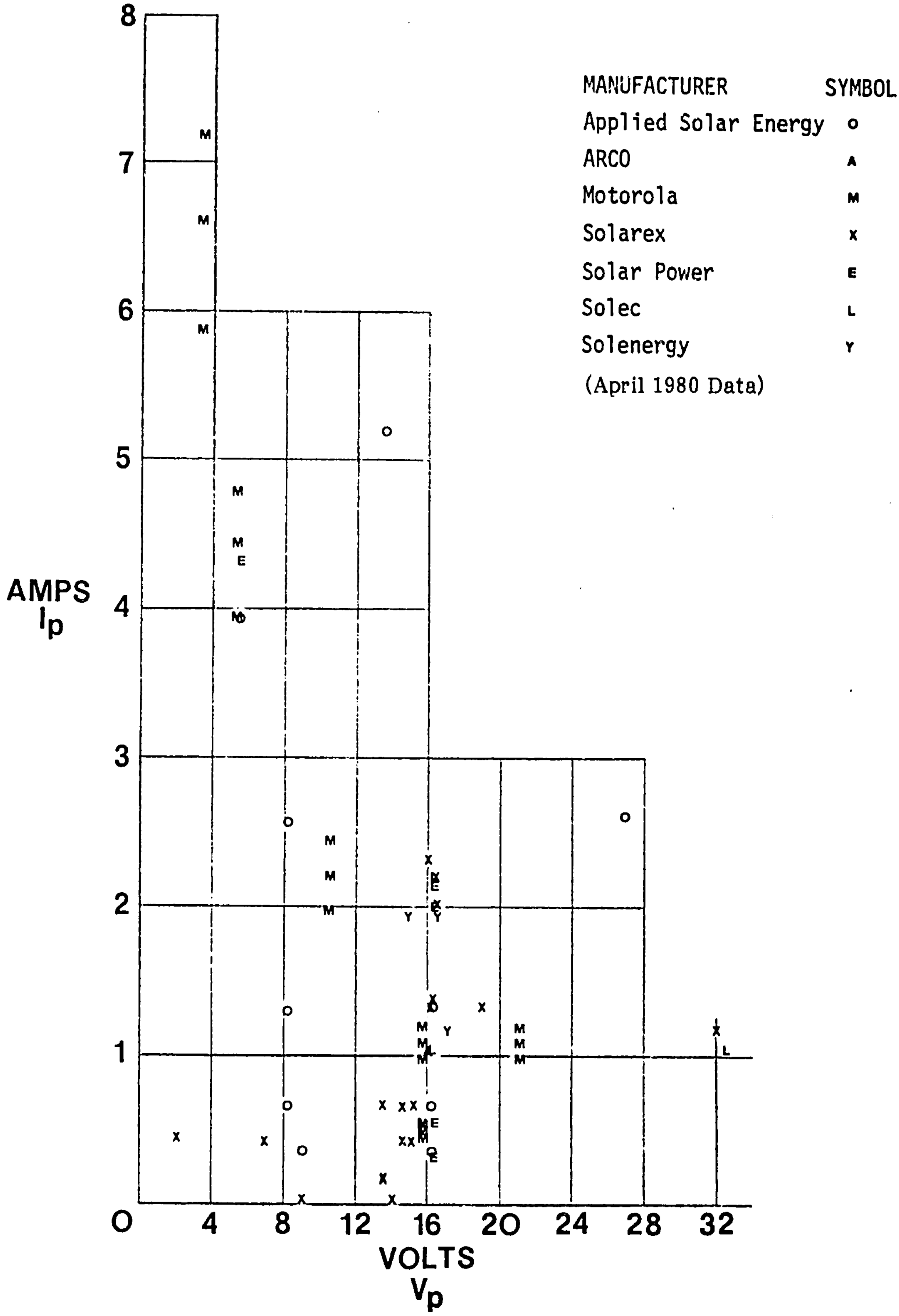



Exhibit 4.2-10

TYPICAL AVAILABLE SILICON SOLAR MODULES

| ELEMENT | UNITS | COST | | |
|---|---|---|---|---|
| | | 2 x 4 | 4 x 4 | 4 x 8 |
| **INITIAL:** | | | | |
| MODULE DIRECT COST | $/m$^2$ | 60 | 60 | 60 |
| MODULE YIELD COST | $/m$^2$ | 0-5 | 0-8 | 0-23 |
| • MODULE SUBTOTAL | $/m$^2$ | 60-65 | 60-68 | 60-83 |
| PANEL FRAME | $/m$^2$ | 24 | 18 | 15 |
| PANEL WIRING | $/m$^2$ | 2-4 | 2-3 | 1-2 |
| • PANEL SUBTOTAL | $/m$^2$ | 26-28 | 20-21 | 16-17 |
| PANEL INSTALLATION | $/m$^2$ | 1 | 1 | 1 |
| INSTALLED ARRAY STRUCT | $/m$^2$ | 22 | 22 | 22 |
| • ARRAY TOTAL | $/m$^2$ | 109-116 | 103-112 | 99-123 |
| **PER REPLACEMENT ACTION:** | | | | |
| FAULT IDENTIFICATION | $/PANEL | 4 | 4 | 4 |
| PANEL SUBSTITUTION LABOR | $/PANEL | 21 | 21 | 21 |
| MODULE REPLACEMENT LABOR | $/MOD | 12 | 12 | 12 |
| REPLACEMENT MODULE PARTS (INC 1% INVENTORY COST) | $/m$^2$ | 61-66 | 61-69 | 61-84 |

Exhibit 4.2-11

NOMINAL ARRAY COSTS (1975 Cost Levels)

(Source: Reference 4-5)

## 4.3 LEAD-ACID STORAGE BATTERIES

By the end of this sub-section, the reader should be able to (1) list the various reasons batteries enhance the performance of photovoltaic systems; (2) specify reasonable requirements for the batteries used in photovoltaic systems; and (3) analyze the battery-photovoltaics interaction so the system performance can be predicted. Sample problems, illustrating this use of this sub-section, are presented in Section 7.2.

### 4.3.1 Advantages and Disadvantages of Batteries in Photovoltaic Systems

Batteries give photovoltaic systems the following advantages:

- Capability to provide energy for sunless periods
- Capability to meet momentary peak power demands
- A stable voltage for the system
- Capability to store energy produced by the array in excess of the instantaneous demand, thereby reducing energy loss

One recent study showed that systems without batteries deliver an average of 2.5 hours per day of rated output, whereas systems with batteries deliver 4.5 hours. Another study showed little difference in annual system output when operated at constant (battery) voltage as compared to operation at the instantaneous optimal peak-power array voltage.

Because batteries and the associated charge-rate regulator add to the number of parts in the system, certain disadvantages accrue. Batteries (1) add to the system complexity; (2) add to its cost; (3) increase the maintenance activity and maintenance cost for the system; and (4) frequently reduced the system reliability. Only in those rare circumstances for which low charge rates are acceptable can the charge controllers be omitted. Despite these disadvantages, batteries are frequently worth including in the design, so the understanding of their operation is important.

## 4.3.2 Battery Operation

Of the many types of batteries available (Exhibit 4.3-1), we will concentrate on lead-acid batteries, because these are the most frequently used in photovoltaic systems. The positive electrode of the lead-acid battery consists of lead oxide; the negative, lead. Both are converted to lead sulfate in the discharge process. The electrodes are immersed in sulfuric acid with an approximately 40% acid concentration.

In practice, the electrodes and sulfuric acid are enclosed in a polyethlene container. The electrodes themselves are formed by a grid made from a lead-calcium alloy. (The less expensive lead-antimony alloy is not suitable for photovoltaics because it causes a higher battery self-discharge rate than desirable). A paste of lead oxide is pressed into the grid such that the paste, when cured, forms a porous structure, thereby exposing a large surface area to the acid. Various fibrous mats separate the two electrodes. The mats are strong enough to keep the electrodes apart and to hold the pasted material in place, but are loose enough to permit the easy flow of ions from electrode to electrode. When the electrons flow through the electrodes, they are captured or released by the porous materials, but are conducted to the grid and hence to the external battery terminal.

## 4.3.3 Battery Current/Voltage Characteristics

The effect of various processes on the output voltage and current of lead-acid batteries are illustrated in Exhibit 4.3-2. The batteries' discharge period is shown in (a) and the charging period in (b) of the exhibit.

When the discharge period starts, the terminal voltage is high because the ions are uniformly distributed throughout the electrolyte. Shortly thereafter, the voltage has dropped considerably because the ions must migrate between the electrodes, thereby adding to the internal resistance. Since, at this time, the ions are not uniformly distributed, the process is known as polarization. At high currents, the internal resistance causes the terminal voltage to drop. At low

| Characteristic | Units | LEAD-ACID ($Pb/H_2SO_4/PbO_2$) — AUTOMOTIVE (SLI) Calcium | AUTOMOTIVE (SLI) Antimony | DIESEL STARTING | MOTIVE POWER Antimony | MOTIVE POWER Calcium | STATIONARY Antimony | STATIONARY Calcium | STATIONARY Plante | SEALED | PHOTOVOLTAIC Low Rate Calcium | PHOTOVOLTAIC Low Rate Pure Lead | PHOTOVOLTAIC Medium Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rated capacity - 77°F | Ah cell | | 13-340 (1) | 57-568 (2) | 180-2175 (3) | 150-2250 (3) | 10-8000 (2) | 50-2550 (2) | 10-1000 (2) | 1-40 (1) | 50-3000 (4) | 26-600 (5) | 150-2250 (3) |
| Nominal operating voltage | volts cell | 1.98 (1) | 1.98 (1) | 1.96 (2) | 1.94 (3) | 1.94 (2) | 1.94 (2) | 1.94 (2) | 1.94 (2) | 1.97 (1) | 2.05 (4) | 2.00 (5) | 1.94 (2) |
| Nominal end of charge voltage | volts cell | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.55 | 2.45 | 2.40 | 2.55 |
| Nominal discharge cutoff voltage | volts cell | 1.75 (1) | 1.75 (1) | 1.75 (2) | 1.76 (3) | 1.76 (3) | 1.75 (2) | 1.75 (2) | 1.75 (2) | 1.75 (1) | 1.95 (4) | 1.75 (5) | 1.76 (3) |
| Available capacity - 104°F | of rated | 105 | 105 | 105 | 105 | 105 | 105 | 105 | 105 | 108 | 102 | 102 | 105 |
| Available capacity - 32°F | of rated | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 87 | 70 | 70 | 70 |
| Available capacity - -20°F | of rated | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 60 | 20 | 20 | 20 |
| Nominal energy efficiency | | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 | 70-80 |
| Self discharge rate - 77°F | per month | 1 | 7-50 (8) | 7-50 (8) | 7-50 (8) | 1 | 7-50 (3) | 1 | 3 | 7 | 1 | 3 | 1 |
| Nominal cycle life (10) | Cycles | 20-50 | 150-250 | 500 | 1500-2000 | 1000-1500 | 250-500 | 100-500 | 250-500 | 100-200 | 350 | TBD | 1000-1500 |
| Nominal calendar life (11) | Years | 2-5 | 2-5 | 8 | 5-15 | 10-20 | 15 | 15-24 | 24-30 | 2-5 | 5-15 | 5-15 | 10-20 |
| Energy density | Wh/lb | 13-22 (1) | 13-22 (1) | 5-8 (2) | 8.4-11.0 (3) | 8.4-12.3 (3) | 5-10 (2) | 6-10 (2) | 4-7 (2) | 9-16 (1) | 5.8-18.8 (4) | 17-19 (5) | 6-13 (3) |
| Energy density | $Wh/in^3$ | 0.8-1.6 (1) | 0.8-1.6 (1) | 0.3-0.5 (2) | 1.1-1.4 (3) | 0.7-1.5 (3) | 0.3-0.8 (2) | 0.4-0.8 (2) | 0.2-0.6 (2) | 0.8-1.5 (1) | 0.4-1.4 (4) | 1.1-1.4 (5) | 0.6-1.5 |
| Cost (12) | $/kWh | 70-77 | 70 | 142-162 | 112-130 | 150-200 | 112-130 | 122-130 | 365 | 375 | 135-175 | 98 | 165-195 |
| Cost | $/kWh cycle | 1.40-3.85 | 0.28-0.47 | 0.28-0.32 | 0.06-0.09 | 0.10-0.20 | 0.22-0.52 | 0.24-1.30 | 0.73-1.46 | 1.88-3.75 | 0.39-0.50 | TBD | 0.11-0.20 |
| Cost | $/kWh year | 14.0-38.5 | 14.0-35.0 | 17.8-20.3 | 7.5-26.0 | 7.5-20 | 7.5-8.7 | 5.1-8.7 | 12.2-15.2 | 75-188 | 9.0-35.0 | 6.5-19.6 | 8.3-19.5 |

| Characteristic | Units | NICKEL-CADMIUM (Ni/Cd) — SEALED SINTERED PLATE | SEALED POCKET PLATE | VENTED POCKET PLATE Low Rate | VENTED POCKET PLATE Medium Rate | VENTED POCKET PLATE High Rate |
|---|---|---|---|---|---|---|
| Rated capacity - 77°F | Ah cell | 0.1-23 (6) | 0.8-30 (6) | 5-488 (2) | 9-382 (2) | 9-470 (2) |
| Nominal operating voltage | volts cell | 1.25 (6) | 1.25 (6) | 1.20 (2) | 1.25 (2) | 2.25 (2) |
| Nominal end of charge voltage | volts cell | 1.45 | 1.60 | 1.65 | 1.60 | 1.60 |
| Nominal discharge cutoff voltage | volts cell | 1.00 (6) | 1.00 (6) | 1.00 (2) | 1.00 (2) | 1.00 (2) |
| Available capacity - 104°F | of rated | 98 | 98 | 98 | 98 | 98 |
| Available capacity - 32°F | of rated | 90 | 90 | 90 | 90 | 90 |
| Available capacity - -20°F | of rated | 65 | 65 | 65 | 65 | 65 |
| Nominal energy efficiency | | 60-70 | 60-70 | 60-70 | 60-70 | 60-70 |
| Self discharge rate - 77°F | per month | 5 (9) | 5 (9) | 5 (9) | 5 (9) | 5 (9) |
| Nominal cycle life (10) | Cycles | 500 | 500-1000 | 1500-2000 | 1500-2000 | 1500-2000 |
| Nominal calendar life (11) | Years | 8 | 12 | 24 | 24 | 24 |
| Energy density | Wh/lb | 7-19 (6) | 4-11 (6) | 9-11 (2) | 9-10 (2) | 6-7 (2) |
| Energy density | $Wh/in^3$ | 0.8-2.2 (6) | 0.3-1.0 (6) | 0.4-0.5 (2) | 0.3-0.6 (2) | 0.3-0.4 (2) |
| Cost (12) | $/kWh | 900-52,000 | 900-1100 | 315-1050 | 315-1050 | 315-1050 |
| Cost | $/kWh cycle | 1.8-104 | 0.90-2.20 | 0.16-0.70 | 0.16-0.70 | 0.16-0.70 |
| Cost | $/kWh year | 11.3-6500 | 7.5-9.2 | 13.1-43.8 | 13.1-43.8 | 13.1-43.8 |

(1) At the 20 hour rate
(2) At the 8 hour rate
(3) At the 6 hour rate
(4) At the 500 hour rate
(5) At the 600 hour rate
(6) At the 5 hour rate
(7) At the 1 hour rate
(8) Range indicates increase in self discharge rate with age
(9) For first 4 months after complete charge after 4 months rate reduces to 0.25 per month
(10) To 80 percent depth of discharge
(11) In the absence of cycle operation
(12) 1979 dollars. Prices fluctuate with material costs. Battery costs presented in this table should be used for purposes of comparison only

N.A. – Not applicable
TBD – To be determined

Exhibit 4.3-1

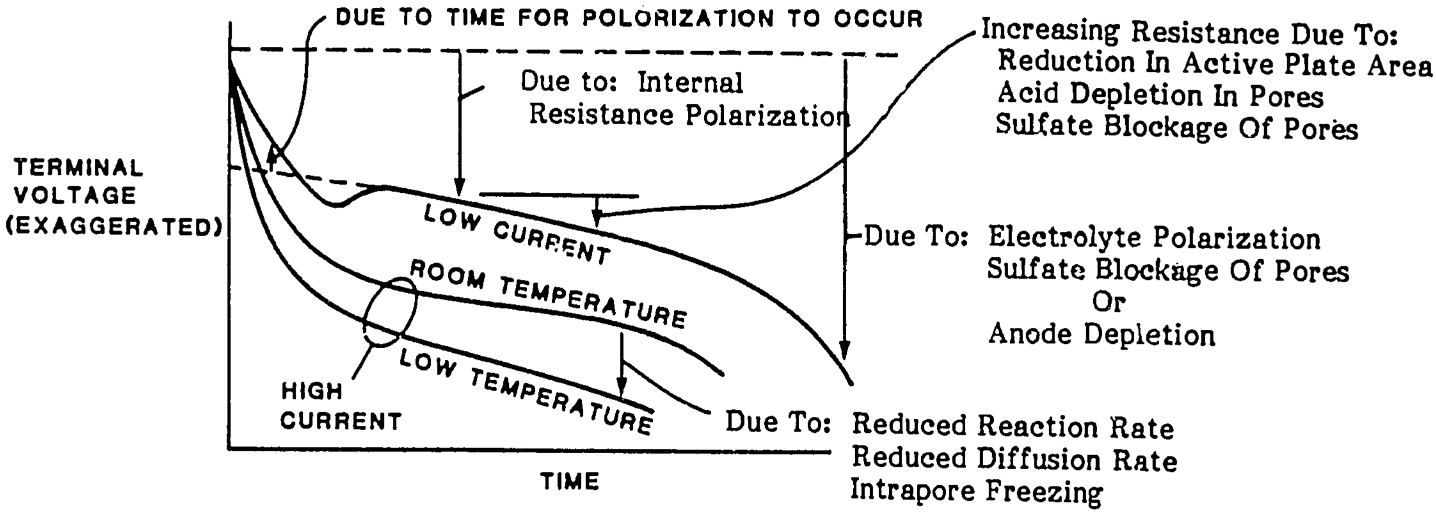
CHARACTERISTICS SUMMARY TABLE: COMMERCIALLY AVAILABLE BATTERIES

(Source: Reference 4-1)

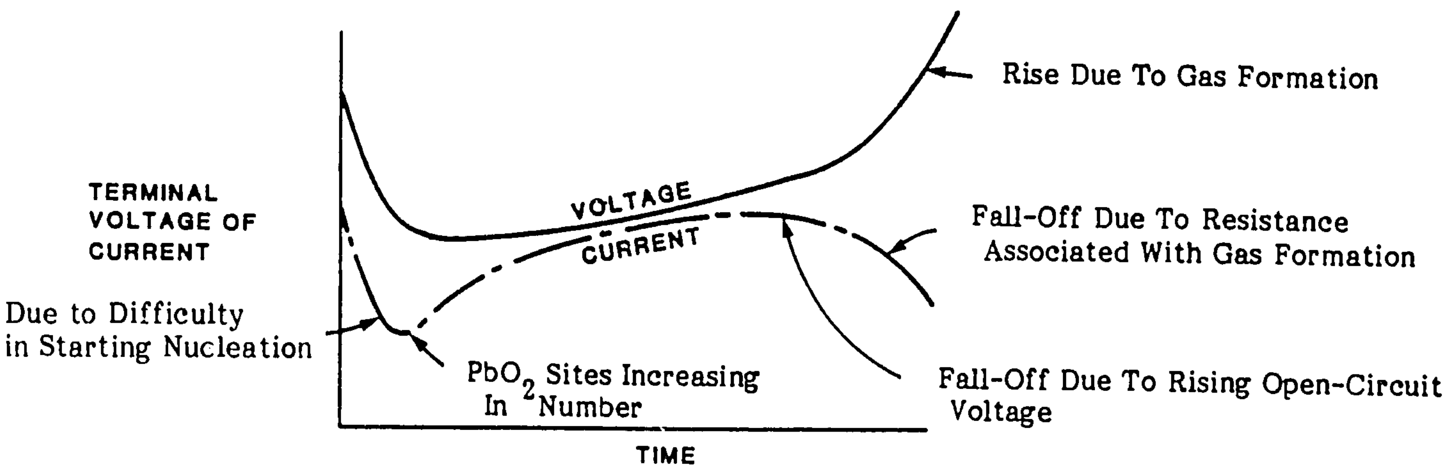
Exhibit 4.3-2

LEAD-ACID BATTERY CHARACTERISTIC CURVES

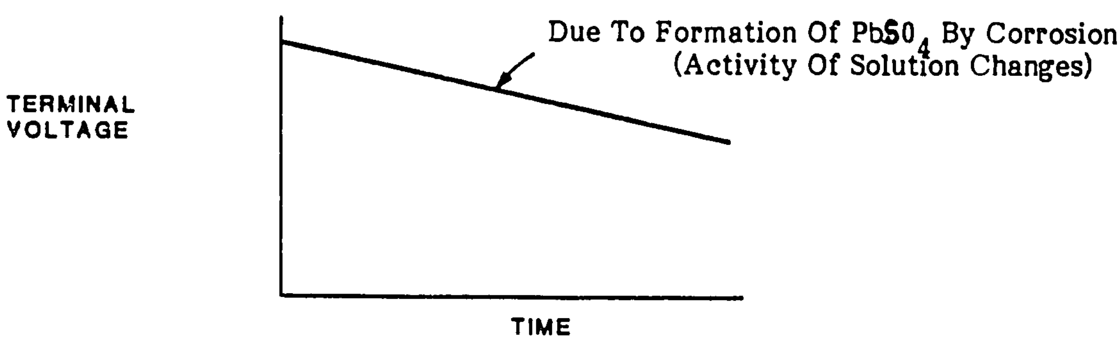
(a) DISCHARGING




(b) CHARGING




(c) REST (OPEN CIRCUIT)



temperatures, the reactivity of the cell decreases, so the terminal voltage drops further. Near the end of the discharge period, the sulfuric acid is nearly completely consumed, so its electrical resistance increases greatly. In addition, the lead with which it can react is nearly exhausted. (Most cells are designed such that the acid is depleted before the lead).

At the beginning of the charge cycle, there are few sites of lead oxide. As a result, the terminal voltage must be high to obtain nucleation and a significant charge rate. As the number of lead-oxide sites increases, the terminal voltage can decrease while the current remains constant. However, after a while, the number of sites requiring charging starts to decrease, so ions must congregate at those few sites and the effect of polarization increases. Near the end of the charge period, hydrogen forms at the anode, with the gas layer greatly increasing the internal resistance of the cell.

If left standing (Exhibit 4.3.2 (c)), the terminal voltage of the cell will decrease with time, due to the impurities in the water and the alloys in the cell, which react with the electrolyte and decrease the acid concentration.

The current and voltage during discharge can be described in terms of the state of charge of the cell (SOC, ranging from 0 to 1.0) by the equation:

$$V = V_r - \frac{I}{AH}\left[\frac{0.189}{SOC} + IR\right]$$

where the SOC is the ratio of the charge at the time of interest to the maximum charge, as measured for the 500-hour discharge rate. The symbols are defined as follows:

$V_r$ = rest voltage = $2.094 * \left[1.0 - 0.001 * (T - 25.\ ^{o}C)\right]$
$V$ = Terminal Voltage
$I$ = current (Amperes)
$AH$ = the ampere-hour rating of the battery for the discharge rate
$IR$ = internal resistance of the cell
= $0.15 * \left[1.0 - 0.02 * (T - 25)\right]$

The 0.189 factor represents the internal resistance due to polarization.

During the charging period, the current and voltage are given by

$$V = Vr + \frac{I}{AH}\left[\frac{0.189}{1.142 - SOC} + IR\right] + \underline{(SOC - 0.9)\ Ln\left(\frac{300*I}{AH} + 1.0\right)}$$

The underlined term is included only if the first two terms sum to more than 2.28 volts. During the idle period (neither charging nor discharging), the state of charge decreases according to the equation (lead-calcium)

$$SOC = SOC_o * Exp(-k*t)$$

$$k = 300 * Exp(-4400/T)$$

with T in $^{o}$k, t in hours, and K in hours$^{-1}$. At room temperature, K = 0.0001.

### 4.3.4 Battery-System design

The design of the battery system is an iterative process: (1) the battery size is selected; (2) the system performance is computed; and (3) the life-cycle cost is computed. These three steps are repeated until the system with the minimum life-cycle cost is found.

The iterative process must be performed with the battery selection eventually being confirmed by the manufacturer. Most, if not all, battery manufacturers want to know how many ampere-hours or kWh must be stored and in what environment (temperature, charge/discharge cycles, etc.). They will then recommend a battery. Therefore, the manufacturer's recommendation must be anticipated to determine the optimal storage requirements for the system. Thus it is important to be able to compute the battery performance.

The exact computation of the battery performance would require a detailed circuit analysis using Kirchhoff's current law. Because the batteries, power conditioning equipment and photovoltaic cells have non-linear current/voltage characteristics, solutions to the governing equations are difficult to obtain. Usually, the solution to a set of non-linear algebraic and differential equations must be computed for each instant of time.

A more common procedure is to treat the battery as a simple constant-voltage kWh or Ah storage device. The energy produced by the photovoltaic array is computed first. The load demand is determined, with the excess energy available to the battery. If the battery is fully charged, the excess is assumed to be used by the load. If the battery is not fully charged, the excess energy is absorbed by the battery, increasing the amount of energy stored therein. If the load exceeds the power output of the array, the difference is withdrawn from the battery, decreasing the energy stored therein, until the battery is fully discharged. This state-of-charge accounting can be done on an hourly, daily, weekly or monthly basis. This more common procedure is a reasonable approach to conceptual system design; however, the voltage variation of the battery is significant so final designs should be based on the more accurate method of solving the circuit equations. The foregoing equations, and those to follow, can be used in either approach. The sample problems presented in Section 7.3 will illustrate the use of the more common energy or ampere-hour accounting procedure.

### 4.3.5 Battery Life

Numerous factors, only some of which can be evaluated quantitatively, influence battery life (Exhibit 4.3.3). Corrosion inside the batteries is controlled by the acid concentration and the temperature. High temperatures also hasten evaporation of the water. Overcharging results in water loss, which can shorten the battery life if the water is not replenished. Low temperatures reduce the capacity by increasing the polarization loss (no equation is available to describe this effect at present). Low temperatures can also cause freezing. Charge/discharge cycles are limited by mechanical and chemical interactions. The only available data is for the same minimum state of charge during each cycle. A typical state-of-charge history for batteries in photovoltaic systems is depicted in Exhibit 4.3.4. There is no equation to predict cycle life under such variable minimum states of charge.

Exhibit 4.3-3

LEAD-ACID BATTERY FAILURE MECHANISMS

a. Chemical: Life = Life at $25^{o}C$ * exp [-5070* (1/T - 1/298)]

T = Temperature $^{o}K$

Corrosion of the terminals

Corrosion of the grid

Growth of large lead sulfite crystals

b. High temperature: T = T ambient + 125 * (V - Vr) *I/AH

Hastens chemical effects

Hastens evaporation

c. Water loss: ml = 0.336 * ampere-hours of overcharge + evaporation

d. Low temperature

Loss of capacity, per I-V characteristic

Freezing

| | | | | | | |
|---|---|---|---|---|---|---|
| specific gravity: | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 |
| freezing point ($^{o}C$) | -0 | -8 | -27 | -70 | -36 | -29 |

e. Mechanical: Cycle life = 9000 *exp [-(1. - minimum state of charge)]

Shorting by dendrite growth

Shorting by sediment at the bottom of the plates

Flaking due to vibration

Flaking due to differential expansion

Dirt

Non-uniform plate growth

f. Self discharge: SOC = Initial SOC * exp -300*t*(exp-4400/T), where

t = Time, hours

T = Temperature, $^{o}R$

Chemical reactions accelerated by Fe and Cl in the water

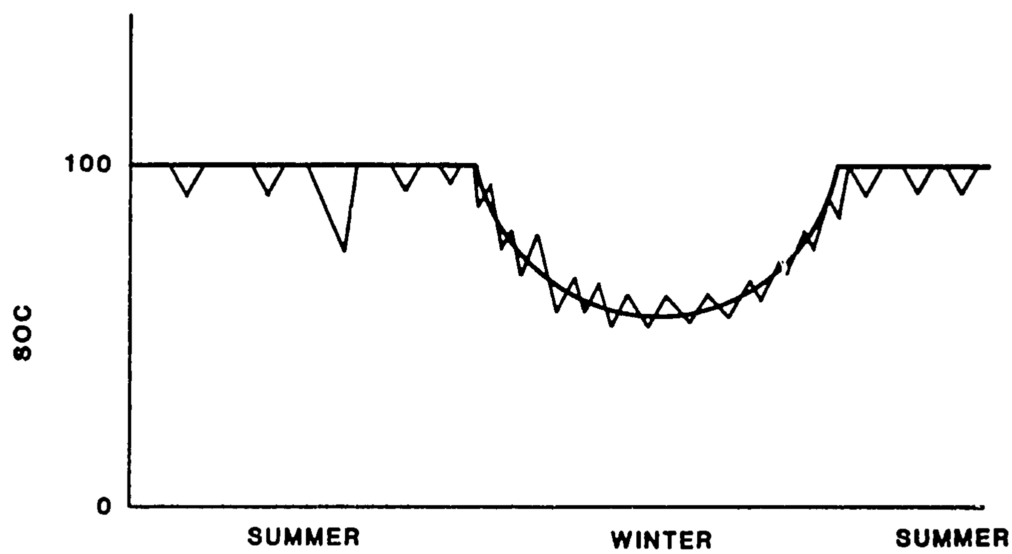



Exhibit 4.3-4

TYPICAL BATTERY STATE OF CHARGE (SOC) HISTORY

Exhibit 4.3-3 lists equations from which an estimate can be made of the life of a battery in any set of circumstances, provided certain assumptions are made concerning the effective minimum state of charge to be used in the cycle-life equation. (Note that the cycle life and the life per item (a) of the exhibit are independent. Item (a) gives the years the battery will last before corrosion prevails. The overall life is the lesser of items (a) and (e), as modified by the other life-determining factors).

The self-discharge characteristic of batteries sometimes causes failures of systems of batteries, rather than a single battery. The equation presented in Exhibit 4.3-3 is the nominal self-discharge rate. However, the rate will vary from battery to battery, depending on the particular materials used. Therefore, in a group of batteries connected in series, some batteries (cells) will be at a lower state of charge than others. On recharging, unless overcharging is used, the lower-SOC cells may not completely recharge before the voltage regulator interrupts the current. Then, while the system is idle, the more rapidly self-discharging cells will self-discharge further and may eventually become totally discharged. Testing of the batteries with an hydrometer will reveal the problem but not eliminate the cause. Overcharging eliminates the cause but depletes the water reserves and increases the maintenance.

Stratification of the electrolyte in the cells also can cause a loss of capacity. The problem occurs at SOC below 1.0 in tall batteries. Although there is no quantitative evaluation available, pumps are sometimes recommended by the manufacturer to keep the electrolyte mixed.

### 4.3.6 Lead-Acid Storage Battery Safety

Several important safety criteria that are applicable must be considered if lead-acid storage batteries are to be incorporated in the stand-alone system. Lead-acid batteries are of two general types:

- Lead-antimony battery, with voltage output about two volts per cell and ampere-hour (Ah) rating from 100 Ah to 1000 Ah for an 8-hour discharge rate. Charge/discharge efficiency is high (85% to 90%). During the charging cycle, an overvoltage (equalizing charge) is required for a period of time to assure that all cells in a battery bank will be recharged to the same voltage level.

- Lead-calcium battery, with output voltage and ampere-hour rating similar to those of the lead-antimony battery. Lead-calcium batteries usually require less maintenance than lead-antimony batteries and do not require an equalizing charge during recharge. Depending on the degree of discharge and cycling rate, batteries can be operated for long periods (e.g., several months) without adding water.

The following design "safety" considerations correspond to the more serious hazards experienced in the use of lead-acid batteries in uninterruptable power supplies:

(1) Danger of Hydrogen Explosion. Hydrogen which was liberated during the charging cycle can accumulate in an unvented room and may result in an explosive mixture. A flame or spark can then cause an explosion, with possible injury to personnel or damage to the charging equipment, although flame arrestors greatly reduce the probability.

Design Guideline: Provide for ventilation in the layout of the proposed battery area or "room" (NEC 480-8(a)) . Ensure that no flame-producing or spark-producing devices are installed within the battery area or room. Each vented cell must be equipped with a flame arrestor to prevent destruction of the cell due to ignition of gases (NEC 480-9(a)) . Install a "No Smoking - No Sparks" warning sign in the battery area.

(2) Danger of Electrolyte Spillage. Direct contact with the electrolyte (a mixture of sulfuric acid ($H_2So_4$) and water) can cause severe injury (burns) to the skin and possibly permanent damage to the eyes. Unless properly designed to

release accumulated gas pressure, battery cells can explode scattering cell parts and electrolyte. Volumes of fresh water applied quickly and continuously may avert serious damage.

Design Guideline: Provide a fresh-water emergency shower or safety fountain within a few feet of the battery bank. Ensure sealed battery cells are equipped with pressure release vents (NEC 480-9(b)) . Ensure that proposed maintenance manuals for the battery bank include appropriate cautionary notes, e.g.: "Wear rubber apron, gloves, boots, and facemasks when handling, checking, filling, charging, or repairing a battery"; "Wear protective clothing and goggles when mixing acid and water"; "Always add acid carefully to water and stir constantly to mix well when preparing electrolyte". Specify that no sulfuric acid solutions of more than 1.400 specific gravity acid may be used inasmuch as when water is added to high specific gravity acid considerable heat and violent reaction will occur, possibly splashing the handler.

(3) Danger of Electrical Shock. If terminal voltage of the proposed battery bank is to be designed for greater than 50 volts ($V_o \geq 50V$ dc), there is danger of electrical shock during inspection/maintenance/servicing the battery bank (NEC Article 110-17(a)).

Design Guideline: Ensure that batteries are installed in groups having total voltage of not more than 250 volts on any one rack. Provide spacing (or insulation) between racks (NEC 480-6) . Provide a safety ground-disconnect circuit to allow the battery bank to "float" i.e., (+) and (-) terminals of a high-voltage string are disconnected during maintenance involving servicing, filling, or replacing a battery in a string within the battery bank. Design of the disconnect circuit must provide clearly visible visual indication of the disconnect status. The design should also provide shut-off and disconnection of dc/dc regulator chargers from both the solar array (input) side and battery (output) side during repair of the dc/dc regulator.

(4) Danger of Personnel Physical Injury. Batteries constitute a heavy, concentrated load and can easily cause painful strains or injury to a handler's back, hands, face, or feet. Also, dropped batteries may be damaged, causing injury due to electrolyte spillage as described in (2) above.

Design Guideline: Batteries should be lifted with mechanical equipment, such as hoist, crane, or lift truck. They should be moved horizontally with power trucks, conveyors, or rollers. Safety shoes and "hard hats" are recommended for handlers' protection (metallic safety hats should be avoided). The system design must include the tools and equipment required for handling individual battery replacement as a routine maintenance task. The system layout and structural design for battery racks/benches should facilitate maintenance and thus encourage the use of available handling equipment.

(5) Facility Damage. Spillage or leakage of electrolyte on benches, battery terminals, racks, floors, etc., can cause corrosion or severe damage unless promptly cleaned up with appropriate neutralizing solution (e.g., one pound of baking soda with one gallon of water). Furthermore, loss of electrolyte by leakage from a battery will lower battery capacity and can cause faults to the rack ( and ground circuit).

Design Guidelines: Provide reasonably controlled temperature ambient in the battery room to prevent freezing if decrease in battery electrolyte specific gravity raises the freezing point of the battery above the local ambient temperature.

(6) Damage Due to Corrosion. Fumes and fine spray of dilute acid given off by lead-acid batteries are very corrosive, particularly to metal work and structural items constructed of iron or steel brought in close proximity to cells.

Design Guideline: If steel conduit, structural elements, fasteners, etc., are considered for use in the battery area or room, it is recommended that these items be zinc-coated and kept well painted with asphalt-based paint.

## 4.4 POWER HANDLING

The power handling portion of the PV power system is essentially that part of the system which interfaces the arrays with the end-use loads. It is comprised of the necessary array control system, voltage regulators, storage batteries, inverters, and distribution system (including cables, overcurrent protection devices, disconnecting means, grounding system and any load management controllers). Except for the array control system, the power handling system ordinarily consists of electrical equipment which is quite conventional in function and design. This sub-section covers those functions and design concerns of the power handling system.

### 4.4.1 Dc Power Conditioning

The parameters under which solar arrays operate at a given location cause the characteristic dc output voltages to vary over a considerable range throughout the year. Some of these variations are random, such as the levels of insolation during intermittent cloud cover. Insolation and ambient temperature also undergo variations of a more gradual nature due to diurnal and seasonal factors. The voltage and power output of a photovoltaic power system is more variable than that of most conventional generators and thus needs some "conditioning" and storage or back-up before it can be used for most purposes. (For those stand-alone systems having ac loads in whole or in part, an inverter would be required to convert the dc output to an alternating current waveform at a specified voltage and frequency).

Design of a stand-alone photovoltaic (PV) system which includes batteries for energy storage requires not only sizing the array power output and battery storage capacity to meet the load, but also fixing the number of battery cells placed in series relative to the number of PV cells in series in order to keep the battery voltage in the neighborhood of the array maximum-power-point voltage during operation.

In a photovoltaic (PV) system, it is desirable to extract the maximum amount of energy out of the array; a situation that would exist if the array were to be operated at the maximum power point at every instant. In a stand-alone system where the array is connected in parallel with a battery storage subsystem, the number of battery cells which are connected in series defines the nominal dc bus voltage. Although the nominal dc bus voltage may lie in the neighborhood of the array maximum-power-point voltage for some nominal combinations of insolation level and cell temperature, there will generally be a mismatch between the actual operating dc bus voltage and the maximum-power-point voltage of the array at any particular instant in time. This mismatch, which will result in an effective decrease in the efficiency of the array, depends on the state-of-charge of the battery, the battery charge or discharge current, and on the temperature and insolation level of the PV array. If a variable lossless matching network is interposed between the array and the battery, then a maximum-power-point tracking strategy can be used to constrain the array to always operate at the maximum power point.

The decision to include or not to include a maximum-power-point tracker (MPPT) will depend on the additional useful energy which could be collected by using the MPPT and on MPPT costs.

Of those dc systems containing storage, the simplest configuration of the power conditioning system is the direct connection (though a blocking diode) of the array to the storage system and then to the load. This is illustrated in Exhibit 4.4-1. This configuration finds cost-effective applications for smaller systems up to approximately 2 kWp capacity. The direct connection of the array to the battery 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 in the system.

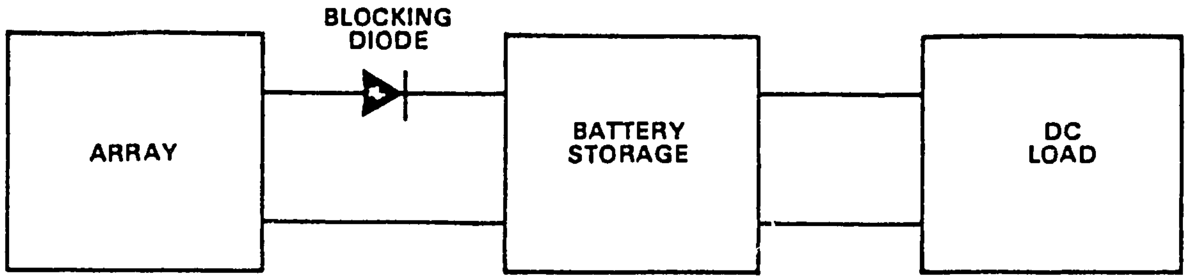



Exhibit 4.4-1

SELF-REGULATED PV SYSTEM

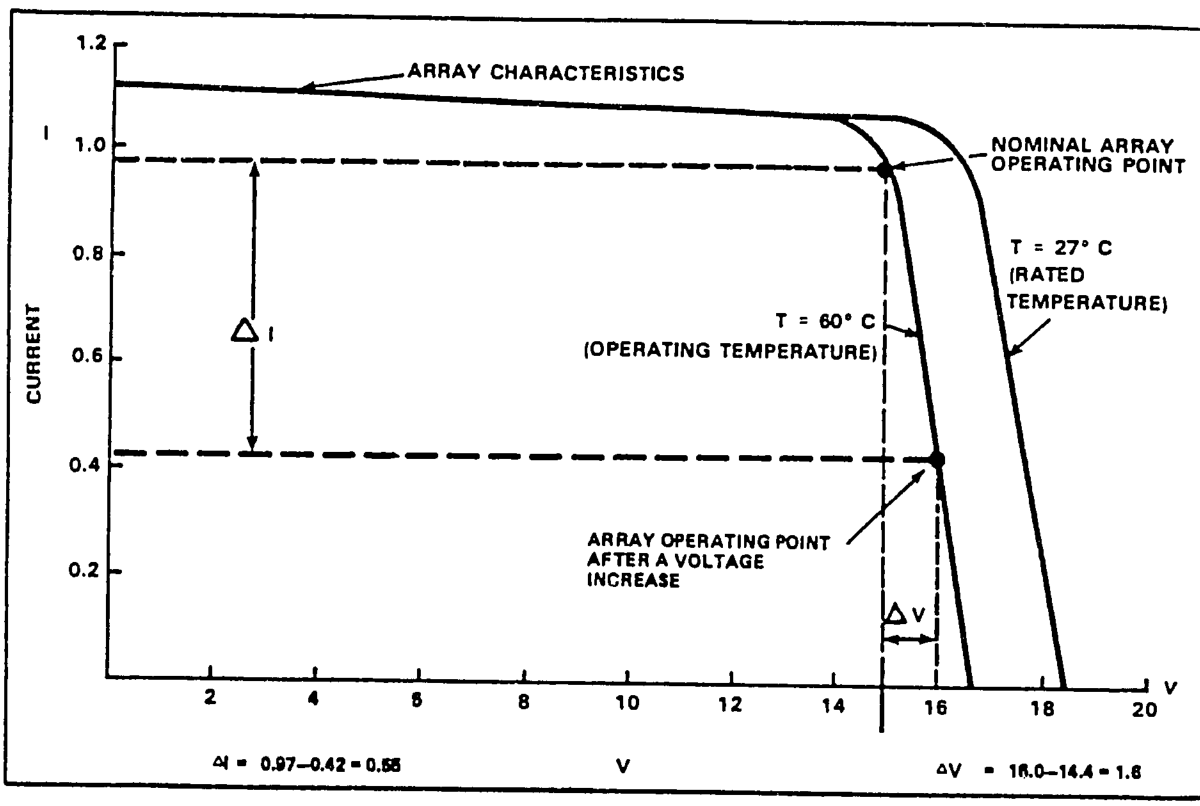



Exhibit 4.4-2

I-V CURVE OF PV MODULE EXHIBITING SELF REGULATION

(Source: Reference 4-6)

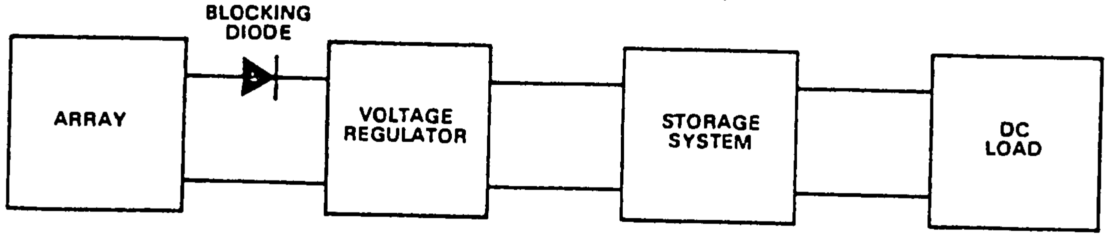



Exhibit 4.4-3

VOLTAGE-REGULATED PV SYSTEM

The storage battery continually supplies power to the loads and is charged by the power produced by the PV array during periods of insolation. When the voltage of the battery storage system equals that of the array (less the voltage drop across the blocking diode), current flow into the storage system would stop, with the batteries being at a full state of charge.

The self-regulated PV system configuration 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 battery's charging voltage requirements. For a 12 V lead-acid battery, the voltage range under charge varies from 12.8 V (at 60% discharge) to 14.4 V (at full charge). To transfer the maximum power from the array to the battery, the voltage operating-point of the array should be approximately 14.4 V plus the voltage drop across the diode of approximately 0.75 V, or a level of 15.15 V, as shown on Exhibit 4.4-2. The output current of the array is 0.97 A at this operating point. For a slight increase in cell voltage above the nominal array voltage, cell current will decrease rapidly, limiting the charging current.

The voltage variations caused by changing weather conditions and degradation due to aging can be compensated by controlling the array voltage by means of a voltage regulator. A typical voltage regulator, either in parallel or series with the array, the storage system, and the load, is shown in Exhibit 4.4-3. In order to regulate the voltage with the required limits to prevent battery over-charge and outgassing, the (shunt) voltage regulator must dissipate a certain amount of power to ground. If the load can utilize all of the PV power, the shunt regulator consumes no power. Based on the output voltage, a simple design regulator "shunts" current through a regulating transistor to keep the output voltage constant.

### 4.4.2 Control Schemes

The output of a PV array has the same characteristics as portrayed in Exhibit 4.2-6 as a series of I-V curves, dependent upon illumination levels and temperature. The specific operating point on a particular curve is dependent upon both the characteristics of the load and the available output from the array. Possible types of loads are constant resistance, constant voltage loads (such as batteries) and constant power loads with dynamic impedances. Fluctuations in operating points can be caused by changes in the load as well as from changes in the array's output due to dynamic variation with either insolation, temperature or wind.

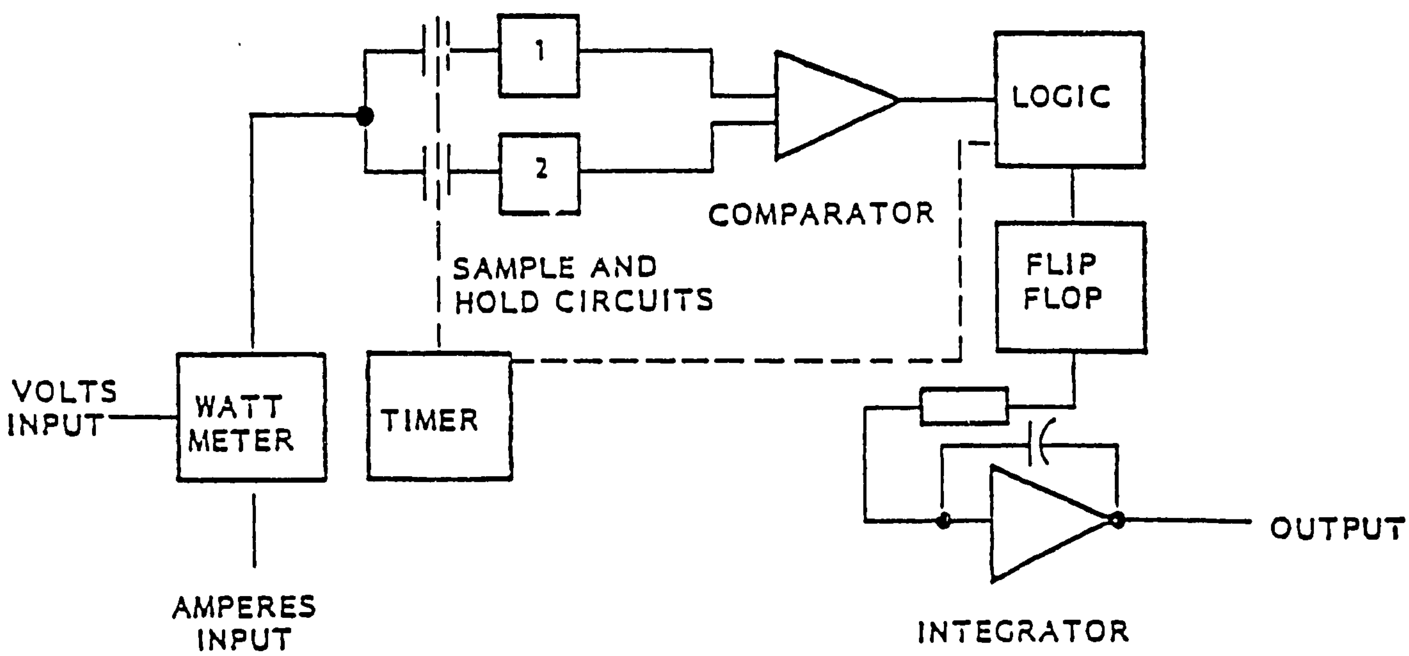
The voltage and current output of the array can be manipulated so that maximum energy can be extracted from the system. Maximum power tracking allows the greatest precision in operating near the maximum power point of the photovoltaic I-V characteristics as shown in Exhibit 4.2-6 by using a feedback method to determine operating points. The control accomplishes the change of operating point voltage with respect to the required load voltage by driving a dc/dc converter. The converter provides the interface between the array and the loads as shown in Exhibit 3-1. A simplified block diagram is shown in Exhibit 4.4-4 for a tracking controller. The basic elements include:

- A wattmeter circuit that continuously measures the power level and provides a signal output proportional to actual power.
- Two sample and hold circuits, controlled by a timer, that alternately sample the wattmeter signal output and hold it for comparison with the next sample.
- A flip-flop circuit that changes state whenever a new sample is smaller than the preceding one, but remains in the same state if a new sample is larger than the preceding one, thus representing an increase in power level.
- An integrator circuit that provides a constantly changing output whose direction of change is increasing for one state of the flip-flop and decreasing for the other state of the flip-flop.

The decision of whether to use maximum power tracking or not can be best answered by performing a system simulation on an hourly basis with the control system modeled in detail. The performance of the system both with and without maximum power tracking can be measured and used as a gauge in determining the cost-effectiveness of the control system and the required dc/dc converter.

Exhibit 4.4-4

SIMPLIFIED BLOCK DIAGRAM FOR
A MAXIMUM POWER TRACKING CONTROLLER



The various control functions which a power conditioning system can incorporate include:

- Configuration Control
- System autostart/shutdown
- Battery state of charge estimation (if applicable)
- Maximum power point tracking (if applicable)
- Selection of emergency back-up source
- System operation summary displays
- Data recording interface
- Load management
- Failure reporting/automatic recovery

### 4.4.3 Electrical Wiring

The electrical systems which require wiring in the field and which must be addressed consist of intra- and inter-array wiring, wiring to the power conditioning system, control and instrumentation wiring, and distribution wiring to the loads. A wiring installation for a power system must consider the following factors:

- Safety and reliability
- Avoidance of excessive voltage drop
- Avoidance of excessive copper (power) loss
- Flexibility in changing locations of equipment
- Provision for supplying increased loads
- Provision for economical maintenance

The interconnection and cabling (I & C) design criteria for a photovoltaic power system are similar to those for dc power systems. The design load and the photovoltaic array design configuration must be completed before attempting I & C design.

Proper wiring design involves the cost-effective selection of cabling to:

- Intraconnect panels of the PVPS array
- Interconnect the PVPS array to the load
- Provide integrated grounding of the arrays and a lightning protection system (NFPS 78-1975)
- Comply with national/local electrical installation codes
- Satisfy environmental requirements

Tables 250-94, 250-95, and 310-16 through 310-19 of the National Electrical Code (NEC) provide the requirements for cable sizing. Table 310-13, of the NEC provides the insulation requirements based on the cable's environment. Normally, more than one cable type will satisfy the load and environmental requirements. For such a case, the least expensive cable should be selected.

To ensure satisfactory operation of electrical devices, full voltage should be applied. Under load, the voltage drop from the source should be minimized. Good practice is to limit the voltage drop from the service entrance to any motor to 5%. In electric heating equipment, the voltage drop should generally not exceed 2%.

Power Loss

The power loss in a distribution system depends upon the resistance of the wires and the square of the individual currents which each carries. Feeders sized by the NEC will not always be the most economical size, especially if loads such as motors are operated at or near full load any considerable part of the time. In many cases, it may be more economical to increase the conductor size to reduce copper losses.

Flexibility of Wiring Systems

In industrial power systems, the changing of locations of loads such as motors is a more or less common occurence throughout the life of the facility and suitable designs should be incorporated to meet these changing conditions. Flexibility is usually accomplished by using busways which will accommodate plug-in devices, wireways and raceways where a large number of feeders and motor branch circuits are carried. Where motor sizes may increase, some oversizing of raceways is prudent.

## Provisions for Expansion and Maintenance

Spare capacity for future load growth can be installed initially at less cost than if provided after construction is completed. The provision for providing capacity for increased loads must be made with respect to physical constraints as well as electrical capacity limitations. For example, conduits embedded in a concrete slab imply a permanent job and future demands must be considered in the early stages of the layout. Maintenance must likewise be considered by providing enough access for working clearances in front of equipment line-ups such as switchgear and for the complete removal of the same.

## Economics of Wiring Design

There are many considerations in selecting a conductor for a particular wiring installation. Some of these are mechanical strength, current carrying capacity, reasonable voltage drop and insulation. With increasing costs of electrical energy, it is more apparent that the cost of annual losses often may dictate a higher initial investment in larger copper. This is especially true for both PVPS and for any circuits which operate at high capacity factor such as main feeders and where conductor and raceway investment is heavy.

Annual costs of different alternative systems should be compared to select the most economical. These costs are made up of the annual fixed charges of the investment and the cost of copper losses. By using the resistance of a circular mil-foot of commercial copper wire (a wire 1 foot long and having a cross sectional area of 1 cmil) at 10.7 ohms, the power loss in a circuit at 20°C is:

$$P = \frac{10.7 \times I^2 \times L \times n}{\text{cmils}}$$

Where:

| | | | |
|---|---|---|---|
| | P | = | the power lost in the conductors in watts |
| | I | = | the current in amperes in the conductor |
| | L | = | length of the conductor in feet |
| | cmils | = | the area of the conductor in circular mils |
| | n | = | 2 for a 2 wire circuit (dc or single phase) |
| or | n | = | 3 for a 3-wire 3-phase circuit (assuming balanced currents) |

The cost of the energy lost due to the power losses should be based upon the number of hours of operation each year and the cost of replacement energy at the PV site. By reducing the information to a table, the total annual costs of various sized conductors may be readily determined and the minimum annual cost scheme chosen.

### Array Wiring

Array wiring costs tend to increase greatly as module size is reduced. Wiring costs are inversely proportional to branch circuit voltage level, the optimum (minimum) for residential applications being between 100 V dc and 300 V dc. Electrical terminations are the principal cost drivers for array branch circuit wiring, although a modular quick-connect wiring system can be significantly less expensive than junction box wiring systems, particularly when the branch circuit wiring is exposed to weather. However, until such time as a modular quick-connect system is developed and code-approved, the junction-box system should be used. The conductor construction for use at 600V or less shall comply with section 310-13 of the NEC. Conductors must be selected depending upon their installation (wet, dry) and the resistance of the outer covering to moisture and ultraviolet light.

### Wiring Methods

Numerous wiring methods are authorized by the NEC, with most of them being used to a greater or lesser extent in commercial and industrial buildings. For procedures in planning power distribution systems, the reader is referred to several of the IEEE recommended practices (See Appendix C).

## Sources for Additional Design Data

An analysis of the several factors to be considered in selecting wiring and cabling for photovoltaic purposes is contained in Reference 4-7. These factors, corresponding to chapter headings in the volume are electrical, structural, safety, durability/reliability, and installation. A glossary of terms used within the volume is included for reference.

## 4.5 EMERGENCY BACKUP SYSTEMS

The need for backup to a stand-alone photovoltaic power system is determined by the definition of "criticality" of the load to be serviced by the proposed PVPS. The choice of a particular type of backup suitable for the application is influenced primarily by the size of the critical load (in kWh/day) relative to total load to be serviced by the PVPS; by the design margin of the basic PVPS relative to predicted insolation at the proposed site; and by the owner's plan for operation and maintenance of the installed system.

Thus, all of these factors must be considered early in the preliminary phase of design to produce an integrated PVPS which will satisfy the load demand.

### 4.5.1 Load Analysis

It is necessary to identify, subdivide, and quantitatively describe the characteristics of the total load into those which are classified as emergency, essential, or convenience loads. If none of the load elements are considered as an emergency (or critical) load, a backup system should not be required. However, if any part of the load is critical, then there is the need for sufficient backup to cover only that portion of the critical load. Provision can be made in the PVPS design to unload (disconnect) non-critical elements of the load to delay (or possibly avoid) power loss to the critical load. Emergency, essential and convenience loads are defined as follows:

(1) Emergency Loads -- continuous power is required and loss of such power would have severe and lasting impact. The emergency load category is further subdivided into (a) those loads which are essential for safety to life or whose interruption would produce serious hazards to industrial processes and (b) those loads which are critical whose interruption would lead to economic hardship. Critical loads cannot tolerate power loss in excess of a specified period of power outage. Emergency loads are normally supplied by two separate sources with automatic switching upon loss of one supply.

(2) Essential Loads -- Power normally supplied by two sources with either manual or delayed automatic switching. Power loss would have disruptive impact but would not be classified as critical.

(3) Non-essential or Convenience Loads -- power loss would have little impact on daily operations or routine -- and would, at most, cause some inconvenience.

Not all applications will have all three load categories, and the number and duration of power outages that can be accepted will vary for each category.

### 4.5.2 Basic PVPS Design Margin

At this time, there is insufficient data to accurately estimate the frequency and duration of power losses (outages) due to the various "failure modes" which can jeopardize the operational success of a well designed photovoltaic power system. The major causes of power failure will be due primarily to the inadequacy of the design to cope with the variability of nature and to the limitation of hardware reliability.

Choice of basic PVPS design margins adequate to cope with all possible combinations of extreme weather conditions could not be cost-effective. For example, the insolation in many parts of the country is not known to within perhaps 30%. Some of these variables include the following:

(1) Extremes in Weather Conditions. In the design process, an allowance is made for the maximum number of low-insolation days. However, the design margin will not be based on the worst possible condition, but the worst experienced over the past ten to twenty years. There is always a possibility that there will be less sunlight than considered in the design. Similarly, the design margin considers the recent cold weather history for the site. 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. Again, cold weather is considered in the design, but

nature may provide colder weather than anticipated. In some locations, the PVPS may be subjected to unpredictable extremes of other conditions (lightning, hail, tornadoes, etc.) which cannot be completely designed against.

(2) Changes in Load Demands. An "apparent" deficiency in design margin is often traced either to changes in the load (loads added after completion of system design), or to underestimating the load as defined in the original system specification.

(3) Optical Degradation. Optical degradation of the outer surface of the solar array is caused by "dirt" accumulation. Arrays covered with silicon rubber have experienced a 30-percent loss of power in 15 months in some circumstances. 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 rated power required by the load. (As a consequence of the high losses with silicone, most modules now have cover material made of glass).

(4) Component Failure. Failure rates of components integrated into the PVPS design can be estimated on the basis of historical data, plus test data accumulated by vendors and certified test facilities. The PVPS design is configured (as described in subsection 6.4) to provide an adequate design margin to protect (at a specified risk) against power loss due to component failure for a given period (e.g., 30 days, 90 days, 6 months, etc.), consistent with specified operating and maintenance provisions.

### 4.5.3 Types and Suitability of Backup Systems

Several backup systems might be suitable for the applications envisioned for the proposed stand-alone system. In many cases, the loss of power will not be critical, and backup will not be required. However, as discussed above, those loads which are judged to be critical are sensitive primarily to downtime (i.e., time that will elapse before the power can be restored). Maintaining some



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inventory of spares will help keep the elapsed time to a minimum, and standardizing replacement components (e.g., modularity of the array) will reduce the cost of replacement spares.

Manual backups are a viable, low-cost alternative for inhabited PVPS installations. For example, village water can be hand pumped on an emergency basis, although provision must be made in the initial design for hand pumping by positive-displacement pumps (centrifugal pumps cannot be manually operated). For larger pumping operations or large-power operations, an engine can be justified for the backup system. Since the engine will be used only on occasion, it may prove troublesome to start; therefore, it should be started regularly (e.g., once a week).

Low power radio communications equipment (transceivers) and other low power devices can be powered by primary batteries or pedal-powered generators in emergencies. However, primary batteries (e. g., zinc-air batteries), once discharged, must be manually replaced when depleted, so the operating costs (replacement costs) would be high.

Battery backups may be more practical, if standby rechargeable batteries are used. For example, lead-acid batteries could be maintained in fully charged state by the solar array, although the backup battery should not be connected to the main battery bank. However, if the solar-recharged battery cannot recover from an emergency condition, it may be necessary to recharge the backup batteries by a fixed engine/generator (or by a portable engine/generator carried by the maintenance team). The engine/generator may be considered an essential backup for those unpredicted periods of extremely low insolation for many days.

The advantages and disadvantages of various combinations just described are summarized in Exhibit 4.5-1. Life cycle cost of alternative backup types should be performed, taking into account the maintenance support cost as well as the initial cost. For example, a low-power engine/generator may be low in initial cost, but the cost of maintenance support might make the life cycle cost higher than a solar (or wind) recharged battery. Moreover, the engine/generator requires periodic transport of fuel (gasoline or diesel oil) to the site, which may be a physical problem for remote installations.

## Exhibit 4.5-1

## SUMMARY DESCRIPTION OF BACKUP SYSTEMS

| Type of System | Application Suitability | Advantages | Disadvantages |
|---|---|---|---|
| 1. **Manual** (e.g., Hand pumps, manual hoists, hand or pedal driven generators, etc.) | Suitable for low-power loads. Applicable primarily to local (inhabited) sites; can be used in remote (unattended) sites with adequate monitoring (alarm) and response by off-site personnel. Very low initial cost ($200 - $500). | Simple to operate; highly reliable; minimum maintenance. | Requires operating manhours for duration of power outage. |
| 2. **Primary Battery** (e.g., Non-rechargeable zinc-carbon batteries.) | Suitable for very low power loads. Applicable primarily to remote sites for emergency lighting (signal beacons), communication, instrumentation, etc. Relatively low initial cost ($200 - $500 per KW). | Highly reliable; no maintenance (except for battery replacement). | Requires immediate replacement of battery with new battery. |
| 3. **Gasoline Engine/Generator** | Suitable for medium power load ($P < 5KW$) for long periods of power outage. Readily applicable to local (inhabited) sites; adaptable to remote sites with provision for off-site control. Relatively low initial cost ($200 - $500 per KW). | Highly reliable (local); moderately reliable (remote). Durable (many years) under long periods of operation. Light weight (2-man portability). | Requires weekly preventive maintenance and operability "run-up" test under load, to verify equipment availability. Requires transport and storage of fuel (gasoline) at site. In remote application, may experience carburetion failure in "start" mode, requiring off-site maintenance team. |
| 4. **Diesel Engine/Generator** | Suitable for full critical power load ($5KW < P < 15KW$) of the PVPS. Readily applicable to local (inhabited) sites; adaptable to remote sites equipped with automatic switchover provisions. Relatively low initial cost ($300 - $600 per KW). | Highly reliable under local control; moderately reliable (higher than gasoline engine) under remote control. Durable (many years) under long periods of operation. | Requires weekly preventive maintenance and operability "run-up" test under load, to verify equipment availability. Requires transport and storage of diesel fuel at the site. In remote application, may fail to start in extremely cold weather, requiring off-site maintenance team. |
| 5. **Rechargeable Secondary Battery** (e.g., lead-calcium battery):<br>(A) - solar recharged<br>(B) - wind recharged<br>(C) - fossil recharged<br>(D) - portable charger | Suitable for full capacity of critical load. Readily applicable to local sites; adaptable to remote sites equipped with automatic switching and charge regulation. High initial cost ($150 - $500 per KWH), depending or required capacity:<br>(A) - High initial cost of additional solar modules ($20,000 - $40,000 per KW).<br>(B) - Moderate cost of wind generator ($2,000 - $5,000 per KW).<br>(C) - Relatively low cost of gasoline or diesel engine/generator (as in 3 and 4 above).<br>(D) - Low cost of portable gasoline engine/generator charger ($500 - $1,000). | Backup battery bank is reliable. Recharging either solar array or wind charger highly reliable. Gasoline/diesel engine reliable under conditions described in 3 and 4 above. Portable charger is reliable. | Battery life limited (5 - 10 years). Engine generators require relatively high maintenance (see 3 and 4 above). Solar or wind recharge capability depends on weather conditions. |

As indicated in the exhibit, suitability of a given backup system for critical loads depends on size of the critical load in kWh allowable duration of power outage, whether the application is local (i.e., inhabited) or remote (i. e., unattended), and accessibility of the site for off-site maintenance support.

### 4.5.4 Incorporation of Backup Into the PV System

Once the type of backup has been selected, the backup system must be integrated into the basic photovoltaic power supply. Means of switchover from PV to backup (and visa versa when the emergency is over) may be manual or automatic, depending on whether the system is designed for local or remote operation. Manual operation involves a simple alarm system and a control panel to provide status information (instrumentation), and switching controls to make the timely switch over from PV array to backup system. On the other hand, remote sites must relay this status information by telemetry to the off-site receiver (control) station which alerts the maintenance team when the system is not performing properly. Switchover to the backup system can be accomplished either by transporting the maintenance team to the site, or by including a control channel in the telemetry link by which the backup system can be "commanded" to come on line. A remote actuator will be required for this type of backup, although the actuator can be a simple electrical relay or solid-state switch. Automatic switchover (without telemetry command) is also possible, although the electronic circuitry for the sensing and controlling functions will be more complex and somewhat more failure-prone than the telemetry control method.

A reliability/maintenance/cost tradeoff analysis should be performed to support a design decision between employing on-site manual switching with on-site personnel, or transported off-site personnel, semi-automatic switching via telemetry monitoring and control, or fully automatic on-site sensing and switching.

# SECTION 5
# INFORMATION NEEDED TO START THE DESIGN PROCESS

This section presents the system design engineer with two lists which will guide him in assembling data needed in the design process. The first list presents the minimum data required to perform design computations. The second is a checklist for the entire design process, including tradeoffs, site investigations, and design pitfalls. The reader is expected to use this section as a quick reference to ensure that he has gathered the requisite data.

Little data is needed to perform the design computations for the preliminary stage covered by this handbook. In essence, the daily loads and daily solar radiation are almost sufficient (Exhibit 5-1). Other factors are needed to compute the economics of the system and to compare the photovoltaic life-cycle cost to costs of the competing systems. If each item of Exhibit 5-1 is obtained, then all of the computations required in the various sections of this handbook can be completed. If the data requirements of Exhibit 5-1 are compared to the data requirements of Exhibit 5-2, some appreciation can be obtained of the scope of this handbook. The handbook covers preliminary design approaches only in order to evaluate total photovoltaic systems. The detailed design required to actually construct a system, must address the many questions raised in Exhibit 5-2.

## Exhibit 5-1

## Minimum Data Requirements to Establish Feasibility

Technical requirements

Daily energy to be supplied by the system, on the average for each month

Peak power demands

Future power and energy requirements

Reliability criteria for photovoltaic power system

Estimated output of the system when insolation is 1 kW/sq. meter

Siting requirements such as fences, grading, markers, site preparation, similar weather (world insolation data are listed in Appendix A)

Current costs of photovoltaic system components

- PV modules
- Batteries
- Power conditioning system
- Structures and supports
- Electrical distribution system

Costs of alternate power systems:

Utility-supplied electricity, including connection costs, demand costs, and energy costs or engine-generator set costs

Fuel costs, including the cost of resupplying

Battery recharge costs

Cost of transportation to the site for repairs to whichever system is adopted (depending on distance to nearest repair station)

## Exhibit 5-2

## General Checklist for Detailed Design

### Site

1. Check array location for foundation and structural support.

2. Check site for locations of underground or overhead cables and utilities and any other obstructions which could cause shading problems.

3. Check installation route and shipping route.

4. Check foundation requirements for battery housing.

5. For existing load centers, check power/energy requirements.

   a. Check equipment on line
   b. Check life-styles as they influence use of equipment
   c. Measure total power/energy consumption for sample days

### Criteria

1. Power and energy requirements

2. Reliability requirements for power system operation

3. Allowable load separation for startup purposes.

4. Required voltage regulation.

5. Maintenance strategy/frequency of site inspections

6. Instrumentation and monitoring system requirements for initial checkout and maintenance, and operation.

### System

1. Determine optimal array tilt, including the possibility of tracking and occasional reorientation.

2. Determine the optimal array size, storage size, etc., on the basis of life-cycle cost but meeting the requirements of performance, reliability, and safety.

3. Determine the effect of degradation of the array, power conditioning components, batteries, cables, connectors, etc., on the long-term system performance and the initial design requirements.

4. Determine array output as a function of time of day, month, and year; include in the effects of temperature, dust accumulation, partial system failure (outages), state of battery charge, load demand, etc., using a detailed simulation.

Exhibit 5-2 Continued

General Checklist for Detailed Design

5. Determine the optimal system voltage, including the effects of partial shading, reliability of the array, module failure, safety, component efficiencies, cable costs, component costs, availability of components.

6. Define the auxilary power system: total, partial, etc., connection to the load, interface with the array and power conditioning subsystem.

7. Determine optimal arrangement of diodes in the array, including isolation diodes and shunt diodes.

8. Allocate the voltage losses, such as the diode losses, cable losses, battery losses, etc., justifying on the basis of cost.

9. Examine the load and power-system I-V characteristics so potential mismatches (average or instantaneous) can be identified. List and rectify potential mismatches (e.g., define a control system to provide matching).

10. Determine the temperature control requirements and how the batteries, voltage regulators and power converters will meet them.

11. Determine how the maintenance personnel will identify a failed module component.

12. Define the test points for startup and monitoring of system performance.

13. Determine optimal cleaning cycle, if any.

14. Determine how protection against vandalism will be provided.

15. Determine the requirements for spare parts.

Array

1. Obtain from the manufacturers the I-V characteristics of the modules as combined functions of temperature and illumination. Include the range of I-V characteristics.

2. Determine if modules should be matched within a series string to maximize the array output, considering the cost savings possible but also the difficulty in replacement matching.

3. Provide test points within the array.

4. Provide indications to identify failed modules or connections.

5. Segment the array for maintenance safety and performance during maintenance.

Exhibit 5-2 Continued

General Checklist for Detailed Design

6. Determine the least-cost structure, allowing for expansion and contraction due to temperature and humidity. Include aluminum, steel, wood, concrete, and any other native materials. Include foundation design. Include deflection analysis. Protect against corrosion.

7. Estimate the cost of the structure so the optimal cell packing density can be determined.

8. Design the array to withstand the environment: dust, wind, sand, temperature cycling, hail, rain, humidity cycling, installation and maintenance loads, normal and abnormal voltages, lightning, earthquakes, ice, freezing rain, settlement, ground uplift, combinations of loads and their probability of occurence.

9. Review for design compliance with the national codes and standards, such as BOCA, UBC, SBC, ANSI, NEC, NEMA, and their local variations.

10. Obtain the data on soil borings as required for the foundation work.

11. Decide on custom-designing a structure or purchasing a structure from manufacturer.

12. Determine if shading is prevented.

13. Protect the array and cables from falling objects.

14. Design to protect the maintenance personnel from high voltages and temperatures.

15. Provide sufficient redundancy to meet the reliability requirements, such as dual leads, alternate circuit paths, etc.

Conditioning System

1. Develop the voltage/cost/reliability data for the components in the systems.

2. Define the input/output voltages and currents, including auxiliary power requirements, for a complete range of loads for use in the system design.

3. Examine the system for potential instabilities at high loads and other combinations of battery/array/load supply and demand conditions.

4. Define the environmental requirements for the equipment.

## Exhibit 5-2 Continued

## General Checklist for Detailed Design

5. Protect the equipment from weather: rain, dust, wind, humidity, temperature, earthquake, lightning, sand, installation and maintenance loads, shipping loads, normal and abnormal voltages and currents, settlement, ground uplift.

6. Specify compliance to the applicable national standards and codes: ANSI, IEEE, NEC, NEMA and their local variations.

### Energy Storage System

1. Determine if battery use can be minimized by storing the end product (such as pumped water) rather than electricity.

2. Select the battery type: pure lead, lead-calcium, sealed, SLI, silver-zinc, iron-redox, nickel-cadmium (pocket plate). Consider cost, availability, depth of discharge, reliability, life (cycles, years), capacity vs temperature.

3. Obtain the I-V characteristics of the batteries as a combined function of temperature and state of charge for use in the system simulation.

4. Obtain the life estimates for the batteries as a function of temperature and number of cycles.

5. Determine the optimal voltage of the battery array in terms of the entire system.

6. Estimate the frequency of, and provide for the failure of, one battery in the entire storage system.

7. Determine how rapidly the batteries will self-discharge.

8. Estimate the battery reliability and maintenance requirements and costs.

9. Determine the number of spare batteries needed.

10. Estimate the cost of the batteries in place for use in the systems design.

11. Layout the batteries to minimize the potential faults.

12. Determine the need for and method of dispersing hydrogen generated in the battery housing.

Exhibit 5-2 Continued

General Checklist for Detailed Design

13. Design the housing for the following loads: weight, wind, maintenance, earthquake, lightning, hail, deflection, thermal and humidity cycling, ground uplift, dust, sand and combinations thereof.

14. Design to the applicable standards and codes: ANSI, IEEE, NEC, NEMA, OSHA and their local variations.

Emergency Power System

1. Provide a power source as required during the times when the photovoltaics need repair or routine maintenance.

2. Determine if the emergency (backup) power system need be automatically activated.

3. Establish a procedure and cost for maintaining the emergency system in a state of readiness.

4. Estimate the reliability of the emergency power system. Provide a second emergency generating unit if needed to obtain the desired reliability

5. Design the emergency power system to the national standards and codes: BOC, UBC, SBC, ANSI, NEC, IEEE, NEMA, OSHA and their local variations.

6. Design the housing for the following loads: weight, wind, maintenance, earthquake, lightning, hail, deflection, thermal and humidity cycling, ground uplift, dust, sand and combinations thereof.

7. Estimate the installed, operating and maintaining costs for use in the system design.

8. Determine the efficiency of the system versus load for use in the system simulation.

9. Determine the spare-parts requirements.

10. Determine the availability and cost of competent repair services.

## SECTION 6
## PRELIMINARY SYSTEM DESIGN CONSIDERATIONS

### 6.1 INSOLATION AND SITING

A generally open, sunlit area will be required for the array. The first step is to identify such an area. The area can be considered open if the angular elevation of neighboring trees, buildings, etc., within an azimuth angle $\pm 60^{\circ}$ degrees of South (northern hemisphere) or North (southern hemisphere) satisfies the relationship:*

$$\text{elevation angle (above horizon)} \leq 56^{\circ} - |\text{Latitude angle}|$$

The next step is to determine if the area is large enough. The clearness index, $\overline{K}_H$, for the site should be estimated from Appendix A, based on the closest city that also has similar weather. Values of $\overline{K}_H$ should be read for the four winter months. For each of these months, the corresponding solar radiation (called insolation in the U.S.) should be read from Exhibit 6.1-1. (Linear interpolation is permissible between values of $\overline{K}_H$ for any one month.). The area of the clearing required for the array is given by the equation:

$$\text{Area (sq. meters)} = \frac{\text{Load (in kWh/day)} * [\cos(t) + \sin(t)/\tan(66.5-|L|)]}{\eta * \text{solar radiation (in kWh/m}^2\text{ - day)}}$$

where, as in the first equation, the magnitude of the latitude angle L is used. The array tilt angle is given by t; it is usually equal to the absolute value of the latitude angle. The system efficiency, $\eta$, typically is composed of 14 percent for the array, 80 percent for the battery, and 90 percent for the power conditioner, giving $\eta$ = 0.14*0.80*0.90 = 10 percent. The solar radiation to be used on the equation is the minimum for the four winter months.

*The sun-angle charts of Section 11.4 can be used to estimate how much the horizon obstructs the sun. The charts must be used at latitudes above $56^{\circ}$ because there may be no sunlight in December.

Example: Suppose two candidate sites for a 12 kWh/day load are in a remote area near Washington, D.C. Suppose a surveyor's transit had been used, looking within $60^o$ of South, to determine the skyline (horizon) to be shown in Exhibit 6.1-2 for the two sites. Both have 110 $m^2$ available. Which site is most suitable?

From Appendix A, we find that Washington, D.C. is at a latitude of 38.95 degrees. For the space to be considered "open", the skyline must be lower than

$$56 - 38.95 = 17.05$$

Site A (Exhibit 6.1-2) is not suitable; Site B is.

The values of the clearness index are first obtained from Appendix A, and the average daily insolation on an array tilted at the latitude angle is obtained from Exhibit 6.1-1 by interpolation for the winter months. For November, for example:

a. Interpolation between 30 degrees and 45 degrees latitude:

at $\bar{K}_H = 0.3$: $2.180 + (1.636 - 2.180) * (38.95 - 30) / (45 - 30) = 1.855$

at $\bar{K}_H = 0.5$: $4.011 + (3.328 - 4.011) * (38.95 - 30) / 45 - 30) = 3.603$

b. Interpolation between $\bar{K}_H$'s:

at $\bar{K}_H = 0.421$: $1.855 + (3.603 - 1.855) ( 0.421 - 0.3) / (0.5 - 0.3) =$ 2.912 $kWh/m^2$ day

Similarly, for December, interpolation gives 2.32 $kWh/m^2$ day, so the land area required is ($\eta = 10\%$):

$A = 12 * R/(2.32 \eta) = 103$ square meters of land

Where $R = \cos t + \sin t/\tan (66.5 - L) = 1.983$. The required area is 103 square meters and 110 square meters are available, so Site B is a good candidate.

## Exhibit 6.1-1

### AVERAGE MONTHLY INSOLATION (KWH/M$^2$-DAY) AND THE RATIO (SIGMA 1) OF STANDARD DEVIATION TO AVERAGE

$K_H = 0.3$

| KH = .3 | | Tilt = Latitude | | | | | Tilt = Latitude + 10° | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Latitude | | 0° | 15° | 30° | 45° | 60° | 0° | 15° | 30° | 45° | 60° |
| JAN | MEAN * | 2.989 | 2.592 | 2.073 | 1.504 | 0.895 | 3.067 | 2.633 | 2.097 | 1.531 | 0.928 |
| | SIGMA 1 | 0.692 | 0.748 | 0.852 | 1.036 | 1.328 | 0.716 | 0.778 | 0.891 | 1.079 | 1.355 |
| FEB | MEAN | 3.092 | 2.800 | 2.360 | 1.842 | 1.307 | 3.130 | 2.801 | 2.342 | 1.826 | 1.310 |
| | SIGMA 1 | 0.692 | 0.731 | 0.808 | 0.948 | 1.182 | 0.706 | 0.751 | 0.837 | 0.985 | 1.217 |
| MAR | MEAN | 3.130 | 2.995 | 2.681 | 2.248 | 1.772 | 3.111 | 2.936 | 2.597 | 2.159 | 1.701 |
| | SIGMA 1 | 0.692 | 0.709 | 0.757 | 0.848 | 1.007 | 0.693 | 0.716 | 0.770 | 0.870 | 1.038 |
| APR | MEAN | 3.040 | 3.073 | 2.910 | 2.589 | 2.177 | 2.965 | 2.955 | 2.757 | 2.418 | 2.008 |
| | SIGMA 1 | 0.692 | 0.689 | 0.710 | 0.761 | 0.852 | 0.680 | 0.682 | 0.709 | 0.766 | 0.866 |
| MAY | MEAN | 2.875 | 3.044 | 3.018 | 2.817 | 2.504 | 2.758 | 2.883 | 2.815 | 2.583 | 2.256 |
| | SIGMA 1 | 0.692 | 0.673 | 0.677 | 0.703 | 0.754 | 0.668 | 0.655 | 0.664 | 0.696 | 0.753 |
| JUN | MEAN | 2.761 | 2.996 | 3.042 | 2.910 | 2.664 | 2.626 | 2.816 | 2.816 | 2.647 | 2.379 |
| | SIGMA 1 | 0.692 | 0.665 | 0.661 | 0.677 | 0.712 | 0.662 | 0.642 | 0.643 | 0.665 | 0.705 |
| JUL | MEAN | 2.793 | 3.003 | 3.023 | 2.866 | 2.595 | 2.665 | 2.831 | 2.806 | 2.614 | 2.325 |
| | SIGMA 1 | 0.692 | 0.668 | 0.667 | 0.686 | 0.726 | 0.665 | 0.647 | 0.651 | 0.676 | 0.722 |
| AUG | MEAN | 2.935 | 3.039 | 2.949 | 2.691 | 2.328 | 2.838 | 2.899 | 2.770 | 2.487 | 2.119 |
| | SIGMA 1 | 0.692 | 0.680 | 0.692 | 0.729 | 0.798 | 0.674 | 0.668 | 0.685 | 0.728 | 0.804 |
| SEP | MEAN | 3.066 | 3.014 | 2.775 | 2.396 | 1.950 | 3.019 | 2.926 | 2.657 | 2.268 | 1.832 |
| | SIGMA 1 | 0.692 | 0.699 | 0.733 | 0.803 | 0.926 | 0.687 | 0.699 | 0.739 | 0.816 | 0.949 |
| OCT | MEAN | 3.091 | 2.873 | 2.493 | 2.018 | 1.520 | 3.103 | 2.847 | 2.446 | 1.971 | 1.492 |
| | SIGMA 1 | 0.692 | 0.721 | 0.783 | 0.899 | 1.098 | 0.700 | 0.734 | 0.805 | 0.930 | 1.133 |
| NOV | MEAN | 3.017 | 2.665 | 2.180 | 1.636 | 1.067 | 3.079 | 2.690 | 2.188 | 1.646 | 1.090 |
| | SIGMA 1 | 0.692 | 0.741 | 0.833 | 0.998 | 1.265 | 0.712 | 0.767 | 0.868 | 1.039 | 1.297 |
| DEC | MEAN | 2.945 | 2.524 | 1.989 | 1.411 | 0.773 | 3.034 | 2.575 | 2.023 | 1.446 | 0.809 |
| | SIGMA 1 | 0.692 | 0.753 | 0.864 | 1.060 | 1.369 | 0.718 | 0.786 | 0.906 | 1.105 | 1.392 |

*Note: In all cases the MEAN is (I) and SIGMA 1 is (R)

For southern latitudes, the values listed for July pertain to January, August to February, etc. Otherwise, the tables are equally valued for northern and southern latitudes.

Exhibit 6.1-1 (Continued)

## AVERAGE MONTHLY INSOLATION (KWH/M$^2$-DAY) AND THE RATIO (SIGMA 1) OF STANDARD DEVIATION TO AVERAGE

$K_H = 0.5$

| KH = .5 | | Tilt = Latitude | | | | | Tilt = Latitude + 10° | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0° | 15° | 30° | 45° | 60° | 0° | 15° | 30° | 45° | 60° |
| JAN | MEAN* | 4.955 | 4.489 | 3.861 | 3.126 | 2.150 | 5.182 | 4.663 | 4.005 | 3.255 | 2.256 |
| | SIGMA 1 | 0.413 | 0.453 | 0.517 | 0.608 | 0.718 | 0.430 | 0.473 | 0.538 | 0.627 | 0.726 |
| FEB | MEAN | 5.126 | 4.787 | 4.268 | 3.642 | 2.930 | 5.248 | 4.863 | 4.319 | 3.688 | 2.986 |
| | SIGMA 1 | 0.413 | 0.441 | 0.491 | 0.568 | 0.667 | 0.424 | 0.455 | 0.508 | 0.585 | 0.680 |
| MAR | MEAN | 5.188 | 5.033 | 4.674 | 4.176 | 3.625 | 5.161 | 4.962 | 4.574 | 4.070 | 3.537 |
| | SIGMA 1 | 0.413 | 0.426 | 0.459 | 0.515 | 0.595 | 0.414 | 0.431 | 0.468 | 0.527 | 0.609 |
| APR | MEAN | 5.039 | 5.079 | 4.895 | 4.529 | 4.057 | 4.863 | 4.855 | 4.631 | 4.245 | 3.776 |
| | SIGMA 1 | 0.413 | 0.411 | 0.426 | 0.462 | 0.517 | 0.404 | 0.405 | 0.425 | 0.465 | 0.525 |
| MAY | MEAN | 4.766 | 4.962 | 4.937 | 4.711 | 4.356 | 4.480 | 4.627 | 4.554 | 4.294 | 3.923 |
| | SIGMA 1 | 0.413 | 0.398 | 0.401 | 0.421 | 0.457 | 0.395 | 0.384 | 0.392 | 0.416 | 0.457 |
| JUN | MEAN | 4.578 | 4.850 | 4.907 | 4.762 | 4.487 | 4.242 | 4.465 | 4.471 | 4.284 | 3.984 |
| | SIGMA 1 | 0.413 | 0.392 | 0.389 | 0.402 | 0.428 | 0.390 | 0.373 | 0.375 | 0.392 | 0.423 |
| JUL | MEAN | 4.630 | 4.874 | 4.901 | 4.727 | 4.422 | 4.313 | 4.508 | 4.485 | 4.272 | 3.946 |
| | SIGMA 1 | 0.413 | 0.394 | 0.393 | 0.409 | 0.438 | 0.392 | 0.377 | 0.381 | 0.400 | 0.435 |
| AUG | MEAN | 4.865 | 4.987 | 4.887 | 4.594 | 4.181 | 4.632 | 4.705 | 4.561 | 4.241 | 3.822 |
| | SIGMA 1 | 0.413 | 0.404 | 0.413 | 0.440 | 0.485 | 0.399 | 0.394 | 0.407 | 0.439 | 0.489 |
| SEP | MEAN | 5.082 | 5.023 | 4.750 | 4.317 | 3.804 | 4.981 | 4.877 | 4.570 | 4.125 | 3.624 |
| | SIGMA 1 | 0.413 | 0.418 | 0.443 | 0.488 | 0.556 | 0.409 | 0.418 | 0.447 | 0.496 | 0.568 |
| OCT | MEAN | 5.124 | 4.872 | 4.432 | 3.874 | 3.265 | 5.176 | 4.881 | 4.415 | 3.855 | 3.263 |
| | SIGMA 1 | 0.413 | 0.434 | 0.476 | 0.543 | 0.634 | 0.419 | 0.444 | 0.489 | 0.559 | 0.648 |
| NOV | MEAN | 5.002 | 4.590 | 4.011 | 3.328 | 2.490 | 5.184 | 4.724 | 4.117 | 3.425 | 2.581 |
| | SIGMA 1 | 0.413 | 0.448 | 0.506 | 0.591 | 0.697 | 0.428 | 0.465 | 0.526 | 0.610 | 0.707 |
| DEC | MEAN | 4.883 | 4.387 | 3.735 | 2.971 | 1.891 | 5.135 | 4.585 | 3.899 | 3.116 | 1.999 |
| | SIGMA 1 | 0.413 | 0.456 | 0.524 | 0.619 | 0.731 | 0.432 | 0.477 | 0.546 | 0.637 | 0.738 |

*Note: In all cases the MEAN is (I) and SIGMA 1 is (R)

For southern latitudes, the values listed for July pertain to January, August to February, etc. Otherwise, the tables are equally valued for northern and southern latitudes.



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Exhibit 6.1-1 (Continued)

## AVERAGE MONTHLY INSOLATION (KWH/M$^2$-DAY) AND THE RATIO (SIGMA 1) OF STANDARD DEVIATION TO AVERAGE

$K_H = 0.7$

| KH = .7 | | Tilt = Latitude | | | | | Tilt = Latitude +10 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0° | 15° | 30° | 45° | 60° | 0° | 15° | 30° | 45° | 60° |
| JAN | MEAN * | 6.952 | 6.529 | 5.928 | 5.146 | 3.816 | 7.387 | 6.902 | 6.254 | 5.430 | 4.027 |
| | SIGMA 1 | 0.178 | 0.196 | 0.224 | 0.257 | 0.292 | 0.186 | 0.205 | 0.232 | 0.263 | 0.294 |
| FEB | MEAN | 7.193 | 6.890 | 6.418 | 5.817 | 5.028 | 7.434 | 7.086 | 6.585 | 5.970 | 5.170 |
| | SIGMA 1 | 0.178 | 0.191 | 0.213 | 0.243 | 0.277 | 0.183 | 0.197 | 0.220 | 0.249 | 0.280 |
| MAR | MEAN | 7.280 | 7.145 | 6.834 | 6.399 | 5.910 | 7.246 | 7.075 | 6.740 | 6.300 | 5.826 |
| | SIGMA 1 | 0.178 | 0.184 | 0.199 | 0.223 | 0.253 | 0.178 | 0.186 | 0.203 | 0.228 | 0.258 |
| APR | MEAN | 7.071 | 7.108 | 6.952 | 6.638 | 6.230 | 6.762 | 6.759 | 6.572 | 6.241 | 5.835 |
| | SIGMA 1 | 0.178 | 0.176 | 0.184 | 0.200 | 0.224 | 0.173 | 0.174 | 0.184 | 0.202 | 0.227 |
| MAY | MEAN | 6.687 | 6.863 | 6.847 | 6.659 | 6.358 | 6.174 | 6.309 | 6.255 | 6.039 | 5.726 |
| | SIGMA 1 | 0.178 | 0.170 | 0.172 | 0.182 | 0.198 | 0.168 | 0.163 | 0.167 | 0.179 | 0.198 |
| JUN | MEAN | 6.423 | 6.665 | 6.723 | 6.607 | 6.380 | 5.819 | 6.020 | 6.037 | 5.887 | 5.639 |
| | SIGMA 1 | 0.178 | 0.167 | 0.165 | 0.172 | 0.185 | 0.166 | 0.157 | 0.158 | 0.167 | 0.182 |
| JUL | MEAN | 6.496 | 6.714 | 6.745 | 6.603 | 6.348 | 5.926 | 6.103 | 6.094 | 5.920 | 5.648 |
| | SIGMA 1 | 0.178 | 0.168 | 0.168 | 0.175 | 0.190 | 0.167 | 0.159 | 0.161 | 0.171 | 0.188 |
| AUG | MEAN | 6.827 | 6.936 | 6.855 | 6.606 | 6.252 | 6.411 | 6.481 | 6.364 | 6.093 | 5.734 |
| | SIGMA 1 | 0.178 | 0.173 | 0.178 | 0.190 | 0.210 | 0 171 | 0.168 | 0.175 | 0.190 | 0.212 |
| SEP | MEAN | 7.131 | 7.081 | 6.847 | 6.472 | 6.024 | 6.961 | 6.874 | 6.612 | 6.227 | 5.789 |
| | SIGMA 1 | 0.178 | 0.180 | 0.192 | 0.212 | 0.239 | 0.176 | 0.180 | 0.194 | 0.215 | 0.243 |
| OCT | MEAN | 7 190 | 6.968 | 6.578 | 6.071 | 5.476 | 7.303 | 7.042 | 6.628 | 6.115 | 5.528 |
| | SIGMA 1 | 0.178 | 0.188 | 0.207 | 0.234 | 0.266 | 0.181 | 0.192 | 0.212 | 0.240 | 0.271 |
| NOV | MEAN | 7.018 | 6.647 | 6.105 | 5.410 | 4.359 | 7.371 | 6.947 | 6.366 | 5.644 | 4.552 |
| | SIGMA 1 | 0.178 | 0.194 | 0.219 | 0.251 | 0.286 | 0.185 | 0.202 | 0.227 | 0.258 | 0.289 |
| DEC | MEAN | 6.851 | 6.400 | 5.766 | 4.929 | 3.386 | 7.332 | 6.813 | 6.126 | 5.238 | 3.595 |
| | SIGMA 1 | 0.178 | 0.198 | 0.226 | 0.261 | 0.295 | 0.187 | 0.207 | 0.235 | 0.267 | 0.297 |

*Note: In all cases the MEAN is (I) and SIGMA 1 is (R)

For southern latitudes, the values listed for July pertain to January, August to February, etc. Otherwise, the tables are equally valued for northern and southern latitudes.

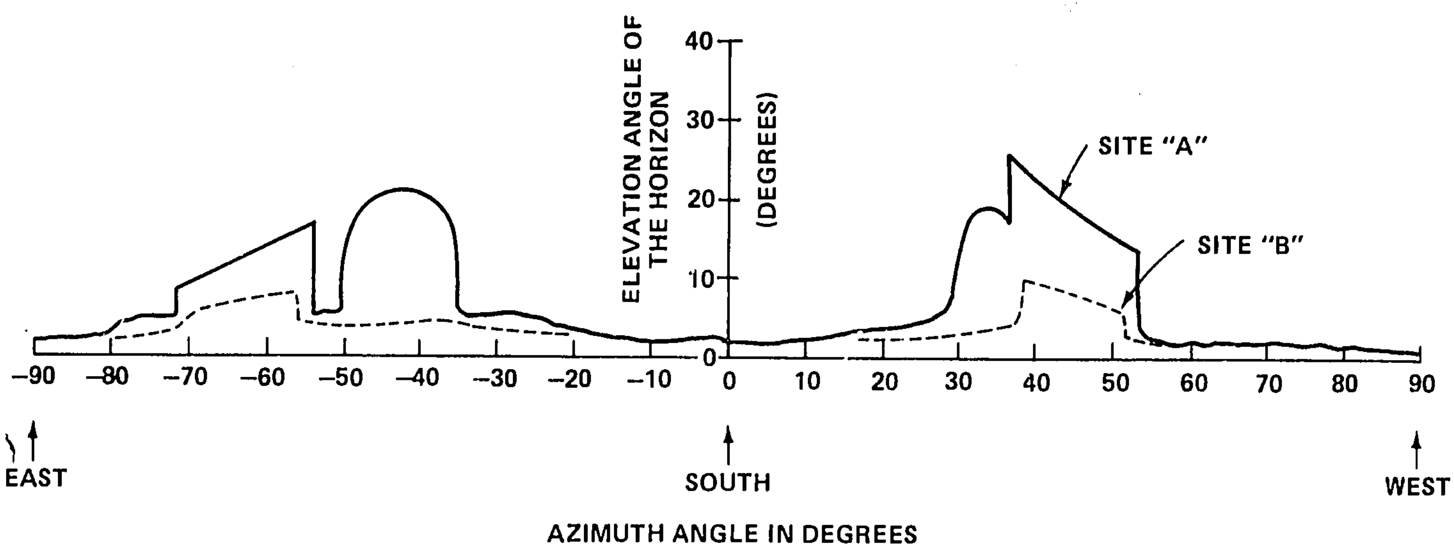



Exhibit 6.1-2

HORIZON PROFILES FOR TWO CANDIDATE SITES

## 6.2 PRELIMINARY ASSESSMENT OF PHOTOVOLTAIC SYSTEM DESIGN

An initial estimate can be made of the array-area and storage-capacity requirements to supply a particular load at a given site, for a required level of reliability, using a quick-sizing system approach. Once the capacity of the system is determined, the major components are sized. The gross system cost can be computed on the basis of the array and battery costs, and the process can be repeated by varying the array tilt angles, array areas and battery capacity until the minimum cost is determined. After the detailed engineering design phase is completed, a final cost estimate should also include the costs of site grading, array structures, buildings, power conditioning equipment, instrumentation, distribution wiring and any emergency (back-up) generator system.

### 6.2.1 Array and Battery Quick-Sizing Method

An estimate of the array-area and storage-capacity requirements by use of a monthly output computation is shown in Exhibit 6.2-1. Implicit in the computation is an assumption concerning the loss-of-load probability (LOLP). The LOLP was assumed to be 1 percent in the development of Exhibit 6.2-2, which is used in the monthly computation of Exhibit 6.2-1. After studying Section 7 of this handbook, adjustments may be made for other LOLP's. The monthly computations proceed as follows:

1. The clearness factor, $\overline{K}_H$, is obtained for the location of interest for each month from Appendix A. The values are entered in Column 1 of Exhibit 6.2-1.

2. A tilt angle is selected for the array at either latitude or latitude plus 10 degrees.

3. The average monthly insolation, $\overline{I}$, on the tilted array is obtained from Exhibit 6.1-1 by interpolation and entered in Column 2.

4. The ratio, R, of the standard deviation of the insolation to the average is obtained from Exhibit 6.1-1 by interpolation and entered in Column 3.

5. The standard deviation (S), is computed for each month from the formula $S = R*\bar{I}$, S being entered in Column 4.

6. The kWh/day load is entered in Column 5.

7. The array performance factor, $\eta_a$, is obtained from the manufacturer, expressed in daily output per unit of array per kWh/day-$m^2$ of insolation.

8. Estimate the system efficiency, $\eta$. It will be approximately equal to the product of the array performance parameter, the battery efficiency and the power-conditioner efficiency. In Exhibit 6.2-1, = 8 percent.

9. Determine the optimal design by trial and error, selecting various values of M* for entry into Exhibit 6.2-1. A reasonable starting value is 0.33. For each selected value of M, compute the array area required for each month, according to the formula

$$\text{Area } (m^2) = \text{Load}/\left[\eta * (I - M*S)\right]$$

In the example of Exhibit 6.2-1, the values of the area are presented in Column 6 for M = 0.33.

10. For the value of M and the ratio R, the storage requirement, C, is read from Exhibit 6.2-2. This capacity is given in days of load. For example, if the load is 20 kWh and the storage capacity C is six days, then the required storage capacity is 120 kWh. The value of C is entered for each month in Column 7. The storage capacity is expressed in the same units as the load in Column 8.

---

*As indicated in the theory described in Section 7 of this handbook, $M = (\bar{I} - I_D)/S$ where $\bar{I}$ is the average monthly insolation; S, the standard deviation of the insolation; and $I_D$, the value of the insolation at which the average daily electrical demand is exactly met by the solar system.

11. The month requiring the largest value of array area and storage capacity will determine the equipment size. At first, several values of M should be selected to determine which gives the lowest life-cycle cost. (The value 0.33 is a reasonable starting point.) If the maximum area and maximum storage do not occur in the same month, the maximum array area should be selected according to the foregoing procedures. However, M must be computed from the equation, $M = (\bar{I} - \text{Load}/\eta A)/S$. The storage capacity C is then obtained from Exhibit 6.2-2 for this M and the monthly R. The month with the maximum product (C * Load) determines the battery size.

### 6.2.2 Component Sizing

Once the operating sizes of the array and the storage system have been computed, all the compnents of the PV system can be sized. The necessary array size has been computed to meet the required reliability criterion, but must be adjusted to allow for degradation with time. Assuming a 10% loss of array performance over its life due to aging, the 12 kW nominal array size must be divided by 0.9, giving a 13.33 kW required capacity at the time of installation.

The necessary battery size to be installed is the equivalent cell capacity to provide a 20-year system life divided by the allowable percent depth of discharge for the battery. A medium rate lead-acid battery is assumed with a 1000 cycle life or a 10 year calendar life. The maximum number of cycles a 9.2 day (184 kWh) battery would be subjected to over a 10 year life would be about 500. Referring to Exhibit 6.2-3 it can be seen that even at the higher mean battery temperatures, an apparent life of 500 cycles would be possible with a maximum depth of discharge of 95%. Thus, the required installed capacity of the battery will be 105% (100%/0.95) of its end-of-life operating capacity, or 193 kWh in the case of the 184 kWh battery.

EXHIBIT 6.2-1

QUICK SIZING COMPUTATIONAL PROCEDURE

FOR ARRAY AND STORAGE(1)

| Units | Clearness Factor(2) $K_H$ | Average Insolation(3) I | R | Standard Deviation(3) S | Monthly Load | Array Area(4) | Storage Requirement(5 C | |
|---|---|---|---|---|---|---|---|---|
| | — | $kWh/m^2$ day | — | $kWh/m^2$ day | kWh/day | $m^2$ | Days | kW |
| Month/Col. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| January | 0.41 | 2.72 | 0.73 | 2.00 | 20 | 122 | 8.1 | 16 |
| February | 0.447 | 3.41 | 0.63 | 2.15 | 20 | 93 | 6.7 | 13 |
| March | 0.460 | 3.99 | 0.55 | 2.19 | 20 | 77 | 5.7 | 11 |
| April | 0.480 | 4.48 | 0.48 | 2.15 | 20 | 66 | 4.8 | 9 |
| May | 0.496 | 4.76 | 0.42 | 2.00 | 20 | 61 | 4.2 | 8 |
| June | 0.521 | 5.01 | 0.37 | 1.85 | 20 | 57 | 3.6 | 7 |
| July | 0.509 | 4.88 | 0.39 | 1.90 | 20 | 59 | 3.8 | 7 |
| August | 0.499 | 4.70 | 0.43 | 2.02 | 20 | 62 | 4.3 | 8 |
| September | 0.494 | 4.43 | 0.48 | 2.13 | 20 | 67 | 4.7 | 9 |
| October | 0.480 | 3.91 | 0.55 | 2.15 | 20 | 78 | 5.7 | 11 |
| November | 0.421 | 2.91 | 0.70 | 2.05 | 20 | 112 | 7.7 | 15 |
| December | 0.383 | 2.32 | 0.81 | 1.89 | 20 | 148 | 9.2 | 18 |

Notes:

(1) Based upon Washington, D.C. location, Latitude = 38.95°, Tilt = 38.95°.
(2) From Appendix A Insolation Tables.
(3) Average monthly insolation from Exhibit 6.1-1.
(4) Array area = Load/($\eta$(I - M*S)): $\eta$ = 0.08.
(5) Based upon M = ($\bar{I}$ - $I_D$)/S = 0.33. Col. 7 entry read from Exhibit 6.2-2 Col. 8 = Col. 5* Col. 7.

Exhibit 6.2-2

BATTERY STORAGE REQUIREMENTS FOR 1% LOLP

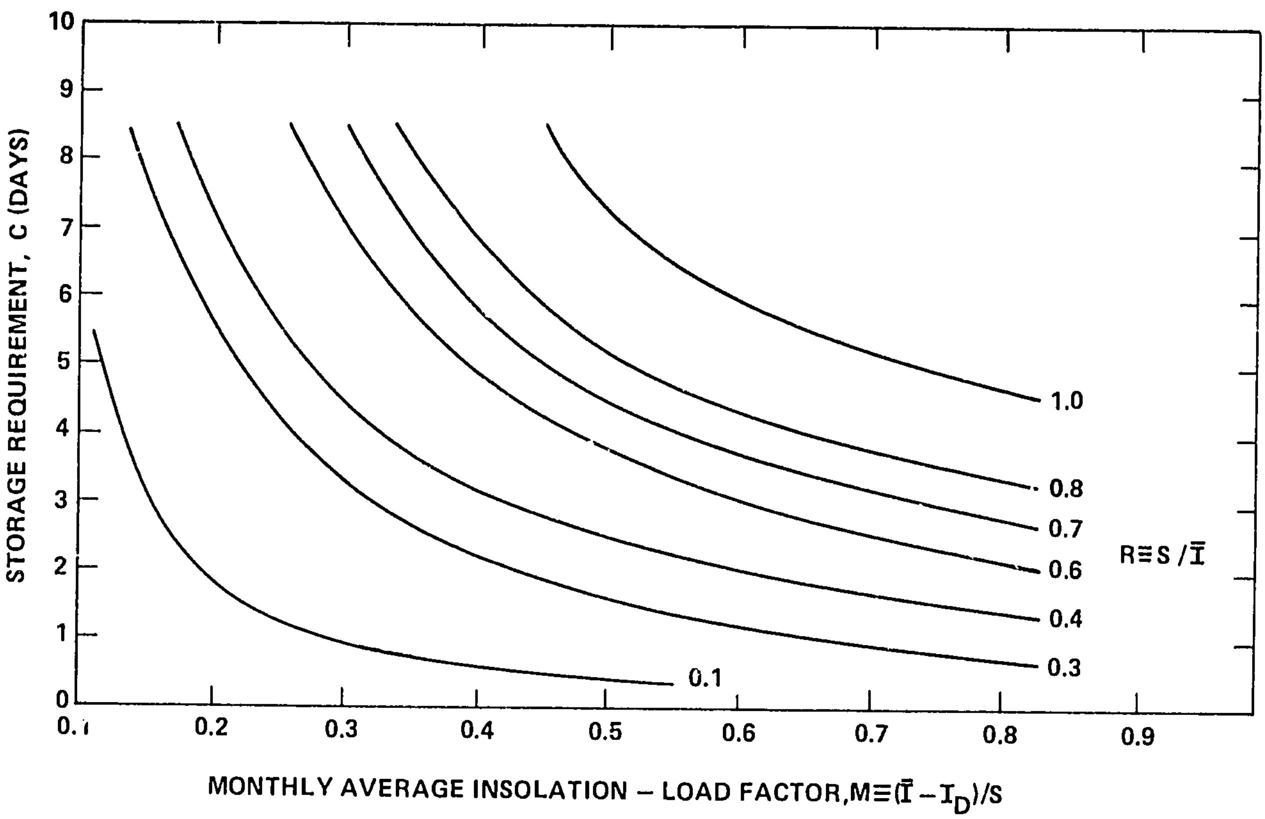
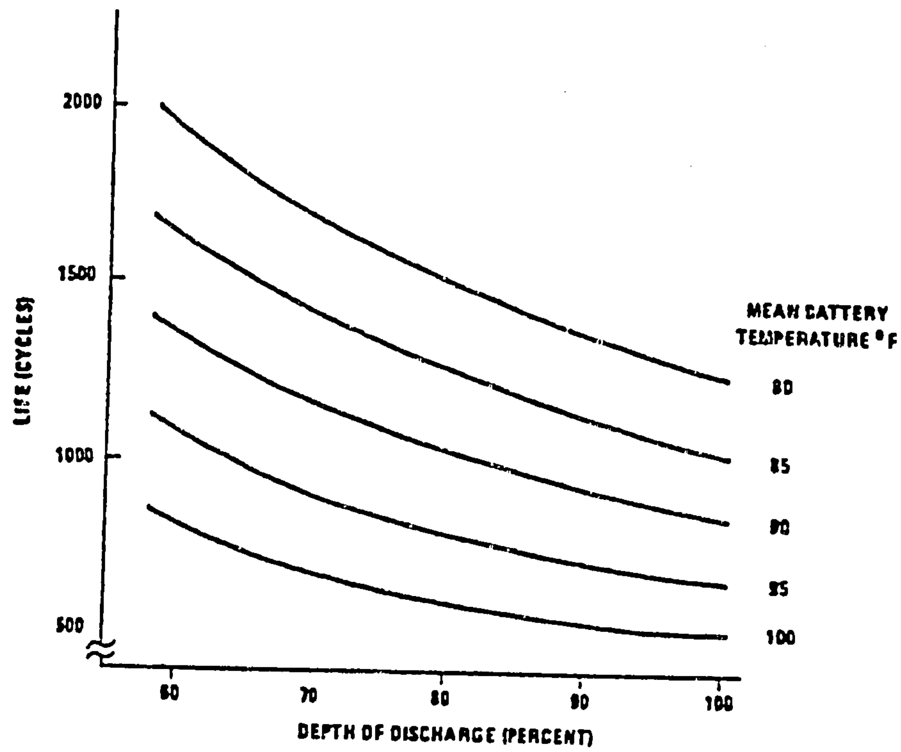


Exhibit 6.2-3

EFFECT OF DEPTH OF DISCHARGE ON BATTERY LIFE
ON TYPICAL LEAD-ACID MOTIVE POWER TYPE CELL (Reference 6-1)



## 6.3 BASIC APPROACH TO FEASIBILITY ASSESSMENT OF PHOTVOLTAIC POWER SYSTEMS

### 6.3.1 Preliminary Estimate

The preliminary estimate of cost effectiveness is the first step in determining whether or not to use a photovoltaic power system when there is an alternative power source. This section provides the methods for evaluating the life cycle costs of a system once the capital and operating costs and system performance factors are known. For a photovoltaic system, the cost of the arrays and the cost of the battery system are the two most important cost elements on which the initial capital and recurring operating costs are based.

The basic approach in making economic comparisons between a photovoltaic power system and a conventional power system is to determine the life cycle costs for each alternative. The life cycle cost procedure includes all initial capital costs and the expenditures for the entire life of each alternative including all replacements, maintenance, fuel and operating costs. Photovoltaic systems typically will require a large initial investment, but the operating cost expenditures are negligable when compared to a fuel-consuming engine-generator. Engines require a relatively modest initial expenditure, but also require continuing (escalating) expenses for fuel. For any power system alternatives which differ so in the time sequence of expenditures, the amount of back-up capacity, the cost and escalation rate of consumables and the amount of energy supplied (load factor) are all important factors in determining the break-even cost between alternatives.

In its simplest form, the life-cycle cost is the amount of money needed on hand today in order to finance the project over its entire lifetime, assuming a known rate of inflation and a given discount or cost of money interest rate. This amount is called the net present value of the project life-cycle cost. It can be written as:

Life-cycle cost = Initial cost + Total Present Worth of Annual Costs

The total present worth of the annual cost streams throughout the life of the project must include all maintenance costs, all battery replacement costs (for a PV system), all operating costs and all fuel costs for those alternatives using engine generator sets.

The present values for the recurrent costs of operations, maintenance, and back-up energy can be formulated to account for both escalation and discounting and expressed in terms of the year of first operation. The expression for the present value of recurrent costs is:

$$X_{pv} = \begin{cases} X_o \cdot \left(\frac{1+g_o}{k-g_o}\right)\left[1 - \left(\frac{1+g_o}{1+k}\right)^N\right], & \text{if } k \neq g. \\ X_o \cdot N, \text{ if } k = g \end{cases}$$

where

$X_{pv}$ = (operation + maintenance, or fuel cost) present value

$X_o$ = Operation + maintenance, or fuel cost in first year

$g_o$ = The escalation rate for operations, maintenance, or fuel cost

k = The cost of money interest rate (discount rate)

N = System life in years

For those recurring replacement costs for equipment such as batteries which have component lives shorter than the system life, the present value of the replacement costs is:

$$R_{pv} = X_1 (1-S) \sum_{i=1}^{\eta} \left(\frac{1+g_1}{1+k}\right)^{\frac{N_i}{n+1}}$$

where

$X_1$ = The replacement cost of the equipment in the first year of operation

S = Per unit salvage value of replaced equipment

N = The system life in years

n = The number of component replacements over N years

$g_1$ = The inflation rate for equipment replacements

k = The cost of money interest rate

The economic analysis should be conducted assuming appropriate system lifetimes for the power system components and the application. For our purpose, a system life of 20 years is assumed. This restriction does not mean, however, that the original solar equipment must be designed to last that long or that components which have longer lifetimes should be discarded in 20 years. It is not intended that the economic analysis should constrain the optimal design. The 20-year standard might be met, for instance, by replacing all the batteries at the end of 10 years or by replacing them at 5, 10, and again at 15 years if the cycling and design depth of discharge result in five year battery lives.

### 6.3.2 Life Cycle Cost Determination

The system components, cost and economic parameters for the system sized in Section 6.2 are presented in Exhibit 6.3-1. The hardware costs are based upon 1980 nominal levels and do not represent industry projections for the future. The indirect costs are expressed as a percentage of the material costs. Installation costs are very dependent upon the location and remoteness of the construction site and are likely to vary from the nominal value of 30% of the hardware costs. Engineering costs are likely to be higher on initial first of a kind projects than on subsequent follow-on jobs.

The inflation rates presented in Exhibit 6.3-1 for use in comparisons were chosen to be typical but may not reflect recent changing economic conditions. The absolute magnitudes of the inflation rates are not really crucial to a comparative engineering economy analysis. The important requirements are uniform assumptions and the relative rates of price change.

Exhibit 6.3-2 presents a form for the computation of the life cycle cost of the system. The costs of components and the factors for determining the present worth of annual recurring operations and maintenance cost as well as the replacement costs for batteries are based upon Exhibit 6.3-1. The evaluated life-cycle cost for the determination of feasibility is shown on Line 13 of the exhibit. This value can be compared with the costs of other alternatives and then refined by testing the sensitivity to different levels of reliability as discussed in Section 7.

Exhibit 6.3-1

COMPONENTS, SYSTEM COSTS AND ECONOMIC PARAMETERS

| Components | Quantity |
|---|---|
| PV Array: 12 kW÷0.9 degradation factor | 13.33 kW |
| Battery: 184 kWh÷0.95 for depth of discharge | 193 kWh |
| Array Life, N | 20 yrs. |
| Battery Life | 10 yrs. |
| **Hardware** | |
| PV Array Cost | $ 10/$W_p$ |
| Battery Cost | $ 150/kWh |
| Salvage Value of Battery, S | 0.10 |
| **Indirect Costs** | |
| Engineering/Total Hardware Costs | 0.10 |
| Installation/Total Hardware Costs | 0.30+* |
| Management/Total Hardware Costs | 0.06 |
| **Economic Parameters** | |
| Discount Rate, k | 0.12 |
| General Inflation Rate | 0.08 |
| Inflation Rate for O&M, $g_o$ | 0.09 |
| Inflation Rate for Battery Replacements, $g_1$ | 0.08 |
| **Annual Recurring Costs** | |
| Array O&M (% of First Costs) | 0.01 |
| Battery O&M (% of First Costs) | 0.01 |

**Present Value Factors**

$$X_{pv}/X_o = (1.09/0.03)\left[1 - (1.09/1.12)^{20}\right] = 15.22$$

$$R_{pv}/\left[X_1\,(1-S)\right] = (1.08/1.12)^{10} = 0.695$$

---

*These costs are very dependent upon location of site.

Exhibit 6.3-2

PHOTOVOLTAIC POWER SYSTEM PRELIMINARY
DESIGN LIFE CYCLE COST COMPUTATION

| | Quantity | |
|---|---|---|
| **Component Size** | | |
| 1. PV Array: nominal size degradation factor | 13.33 | kW |
| 2. Battery size: nominal size depth of discharge | 193 | kWh |
| **Component Costs** | | |
| 3. PV Array | $133,330 | |
| 4. Battery | 28,950 | |
| 5. Power Conditioning System at $1 per watt | 15,000 | |
| 6. Total Components | 177,280 | |
| 7. Engineering | 17,730 | |
| 8. Installation | 53,180 | |
| 9. Project Management | 10,640 | |
| 10. Total First Costs | 258,830 | |
| **Annual Costs** | | |
| 11. Maintenance = 0.01 x Line 3 + 0.01 x Line 4 (from Exhibit 6.3-1) | 1,623 | |
| **Replacements Present Value** | | |
| 12. Battery = 0.695 x 0.9 x Line 4 | 18,108 | |
| **Total Life Cycle Cost** | | |
| Line 10 + Line 12 + 15.22 x Line 11 | $301,640 | |

## 6.4 RELIABILITY ENGINEERING APPROACH

Beginning in the early conceptual and feasibility analysis phase of PV system design, the system design engineer is confronted with many tradeoff decisions involving the alternative choice of PV array configurations, equipment/component types, physical plant (site) layout, etc. These tradeoffs are conducted primarily to optimize system performance with respect to life-cycle cost. In the design of stand-alone PV power plants, system reliability and maintainability (R&M) become key integral factors in these performance/cost tradeoff analyses.

This section discusses the more important R & M engineering and analytical technologies used in these analyses. Maintainability and maintenance aspects of system design are discussed in Section 8.

### 6.4.1 Definition and Specification of PV System R & M Requirements

Reliability and maintainability requirements for stand-alone PV power systems can be expressed in quantitative terms amenable to specification as design requirements, estimation in the design phase, measurement in the development/testing phase, and evaluation during operational use phases of the system life cycle. Definitions and terms are consistent with those used throughout the DOD/NASA industry (Refs. 6-2, 6-3).

#### Reliability

Reliability is generally defined as the probability that an item (PV system, equipment, module, etc.) will perform its specified function (within specified limits of performance) without failure for a specified period of time (or number of cycles) when operated under specified conditions. Reliability characteristic curves (reliability functions for an item are illustrated in Exhibit 6.4-1) for two basic types of failure modes common in PV power systems:

(1) Exponential Case -- failure modes which occur at random points in time (e.g., failure attributed to quality defects in PV cell manufacture, cell failures due to hail damage, etc.), which are independent of prior experience. The reliability function follows exponential (Poisson) law, given as:

$$R(t) = e^{-t/MTBF} = e^{-\lambda t}$$

Where: R(t) = reliability of the item for a given period of time, t

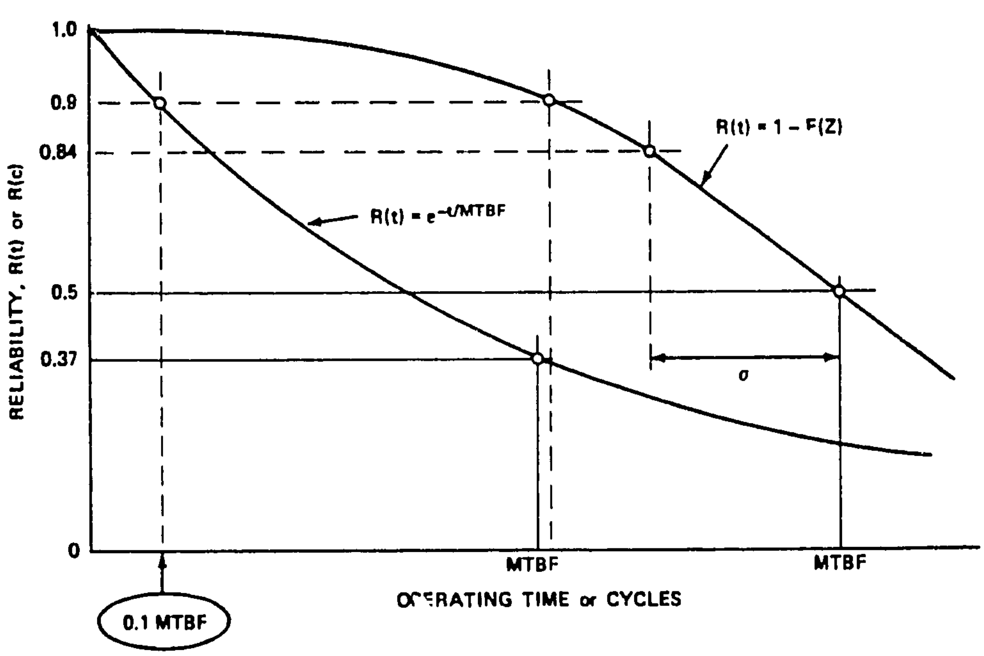
t = calendar time in units of hours, days, months, etc., as applicable

MTBF = mean time between failures for the item

$\lambda$ = item failure rate, in failures per unit of time; = 1/MTBF

Exhibit 6.4-1

RELIABILITY FUNCTIONS FOR EXPONENTIAL (RANDOM) AND GAUSSIAN (WEAROUT) FACILITIES



(2) Gaussian Case --failure modes which occur at predictable points in time, attributed to performance degradation or "wear-out" after an extended period or number of cycles of use (e.g., PV cells and batteries). The reliability function is given by:

$R(t) = 1 - F(Z_t)$, for time-dependent failure modes

$R(c) = 1 - F(Z_c)$, for cycle-dependent failure modes

where: $F(Z) =$ area under the cumulative normal distribution curve (see typical statistics textbook, e.g. Ref. 6-4).

$Z = (x - \mu)/\sigma$

$x =$ time (t) or cycles (c) at which reliability is to be estimated or specified

$\mu =$ mean time between failures (MTBF) or mean cycles between failures (MCBF) for the reliability function at $R \approx 0.50$

$\sigma =$ standard deviation in hours (or cycles) between 50th percentile MTBF (or MCBF) and 84th percentile on the reliability function

## Maintainability (MTTR) and Downtime (MDT)

Maintainability is generally defined in terms of the mean time to repair (MTTR) an item after a failure has occurred. Repair time includes the active time required to: trace and localize the failure; perform the necessary disassembly, corrective repair, and reassemby of the item, and; "check out" (verify) the repair action.

Repair time does not include travel time (time required for the technician to arrive at the site following the indication of a failure) or logistic delay time (time involved in getting the necessary replacement parts). These time elements, along with active repair time, account for the average downtime (MDT) for the repair action.

## Availability (A)

Availability of an item is generally defined as the probability that at any point in time the item will be in a satisfactory state of operation (i.e., either operating or ready to operate when demanded) in accordance with specified performance requirements under the specified use conditions. System availability can be defined for its design (inherent) availability, $A_I$, and for its operating (operational) availability ($A_o$):

$$A_I = \frac{MTBF}{MTBF + MTTR} = (1 + \frac{MTTR}{MTBF})^{-1}$$

$$A_o = \frac{MTBF}{MTBF + MDT} = (1 + \frac{MDT}{MTBF})^{-1}$$

Specification of R&M Requirements

A stand-alone PV power system for particular application may be required to deliver a specified level of dc power without interruption for long periods with only periodic (e.g., weekly or monthly) scheduled maintenance/inspection. The system "operational" requirements should be stated by (or made known to the potential customer) in a formal system specification. The system specification serves two purposes: (1) it provides the contract basis for delivery and acceptance of the installed PV power system; and (2) it provides the basis for translating the system operational requirements into reliability and maintainability parameters allocable to lower-level subsystem/equipment as quantitative design R&M requirements. This section deals with the latter.

Assume, for example, the key system requirements for a particular customer's application might be summarized as illustrated in Exhibit 6.4-2. Since the customer has indicated the proposed PV installation is to be 30 miles NE of Billings, Montana, the solar parameter (e.g., average daily insolation, percent of clear days, etc.) can be computed for the intended site. The system designer must now translate this customer's system requirements into design requirements in quantitative terms (values of performance, reliability, and maintainability characteristics) allocated to the major subsystem. These design requirements are identified and quantitatively allocated to the subsystems in the system design specification. The allocated requirements are appropriately up-dated following each design trade-off iteration during preliminary design phase(e.g., trade-off solar-array, battery-bank, and estimated cycle cost within constraints of a backup generator, load criticality, and available insolation). The following two paragraphs illustrate the reliability and maintainability design requirements which might be included in a proposed system specification. The values shown in these paragraphs are based on the customer's stated operational requirements in Exhibit 6.4-2.

Exhibit 6.4-2

PARTIAL DESCRIPTION OF REQUIREMENTS

FOR HYPOTHETICAL CUSTOMER APPLICATION

| | |
|---|---|
| Voltage: | 200V $\pm$ 20V DC |
| Load Demand: | Continuous, with 1 to 10 kW;<br>Average = 50 kWh per day |
| Load Critically:<br>Load I Critical Level | 10 kWh/day (with less than 1% risk of power loss between scheduled maintenance visits) |
| Load II Essential Load: | 40 kWh/day (with less than 10% risk of power loss) |
| Site/Location: | Remote; 30 miles NE of Billings, Montana;<br>latitude approximately $35^{\circ}$ N; altitude 3,500 ft; rolling terrain |
| Operation: | Unattended |
| Planned Inspection/<br>Maintenance: | 30-day intervals |
| Maintainability: | Not to exceed 2-hour active repair time, on the average (excluding travel and logistic delay time) |
| Spares Provisioning: | Initial spares to provide 90 percent of first-year repairs; to be stocked at the PVPS site |
| Monitoring: | Telemetry (wire or radial) of key parameter status to off-site customer office (30 miles) |

Reliability Design Requirements

1. System Reliability -- System design shall provide continuous dc power to the specified loads for uninterrupted service (excluding 30 seconds start-up of back-up unit, if necessary) during thirty (30) days of unattended operation between scheduled monthly preventive maintenance visits.

| | |
|---|---|
| Load I (Critical Load) | R = 0.99 for specified load, $P_o$ = 10 kWh/day |
| Load II (Essential Load) | R = 0.90 for $P_o$ = 40 kWh/day |

2. Subsystem Reliability--The following subsystem/equipment design requirements shown in Exhibit 6.4-3 are preliminary design allocations to satisfy system requirements specified in (1) above. Values shown in the table are subject to revision as the result of design trade-off iterations in the design verification phase. Subsystem R-values are keyed to the functional block diagram shown in Exhibit 6.4-4 and reliability modeling procedures discussed in Paragraph 6.4.2, following.

Exhibit 6.4-3

EXAMPLE RELIABILITY ALLOCATION
FOR A HYPOTHETICAL SYSTEM

| System/Equipment | | Allocated R Value |
|---|---|---|
| I* Insolation, $\overline{I}_{min}$ = 3.4; $P(I \geq I_{min})$ = | | 0.50 |
| A Solar Array | | 0.95 |
| B Array Terminal Box | | 0.99 |
| C DC/DC Regulator | | 0.98 |
| D Battery Bank and Terminal Box | | 0.95 |
| E Generator, Primary Back-Up | | 0.85 |
| F Generator, Critical Load Back-Up | | 0.90 |
| G Main Power Switching Panel | | 0.99 |
| H Critical Power Switching Panel | | 0.99 |
| J Maintaining & Telemetry Equipment | | 0.995 |
| K Distribution Panel | | 0.995 |
| System Reliability | (Load I and II) | 0.90 |
| | (Load I only) | 0.99 |

*For 35°N latitude (Billings, Montana), the value of minimum solar insolation ($I_{min}$) during January is $\overline{I}_{min} = \overline{K}_T \overline{R} E$ = 3.4 kWh/m$^2$-day, where $\overline{K}_T$ = 0.44, $\overline{R}$ = 1.54 for 50° tilt, and E = 18.1 kWh/m$^2$-day. Thus the value of $P(I \geq I_{min})$ = 0.50 assuming $\overline{K}_T \approx \widetilde{K}_T$.



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## 6.4.2 R&M Networks and Block Diagrams

A reliability block diagram is prepared as a series-parallel network comprising the major components to be used in the proposed PV power system. The block diagram assumes failure-independence (i.e., no interactions) between the blocks. If interactions (failure dependencies) are known to exist between components, these components are combined and identified in the block diagram to account for the interactions. Reliability estimating models (math models) are then developed for each component and path in the network and for the overall PVPS system level. Procedures are illustrated in the following steps:

(1) Prepare a top-level "function-oriented" reliability block diagram based on the preliminary design functional block diagram for the system. Exhibit 6.4-5 shows the functional-oriented reliability block diagram based on the hypothetical system depicted in Exhibit 6.4-4. At the system level, reliability is given as follows for normal operation (with backup), and including solar insolation $R_I* = P(I)$.

- Load II Performance

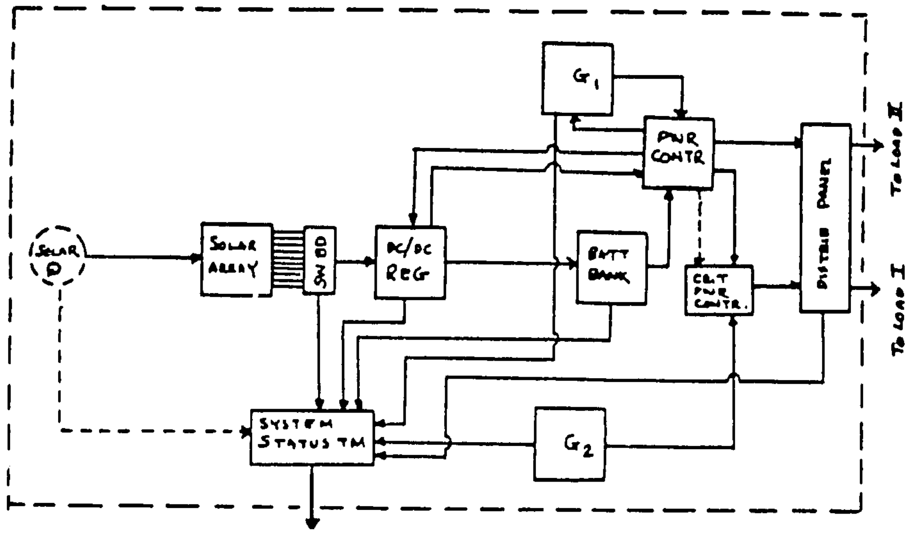
$$R_S\,(II) = \left[1 - (1-R_E)(1-R_I* \; R_A \; R_B \; R_C \; R_D)\right] R_G \; R_K \; R_J$$

- Load I Performance

$$R_S\,(I) = \left[1 - R_F)(1-R_E)(1-R_I* \; R_A \; R_B \; R_C \; R_D)\right] R_G \; R_K \; R_J$$

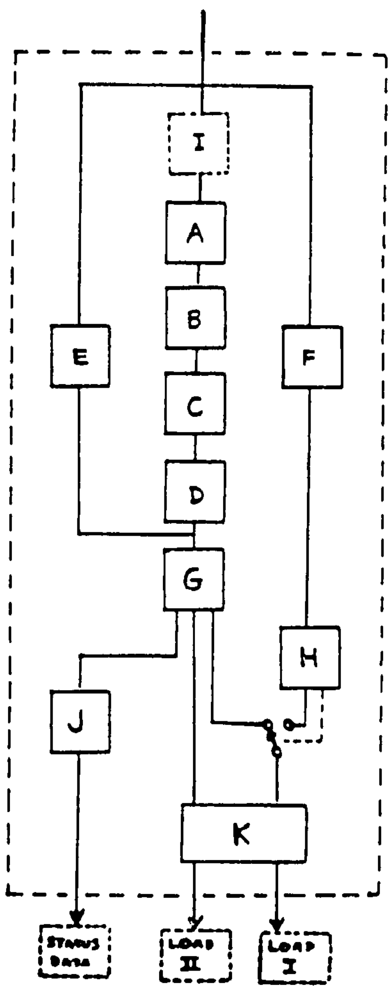
(2) Expand the individual blocks in the "functional" reliability diagram into "equipment/circuit" oriented reliability block diagrams to show series and parallel status and major components in each path in the block.

Develop reliability math models for each block in the system. For example, Block A in Exhibit 6.4-6 is the solar array. The solar array may be configured as simple series "strings" of PV cells, or as a series/parallel network, as illustrated.




To Radio or Wire
Telemetry Transmitter

Exhibit 6.4-4 FUNCTIONAL RELIABILITY BLOCK DIAGRAM



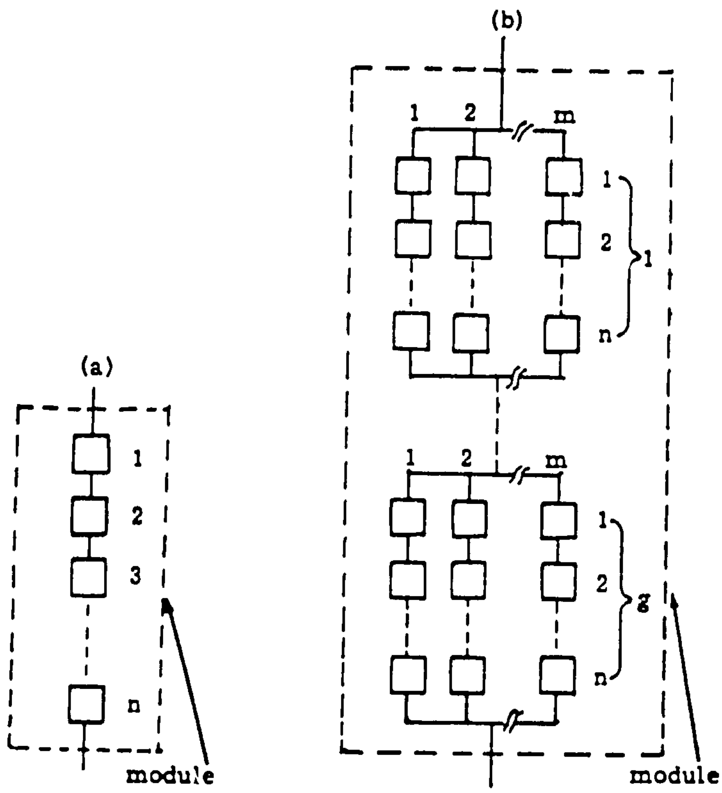

— Solar Insolation (I)
— Solar Array (A)
— Array terminal (switching) board (B)
— Primary Generator Beckup (E)
— Critical Generator Backup (F)
— DC/DC Regulator (C)
— Battery Bank (D)
— Power Switching/Controls (G)
— Critical Load Controls (H)
— Performance Status Monitoring/ Telemetry Equipment (J)
— Distribution Panel (K)

Exhibit 6.4-5

FUNCTION ORIENTED RELIABILITY BLOCK DIAGRAM

Exhibit 6.4-6

OPTIONAL MODULE CONFIGURATIONS:
(A) SERIES: (B) SERIES/PARALLEL



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The choice of one configuration over another will depend on the size of array (in peak watts and voltage), cost of cross-connections vs additonal series strings, ease of maintenance, reliability requirement in unattended installation, etc. Generally, configuration (b) provides higher "system" reliability for a given PV cell population in the array. Reliability models for the two configurations are given as follows:

(a) <u>Series Case</u>

$$R_A = R_i^n \sum_{x=0}^{r} \binom{n}{x} \left( \frac{\bar{R}_i}{R_i} \right)^x,$$

where: $R_i$ = reliability of individual PV "string" in the operative redundent configuration

$\bar{R}_i = (1 - R_i)$

$n$ = number of PV strings in the array

$r$ = number of allowable string failures

and $\binom{n}{x}$ is the binomial coefficient $\frac{n!}{x!\,(n-x)!}$ (For complete tables of values see, National Bureau of Standards, "Tables of Binomial Probability Distribution", GPO 1949, Applied Mathematics Series 6.)

For illustration, assume the first design iteration (preliminary design) has sized the array with 64 parallel strings, each composed of 14 modules in series. Each module is configured with 36 cells in series to deliver rated array power output of 15 kWp at 200 V dc (under standard insolation, $I = 1000 W/m^2$).

Assume that module failure rate for a 30-day unattended operation is

$\lambda m = 780 \times 10^{-6}$ module failures/month and reliability for $R_m = e^{-780 \times -10^6} =$ 0.9992 for a 30day period.

Reliability for a series string of 14 modules for a 30-day period is given by

$$R_S = (R_M)^{14} = (0.9992)^{14} = 0.989$$

Array reliability for a 30-day period can then be estimated for r = 0 1, or 2 string failures using the binomial expression above:

$$R_A\ (r = 0) = R_i^{\,n} = (0.989)^{64} \approx 0.493$$

$$R_A(r = 1) = 0.493\ [1 + 64\ (\frac{0.011}{0.989})] = 0.844$$

$$R_A\ (r = 2) = 0.493\ [1 + 64\ (\frac{0.011}{0.989}) + \frac{63 \times 64}{2}\ (\frac{0.011}{0.989})^2\ ] = 0.967$$

This indicates the simple series configuration (a) would require the addition of two redundant strings to satisfy the allocated reliability requirement, $R_A \geqslant 0.95$. This is verified here to illustrate use of Poisson approximation of the binomial expansion. Techniques for graphical solution of parallel redundant reliability estimation can be found in Ref. 6-4.

$$R(30\ \text{days}) = \sum_{x=0}^{r} \frac{e^{-m\lambda_m tn}(m\lambda_m tn)^x}{x!}$$

where $m$ = number of modules in string, e.g., m = 14

$\lambda_m$ = module failure rate, e.g., $\lambda_m = 26 \times 10^{-6}$ failures/day

$t$ = unattended system operating time between scheduled preventive maintenance visits, e.g., t = 30 days

$n$ = number of strings in the array, e.g., n = 64 +2 redundant strings = 66 strings

then $m\lambda_m tn = 14 \times 26 \times 10^{-6} \times 30 \times 66 = 0.72$

$$R(30\ \text{days}) = \sum_{x=0}^{r=2} \frac{(0.49)(0.72)^x}{x!},\ \text{for } r = 2,\ n = 66\ \text{(2nd iteration)}$$

$$= 0.49 + 0.35 + 0.13$$

$$\approx 0.97$$

However, only one redundant string would be required using the cross-connection configuration discussed in (b), following.

(b) Cross-Connected (Series Parallel Modules)

Assume the circuit configuration is to consist of cross connections to produce two blocks each of 64 substrings (of three series modules) in series with two blocks of 64 substrings (of four series modules).

month, and module reliability = $e^{-778 \times 10^{-6}} = 0.99922.$

Substring (3 module) reliability, $R_{SS_3} = (0.99922)^3 = 0.99767$

Substring (4 module) reliability, $R_{SS_4} = (0.99922)^4 = 0.99689$

$$R_A = \left\{ (R_{SS_3})^{64} \left[ 1 + 64 \frac{(1 - R_{SS_3})}{R_{SS_3}} \right] \right\}^2 x \left\{ (R_{SS_4})^{64} \left[ 1 + 64 \frac{(1 - R_{SS_4})}{R_{SS_4}} \right] \right\}^2$$

$$= \left\{ (0.8613) \left[ 1 + 64 \left(\frac{0.00233}{0.99767}\right) \right] \right\}^2 \left\{ (0.8193) \left[ 1 + 64 \left(\frac{0.00311}{0.99689}\right) \right] \right\}^2$$

$$= (0.9900)^2 \ (0.9829)^2$$

$$= (0.947)$$

Trade-off analysis of configurations (a) and (b) should consider the cost of interconnection required to save one string vs the cost of that string.

In this example, configuration (b) would be recommended from a maintenance/safety standpoint. PV substrings can be grounded at cross-connections during maintenance to limit exposure of voltage less than 50 volts consistent with Article 110-17 of the National Electrical Code (NEC).

### 6.4.3 Reliability Prediction and Feasibility Estimation

Feasibility of the allocated reliability and maintainability requirements defined in 6.4.1 are evaluated by using the math models developed in 6.4.2 based on equipment and component failure rates presented in Appendix B. These failure rates are based on field experience over the past few years and are subject to revision with changes in the state of the art.

For example, failure rates reported on photovoltaic cells may range from $0.005 \times 10^{-6}$ to $0.5 \times 10^{-6}$ (failures per hour) due to variation in application stresses, environmental conditions (temperature, relative humidity, etc.), basic design, materials, and processes used in PV manufacture, and also the scarcity of PV cell failure data itself.

In jointly estimating reliability and maintainability (scheduled periodic maintenance) for the stand-alone PV system, power loss must be considered due to accumulation of "dust" on the surface of PV modules. Dust includes sand, pollen, and other air-borne particles, peculiar to the local atmosphere at the proposed site. Design discusions will involve trade-offs, primarily among cost of frequency of array "cleaning" (preventive maintenance), cost of glass outer covers for the modules, and cost of additional PV strings to make up the power loss during the desired length of unattended operating period.

Field data collected from several existing sites indicates dust accumulation rate and corresponding array power loss ranging from 1% to 38% over a one-year period without cleaning (see Appendix B). Variation in dust accumulation can be attributed to differences in the materials used in module outer surface (e.g., glass, silicone rubber, hard-coated silicone rubber), array tilt angle, and local atmospheric/pollution/weather conditions (e.g., city, suburban, rural, mountainous, desert, etc.).

### 6.4.4 Failure Mode and Effects Analysis

The PV power system designer should perform failure mode and effects analyses (FMEA) for his intended design (and subsequent engineering changes) to identify and evaluate any potential critical failure modes which could jeopardize personnel safety or equipment reliability during installation, operation, or maintenance of the proposed PV power system. These analyses are also useful for identifying potential maintainability problems (excessive maintenance burden in terms of maintenance manhours, equipment downtime rate); logistic support problems (excessive requirements for spares and replacement parts); and inadequacy of specified quality controls (in component production and system installation in terms of process controls, special inspections, test procedures, etc.).

Results of the FMEA should provide design guidance in choosing between several alternatives for the correction or circumvention of the identified critical failure modes -- e.g., choice between use of parts derating, feedback stabilization, circuit redundancy, location of test points for performance monitoring and failure indication (for on-line maintenance), etc.

Procedures for failure mode and effect analysis (and "fault-tree" analysis) are published in the literature,[1] describing the following basic steps:

(1) Develop the Equipment Functional/Reliability Block Diagram

Extend the reliability block diagram and mathematical models described in 6.4.2 down to the lowest replaceable item (e.g., unit, curcuit, component, or part) in each functional path or "network" in the proposed design configuration.

(2) Identify Critical Failure Modes.

Identify and determine the specific failure modes within replaceable items which could render each functional path hazardous (or unsafe) to operating/maintenance personnel, unreliable (inoperable or excessively degraded performance) in equipment operation, or nonconformance to other "desired" specified system performance parameter requirements (e.g., performance tolerance limits, downtime rates, maintenance skills, etc.).

[1] For example, two sources are: Military Standard 2070 (AS), "Procedures for Performing a Failure Mode Effects and Criticality Analysis for Aeronautical Equipment"; Reliability Guides (Vol. 4), NAVORD OD 44622, pp. 7-4 through 7-21, "Failure Mode and Effects Analysis by Prediction".



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(3) Estimate Failure Rate for Identified Critical Failure Modes.

Determine failure rate for each identified critical failure mode by subdividing the failure rates applied in 6.4.3, allocated according to the relative frequency with which the critical failure modes occur within the estimated overall failure rate.

For example, estimated failure rates for a particular type of DC relay may be $5 \times 10^{-6}$ failures per operating hour in all failure modes. Assume that life test data reveal 50 percent of the failures were due to open mode, 20 percent were due to short mode, and 30 percent were due to degraded performance (high resistance contact, chattering contacts, etc.). If "short" mode is critical in terms of safety or reliability in the proposed application, the failure rate for the critical failure mode is:

$$\lambda_c = 5 \times 10^{-6} (0.20)$$
$$= 1 \times 10^{-6} \text{ critical "short" failures per operating hour}$$

In the absence of experience data (operating history or life-test data) for particular items used in the proposed PVPS design, failure-rate estimates for generic part types can be obtained from MIL-HDBK-217.[2] Life-test failure-mode data for certain part types can be obtained from GIDEP reports.[3] However, a "worst-case" analysis may be justified if data are meager, by allocating the total failure rate to the critical failure mode.

[2, 3] See Appendix B-2



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(4) Assess Safety/Reliability Design Adequacy.

Apply estimated failure rates of identified critical failure modes in the reliability modes evolved in (1) above, and compute functional path and system-level reliability (inoperable) failure rate and safety (hazardous or unsafe) failure rate. Transform these critical failure rates to reliability and safety probability estimates (or in terms of mean time between critical failures (MTBCF). Compare these values with the specified PV power system requirements for safety and reliability (or downtime rate).

(5) Evaluate Design Changes.

If results of FMEA indicate nonconformance to specified (or desired) requirements in (4) above, rank the identified problem areas according to their relative impact and evaluate alternative design changes for circumvention of or minimizing the undesired failure modes.

(6) Evaluate Other Hazards to System Safety/Reliability.

Other critical failure modes may be induced by human/equipment interface problems (not due to component failure) resulting in equipment operation or maintenance in modes not intended by design. Although these failure modes usually cannot be quantified in terms of failure rate, they nevertheless can be identified qualitatively as potential threats requiring placement of cautionary labels and protective measures at appropriate points in the installed system.

For example, to evaluate the safety aspect of human/equipment interface design, consider the following: electrical grounds for external metal parts, panels, controls, etc.; safety covers and notations with interlocks in the high-voltage devices; connectors and plugs designed so as not to expose high-voltage "hot" pins; local safety switch at base of solar-tracking arrays; discharging devices for high voltage PV circuits during cleaning or maintenance of solar array; barriers between adjacent test points on terminals to prevent accidental shortage by slippage of test probe; installation of fuses and circuit-breakers at ground or low-voltage end of PV strings; protection from moving parts or high-temperature parts; protection from sharp edges of components and maintenance access openings; identification of points for lifting or hoisting batteries, solar panels, etc., during installation or removal.

## 6.5 ADVANTAGES AND DISADVANTAGES OF PV POWER SYSTEM

Current solar technology and cost suggest that adequately designed PV power systems (PVPS) are well suited for high-reliability/low maintainability requirement applications at remote locations. Typical examples of such applications have included remote weather stations, communications relay stations, navigational buoys and agricultural water-pumping systems. Other power sources are used with varying degrees of success, with or without battery storage and rechargeable on-site battery storage. Generally, the advantages of PV power systems over other systems are their simplicity (fewer moving parts), relative ease of maintenance, high (equipment) reliability, and unattended operation. However, the major disadvantages of PV power systems (by their nature) are their dependence on adequate solar insolation, relative large size of installation area required for the solar array, and the need for dc/ac inversion equipment for ac loads.

# SECTION 7
# SYSTEMS DESIGN

## 7.1 DESIGN PHILOSOPHY

The foregoing sections of this handbook give the ingredients for an analysis of the annual energy output from a photovoltaic system. However, the systems being considered are stand-alone systems; therefore, the design must be based on the photovoltaics supplying all of the electrical power. The average power output from the system must thus be equal to the average power consumption of the load. The question to be answered is: what is the probability that the solar system will not meet the momentary load requirement? This section presents the loss-of-load probability (LOLP) computational procedure to answer this question.

If the LOLP is too high to be acceptable, either the array and/or the storage size can be increased or an emergency power system can be provided as a backup to the photovoltaics. In the latter case, the LOLP computation will indicate how often the emergency system will be used. It can then be determined, for example, how much fuel must be stored at the site to power the emergency system and how frequently it must be replenished.

The procedure, which is intended to provide the basis for developing first cut designs for cost-effective stand-alone PV power systems, involves the following steps:

1. Determination of the load ( see Section 4.1)
2. Computation of the insolation (see Section 11)
3. Selection of the array and storage-system size
4. Computation of the LOLP
5. Computation of the life-cycle costs

The last three elements are considered in this section of the handbook.



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## 7.2 SYSTEM DESIGN PROCEDURE

The system design procedure is iterative. The array and storage sizes must be selected, with the help of the quick-sizing method of Section 6, and the system performance must be computed. The performance computation is then incorporated into a life-cycle cost analysis. If the technical performance or life-cycle cost are unacceptable, then a new set of array and storage sizes must be selected.

The computational process has been systematized in Exhibit 7.2-1. The average insolation is determined via the procedures of Section 11, based on the data in Appendix A and Exhibit 6.1-1. If Exhibit 6.1-1 does not include the tilt angles of interest, then the computational procedure of Section 11.3 can be used. The standard deviation of the insolation -- a measure of its variability -- is presented in Exhibit 6.1-1, as required in Step 2 of Exhibit 7.2-1. The insolation required to meet the load, $I_D$, can be estimated from the load requirements. With the load measured in kWh per day, and system efficiency in kWh/m$^2$ output per kWh/m$^2$ of insolation,

$$I_D = \frac{[\text{kWh/day of load}]}{\left([(\text{kWh/m}^2 \text{ output per kWh/m}^2 \text{ of insolation})^* (\text{the area of the array in square meters})]\right)}$$

The value of $I_D$ is required in Step 3 of Exhibit 7.2-1.

The storage size is expressed in days of storage over which the load could be met in the complete absence of sunlight. If the load were 2 kWh per day and the storage size were 12 kWh, C, the storage capacity as required in Step 4 of Exhibit 7.2-1, would be 12/2 = 6 days. The remaining computations are self-explanatory.

An outline of the procedure is presented herein to enable the reader to understand its applicability. The equation for Step 9 is based on having the storage system initially fully charged, to capacity C. Over N-1 days, the storage would be depleted gradually, so the required average insolation to meet the load up to

## Exhibit 7.2-1

## LOSS-OF-LOAD PROBABILITY COMPUTATIONAL PROCEDURE

1. Obtain the average insolation, $\bar{I}$, from Exhibit 6.1-1.
2. Obtain the standard deviation, s , of the insolation from Exhibit 6.1-1.
3. Select an insolation value, $I_D$ , at which the load will be exactly met ($I_D$ should be less than $\bar{I}$):

$$I_D = \text{Load}/(\eta A)$$

   where A is the array area and the units of $\eta$ should give $I_D$ in kWh/day-m$^2$.
4. Select the storage capacity, C, in days of load.
5. Set N=C+1 and SUM = 0.0
6. Compute $Z_1 = (\bar{I} - I_D)/S$
7. If $Z_1$ is less than 2, read from Exhibit 7.2-2 the value of Y.
   If $Z_1$ is greater than 2, compute

$$Y = \exp(-0.5 * Z_1^{\;2})/(\sqrt{2 * \pi} * Z_1)$$

8. Compute the probability of failing in one day, $F_1 = Y$
9. Compute $Z_{N-1} = \left[\bar{I} - I_D + C * I_D/(N-1)\right] * \sqrt{N-1}/S$
10. If $Z_{N-1}$ is less than 2, read from Exhibit 7.2-2 the value of Y.
    If $Z_{N-1}$ is greater than 2, compute

$$Y = \exp(-0.5 * Z_{N-1}^2)/(\sqrt{2 * \pi} * Z_{N-1})$$

11. Compute the probability of surviving up to day N-1: $F_{N-1} = 0.5 - Y$
12. Compute $Z' = Z_{N-1} + I_D/(\sqrt{N-1} * S)$
13. If Z' is less than 2, read from Exhibit 7.2-2 the value of Y.
    If Z' is greater than 2, compute

$$Y = \exp\left[-0.5 * (Z')^2\right] / (\sqrt{2 * \pi} * Z')$$

14. Compute the probability of surviving corresponding to Z': $F' = 0.5 - Y$
15. Compute SUM = SUM + $(F' - F_{N-1})$
16. If N is greater than N*, where $N^* = 10*(C+1)\, I_D/(I - I_D)$, go to Step 18.
17. Set N = N + 1 and return to Step 9.
18. Compute the probability of failure:

$$\text{LOLP} = F_1 * \left[\text{SUM} + \exp(-C*K_1) * \left[1. - \exp(-K_1)\right] * \exp(-K_2^2)/B\right]$$

$$K_1 = I_D * K/S$$

$$K = (\bar{I} - I_D)/S = Z_1$$

$$K_2 = K * (N^*/20)^{0.5}$$

$$B = K^2 * (K_2 + \sqrt{K_2^2 + 4/\pi})$$

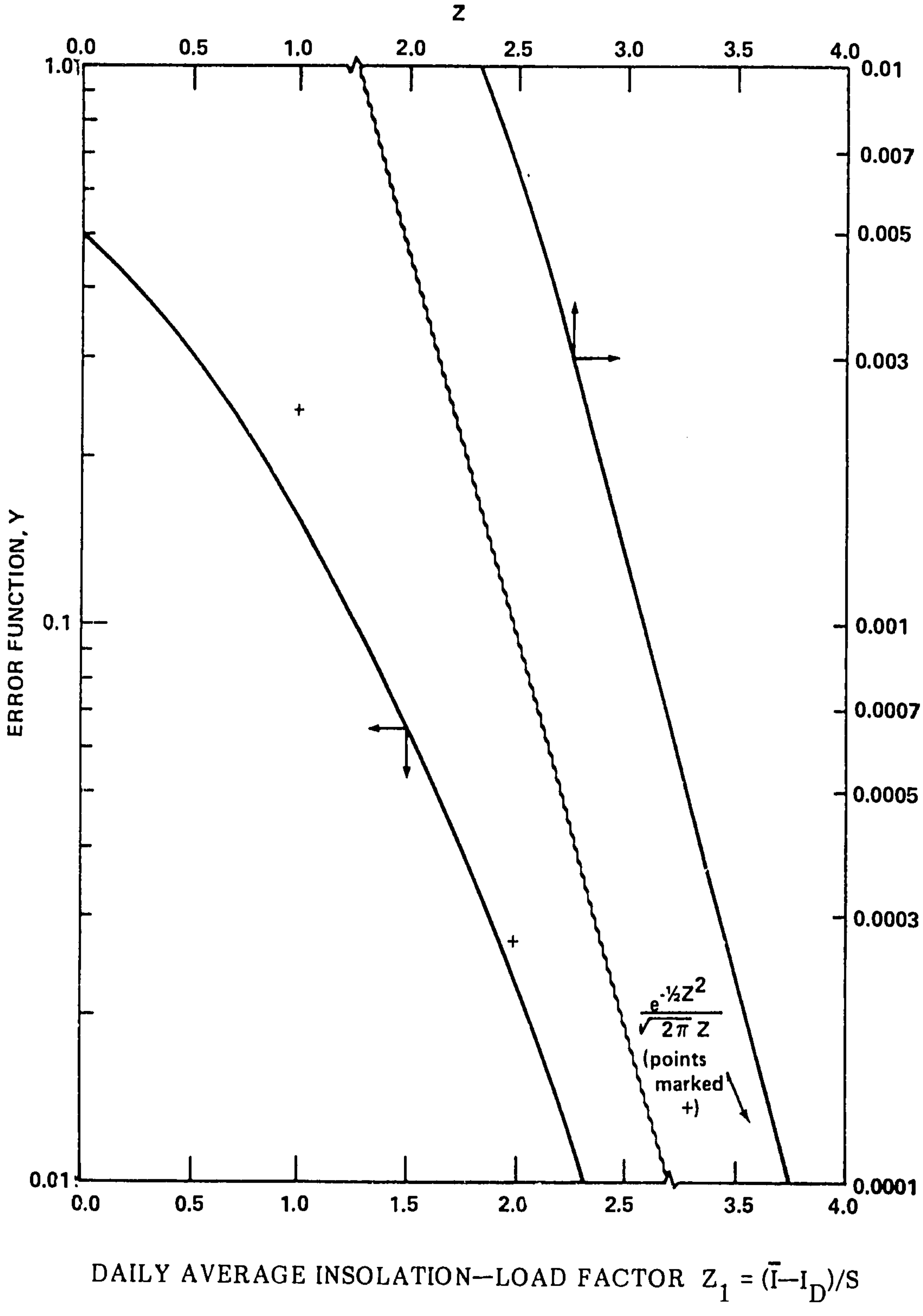


Exhibit 7.2-2

CUMULATIVE DISTRIBUTION FUNCTION
FOR THE NORMAL CURVE

day N-1 is $I_D$ - $C*I_D/(N-1)$. The function $Z_{N-1}$ is the number of standard deviations the required average insolation is from the average, $\bar{I}$. The probability distribution function is not exactly normal (Gaussian), but closely approximates the normal after ten days. Therefore, the insolation on the tilted surface, which has been assumed as averaged over N days, is a normal distribution. This assumption is consistent with the law of large numbers in probability theory. The (cumulative) distribution function for the normal curve is called the error function. There is no simple expression for the error function, nor do hand-held calculators have the error function pre-programmed. Therefore, Exhibit 7.2-2 must be used. However, for Z greater than 2.0, the exponential function, Y, of Step 10, is a close approximation. The crossed points of Exhibit 7.2-2 show the comparison.

The LOLP computation for any one day, N, involves three factors: (1) $Z_1$, which is related to the probability that the load will be lost in a single day; (2) $Z_{N-1}$, which corresponds to losing the load when the insolation is nearly zero on the following day; and (3) Z', which corresponds to the losing the load when the insolation is relatively high on the following day. These three factors are combined in Step 15, although, for speed of computation, multiplication of the sum by the constant factor $F_1$ is deferred until after the summing is completed (Step 18).

The total LOLP must be computed by summing the probabilities for the individual days. Typically, several hundred days are required to provide an adequate estimate. When the number of the day is large, the summation can be approximated by an integral, as given in Step 18. Therefore, the summation computation need be executed only up to 10 times N*, with the integral giving the value of the remaining terms in the summation. Consequently, the probability of failure (LOLP) of Step 18 includes all the days, up to N equal to infinity.

The procedure gives an approximate evaluation of the exact expression:

$$\text{LOLP} = \sum_{N=C+1}^{\infty} \int_{I_{N-1/I}}^{(N/N-1)I_N/I} F_1\,(N*I_N/\bar{I} - (N-1)\,x)\ F'_{N-1}\,(x)\ dx$$

where: $I_N = (1-C/N) * I_D$



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An example of the computational procedure is presented in Exhibit 7.2-3. The example is for a latitude of 45 degrees, a tilt of the array at 45 degrees, and a $K_H$ of 0.5. Starting points for both the array size and battery capacity are chosen. A value of the insolation, $I_D$, required to meet the load, is selected (2.3 kWh/day-$m^2$) based on the average daily kWh load, and an assumed array area with a known efficiency. Eight days storage capacity is used. Computations for only the first day are presented in detail; however, the computations were carried out to completion with a LOLP computed of 0.0016, or approximately six days loss of load over a ten year period. This relatively high level of reliability approaches the reliability criteria of bulk, interconnected utility grids that are generally designed for a one day loss of load per ten year period.

The computations were performed on a Texas Instruments TI-59 electronic calculator using the program listed in Exhibit 7.2-4. Instructions for the operation of the program are presented in Exhibit 7.2-5. Running time on this calculator was approximately 0.1 minute per day, or 0.1*N minutes. The corresponding Hewlett Packard HP-67 calculator program is presented in Exhibits 7.2-6 and 7.2-7.

With the aid of the calculator programs, the LOLP may be obtained for many variations in the design parameters. Exhibit 7.2-8 was prepared to show some of the results of a parametric variation study of LOLPs for a range of array sizes. ($I_D$) and storage capacities (C) that might be tried. Note that the units of insolation are immaterial, although, I, S, and $I_D$ must all be expressed in the same units. The area of the array in square meters is determined from the expression for $I_D$ and is expressed as:

$$\text{Area } (m^2) = (\text{kWh/day of load}) / (\text{system efficiency} * I_D)$$

Where $I_D$ is expressed in kWh/day-$m^2$.



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Exhibit 7.2-3

EXAMPLE OF LOSS-OF-LOAD PROBABILITY COMPUTATION

1. For Latitude = $45^o$, $\bar{K}_H$ = 0.5, $\bar{I}$ = 2.971 kWh/day-$m^2$ (Exhibit 6.1-1)
2. For Latitude = $45^o$, $\bar{K}_H$ = 0.5, (Sigma 1) * $\bar{I}$ = 1.839 kWh/day-$m^2$ (Exhibit 6.1-1)
3. Select $I_D$ = 2.3 kWh/day-$m^2$
4. Select C = 8 days
5. N = 9, SUM = 0.0
6. $Z_1 = (2.971 - 2.3)/1.839 = 0.3649$
7. Read Y = 0.36
8. $F_1 = 0.36$
9. $Z_{N-1} = Z_8 = (2.971 - 2.3 + 8 * 2.3/8) * \sqrt{8}/1.839 = 4.569$
10. Compute: $Y = EXP(-0.5 * \overline{4.569}^2)/(\sqrt{2\pi} * 4.569) = 0.000\ 002\ 55$
11. $F_8 = 0.499\ 997\ 45$
12. $Z' = 4.569 + 2.3/\sqrt{8} * 1.839) = 5.012$
13. Compute: $Y = EXP(-0.5 * \overline{5.012}^2)/(\sqrt{2\pi} * 5.012) = 0.000\ 000\ 28$
14. $F' = 0.499\ 999\ 72$
15. SUM = 0 + 0.499 999 72 - 0.499 997 45 = 0.000 002 27
16. $N < N^* = 10*9 * 2.3/(2.971 - 2.3) = 308.4$
17. N = 9 + 1 =10

    etc.

18. $K = (2.971 - 2.3)/1.839 = 0.3649$

    $K_1 = 2.3 * K/1.839 = 0.4563$

    $K_2 = K * \sqrt{308.4/20} = 1.433$

    $B = (0.3649^2) * (1.433 + \sqrt{1.433^2 + 4/\pi}) = .4336$

    LOLP *= (0.36) [0.00159 + 0.00282]

    = 0.0016

*Variations may occur in the value of LOLP due to different readings off the exhibit.

```
000  76 LBL
001  11  A
002  42 STO
003  06  06
004  32 X:T
005  02  2
006  77  GE
007  14  D
008  32 X:T
009  33 X²
010  55  ÷
011  02  2
012  94 +/-
013  95  =
014  22 INV
015  23 LNX
016  55  -
017  43 RCL
018  06  06
019  55  -
020  53  (
021  02  2
022  65  ×
023  89  π
024  54  )
025  34 √X
026  95  =
027  76 LBL
028  44 SUM
029  92 RTN
030  76 LBL
031  14  D
032  02  2
033  04  4
034  03  3
035  01  1
036  03  3
037  03  3
038  04  4
039  01  1
040  03  3
041  07  7
042  69 OP
043  01  01
044  03  3
045  03  3
046  03  3
047  05  5
048  03  3
049  02  2
050  01  1
051  04  4
052  69 OP
053  02  02
054  69 OP
055  05  05
056  43 RCL
057  06  06
058  91 R/S
059  99 PRT
060  61 GTO
061  44 SUM
062  76 LBL
063  12  B
064  86 STF
065  08  08
066  91 R/S
067  99 PRT
068  42 STO
069  00  00
070  91 R/S
071  99 PRT
072  42 STO
073  01  01
074  91 R/S
075  99 PRT
076  42 STO
077  02  02
078  91 R/S
079  99 PRT
080  42 STO
081  03  03
082  42 STO
083  04  04
084  00  0
085  42 STO
086  05  05
087  53  (
088  43 RCL
089  03  03
090  85  +
091  01  1
092  54  )
093  65  ×
094  43 RCL
095  02  02
096  55  ÷
097  53  (
098  43 RCL
099  00  00
100  75  -
101  43 RCL
102  02  02
103  54  )
104  65  ×
105  01  1
106  00  0
107  95  =
108  42 STO
109  07  07
110  99 PRT
111  98 ADV
112  53  (
113  43 RCL
114  03  03
115  85  +
116  01  1
117  54  )
118  65  ×
119  43 RCL
120  02  02
121  65  ×
122  53  (
123  43 RCL
124  00  00
125  75  -
126  43 RCL
127  02  02
128  54  )
129  95  =
130  34 √X
131  65  ×
132  02  2
133  55  ÷
134  43 RCL
135  01  01
136  95  =
137  32 X:T
138  02  2
139  77  GE
140  19  D'
141  76 LBL
142  81 RST
143  43 RCL
144  00  00
145  75  -
146  43 RCL
147  02  02
148  95  =
149  55  ÷
150  43 RCL
151  01  01
152  95  =
153  42 STO
154  08  08
155  11  A
156  42 STO
157  11  11
158  76 LBL
159  13  C
160  43 RCL
161  08  08
162  65  ×
163  43 RCL
164  04  04
165  34 √X
166  85  +
167  43 RCL
168  03  03
169  65  ×
170  43 RCL
171  02  02
172  55  ÷
173  43 RCL
174  04  04
175  34 √X
176  55  -
177  43 RCL
178  01  01
179  95  =
180  42 STO
181  12  12
182  11  A
183  75  -
184  93  .
185  05  5
186  95  =
187  44 SUM
188  05  05
189  43 RCL
190  12  12
191  85  +
192  43 RCL
193  02  02
194  55  ÷
195  43 RCL
196  04  04
197  34 √X
198  55  ÷
199  43 RCL
200  01  01
201  95  =
202  11  A
203  94 +/-
204  85  +
205  93  .
206  05  5
207  95  =
208  44 SUM
209  05  05
210  43 RCL
211  05  05
212  66 PAU
213  43 RCL
214  07  07
215  32 X:T
216  43 RCL
217  04  04
218  77  GE
219  18  C'
220  01  1
221  44 SUM
222  04  04
223  61 GTO
224  13  C
225  76 LBL
226  18  C'
227  43 RCL
228  08  08
229  65  ×
230  43 RCL
231  02  02
232  55  ÷
233  43 RCL
234  01  01
235  95  =
236  94 +/-
237  42 STO
238  09  09
239  43 RCL
240  08  08
241  65  ×
242  53  (
243  43 RCL
244  07  07
245  55  ÷
246  02  2
247  00  0
248  54  )
249  34 √X
250  95  =
251  42 STO
252  10  10
253  33 X²
254  94 +/-
255  22 INV
256  23 LNX
257      ×
258  53  (
259  43 RCL
260  03  03
261  65  ×
262  43 RCL
263  09  09
264  54  )
265  22 INV
266  23 LNX
267  65  ×
268  53  (
269  01  1
270  75  -
271  43 RCL
272  09  09
273  22 INV
274  23 LNX
275  54  )
276  55  -
277  53  (
278  43 RCL
279  10  10
280  85  +
281  53  (
282  43 RCL
283  10  10
284  33 X²
285  85  +
286  04  4
287  55  ÷
288  69  π
289  54  )
290  34 √X
291  54  )
292  55  ÷
293  43 RCL
294  08  08
295  33 X²
296  95  =
297  85  +
298  43 RCL
299  05  05
300  95  =
301  65  ×
302  43 RCL
303  11  11
304  95  =
305  42 STO
306  05  05
307  99 PRT
308  91 R/S
309  76 LBL
310  19  D'
311  02  2
312  03  3
313  02  2
314  04  4
315  02  2
316  02  2
317  02  2
318  03  3
319  69 OP
320  01  01
321  03  3
322  05  5
323  02  2
324  04  4
325  03  3
326  06  6
327  02  2
328  06  6
329  69 OP
330  02  02
331  69 OP
332  05  05
333  61 GTO
334  81 RST
335  00  0
336  00  0
337  00  0
338  00  0
339  00  0
340  00  0
341  00  0
342  00  0
343  00  0
344  00  0
345  00  0
346  00  0
```

EXHIBIT 7.2-4

LISTING OF A TI-59 PROGRAM FOR CALCULATION OF LOSS OF LOAD PROBABILITY

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Exhibit 7.2-5

# INSTRUCTIONS FOR THE OPERATION OF THE TI-59 PROGRAM FOR COMPUTING THE LOSS-OF-LOAD PROBABILITY

1. Depress B to ready the calculator for input.

2. Enter the average insolation on the tilted surface, I. (Stored in 00)
   Depress R/S.
   Enter the standard deviation of the insolation on the tilted surface, S. (Stored in 01)
   Depress R/S.
   Enter the insolation required to exactly meet the load, $I_D$. (Stored in 02)
   Depress R/S.
   Enter the number of days of storage capacity, C. (Stored in 03)
   Strike R/S.

3. The calculator prints the number of days that must be summed, then proceeds with the computations. If the LOLP is predicted to be high, the calculator will print HIGH RISK. The prediction method is approximate only, being based on the estimated maximum value of $Z_{N-1}$. If this value is less than 2, the risk is likely to be high. After printing HIGH RISK, the calculator proceeds with the computations.

   If Z is greater than 2.0, the calculator uses the approximate formulas. If Z is less than 2.0, it will ask for the user to input the value of the probability, with the words INPUT PROB. The value of Z is displayed. After the probability is read from Exhibit 7.2-2 and entered, the user should strike R/S. The calculator will print the probabil'ty and continue with the computations.

4. The calculator will flash the probability (LOLP) up to the day being calculated, as the computations proceed.

5. If an error should occur, the calculator will stop at the point of the error, because SET FLAG 8 is incorporated in the program.

6. At the end of the computation, the calculator will print the LOLP, stop, and display the LOLP, storing the value in 05.

## Exhibit 7.2-6

LISTING OF AN HP-67 PROGRAM FOR
CALCULATION OF LOSS OF LOAD PROBABILITY

| Step Number | Key-strokes | Key Code | | | Step Number | Key-strokes | Key Code | | |
|---|---|---|---|---|---|---|---|---|---|
| 001 | f LBA A | 31 | 25 | 11 | 029 | 1 | | | 01 |
| 002 | RCL O | | 34 | 00 | 030 | -- | | | 51 |
| 003 | RCL 2 | | 34 | 02 | 031 | STO 6 | | 34 | 06 |
| 004 | -- | | | 51 | 032 | ÷ | | | 89 |
| 005 | RCL 1 | | 34 | 01 | 033 | 1 | | | 01 |
| 006 | ÷ | | | 81 | 034 | — | | | 51 |
| 007 | STO 8 | | 33 | 08 | 035 | RCL 2 | | 34 | 02 |
| 008 | R/S | | | 84 | 036 | X | | | 71 |
| 009 | STO 9 | | 33 | 09 | 037 | RCL 0 | | 34 | 00 |
| 010 | 0 | | | 00 | 038 | | | | |
| 011 | STO 5 | | 33 | 05 | 038 | + | | | 61 |
| 012 | RCL 3 | | 34 | 03 | 039 | RCL 6 | | 34 | 06 |
| 013 | 1 | | | 01 | 040 | f√X | | 31 | 54 |
| 014 | + | | | 61 | 041 | X | | | 71 |
| 015 | STO 4 | | 33 | 04 | 042 | RCL 1 | | 34 | 01 |
| 016 | RCL 2 | | 34 | 02 | 043 | - | | | 81 |
| 017 | X | | | 71 | 044 | f GSB 1 | 31 | 22 | 01 |
| 018 | RCL 0 | | 34 | 00 | 045 | STO + 5 | 33 | 61 | 05 |
| 019 | RCL 2 | | 34 | 02 | 046 | RCL 2 | | 34 | 02 |
| 020 | -- | | | 51 | 047 | RCL 4 | | 34 | 04 |
| 021 | ÷ | | | 81 | 048 | 1 | | | 01 |
| 022 | 1 | | | 01 | 049 | -- | | | 51 |
| 023 | 0 | | | 00 | 050 | f√X | | 31 | 54 |
| 024 | X | | | 71 | 051 | RCL 1 | | 34 | 01 |
| 025 | STO 7 | | 33 | 07 | 052 | X | | | 71 |
| 026 | f LBL B | 31 | 25 | 12 | 053 | ÷ | | | 81 |
| 027 | RCL 3 | | 34 | 03 | 054 | RCL 6 | | 34 | 06 |
| 028 | RCL 4 | | 34 | 04 | 055 | + | | | 61 |

Exhibit 7.2-6 (Continued)

LISTING OF AN HP-67 PROGRAM FOR

CALCULATION OF LOSS OF LOAD PROBABILITY

| Step Number | Key-strokes | Key Code | | | Step Number | Key-strokes | Key Code | | |
|---|---|---|---|---|---|---|---|---|---|
| 056 | f GSB 1 | 31 | 22 | 01 | 083 | f LBL 2 | 31 | 25 | 02 |
| 057 | STO-5 | 33 | 51 | 05 | 084 | h RTN | | 35 | 22 |
| 058 | RCL 7 | | 34 | 07 | 085 | f LBL 3 | 31 | 25 | 03 |
| 059 | RCL 4 | | 34 | 04 | 086 | h x≷y | | 35 | 52 |
| 060 | g x>y | | 32 | 81 | 087 | R/S | | | 84 |
| 061 | GTO C | | 22 | 13 | 088 | GTO 2 | | 22 | 02 |
| 062 | 1 | | | 01 | 089 | f LBL C | 31 | 25 | 13 |
| 063 | STO + 4 | 33 | 61 | 04 | 090 | RCL 7 | | 34 | 07 |
| 064 | RCL 5 | | 34 | 05 | 091 | 2 | | | 02 |
| 065 | h PAUSE | | 35 | 72 | 092 | 0 | | | 00 |
| 066 | GTO B | | 22 | 12 | 093 | ÷ | | | 81 |
| 067 | f LBL 1 | 31 | 25 | 01 | 094 | f$\sqrt{x}$ | | 31 | 54 |
| 068 | 2 | | | 02 | 095 | RCL 8 | | 34 | 08 |
| 069 | h x≷y | | 35 | 52 | 096 | X | | | 71 |
| 070 | g x≤y | | 32 | 71 | 097 | STO A | | 33 | 11 |
| 071 | GTO 3 | | 22 | 03 | 098 | RCL 8 | | 34 | 08 |
| 072 | STO 6 | | 33 | 06 | 099 | RCL 2 | | 34 | 02 |
| 073 | g $x^2$ | | 32 | 54 | 100 | X | | | 71 |
| 074 | CHS | | | 41 | 101 | RCL 1 | | 34 | 01 |
| 075 | g $e^x$ | | 32 | 52 | 102 | ÷ | | | 81 |
| 076 | RLC 6 | | 34 | 06 | 103 | STO B | | 33 | 12 |
| 077 | ÷ | | | 81 | 104 | CHS | | | 42 |
| 078 | h$\pi$ | | 35 | 73 | 105 | g $e^x$ | | 32 | 52 |
| 079 | 2 | | | 02 | 106 | CHS | | | 42 |
| 080 | X | | | 71 | 107 | 1 | | | 01 |
| 081 | f$\sqrt{x}$ | | 31 | 54 | 108 | + | | | 61 |
| 082 | ÷ | | | 81 | 109 | RCL B | | 34 | 12 |

Exhibit 7.2-6 (Continued)

LISTING OF AN HP-67 PROGRAM FOR
CALCULATION OF LOSS OF LOAD PROBABILITY

| Step Number | Key-strokes | Key Code | |
|---|---|---|---|
| 110 | RCL 3 | 34 | 03 |
| 111 | X | | 71 |
| 112 | CHS | | 42 |
| 113 | g $e^x$ | 32 | 52 |
| 114 | X | | 71 |
| 115 | RCL A | 34 | 11 |
| 116 | g $x^2$ | 32 | 54 |
| 117 | CHS | | 42 |
| 118 | g $x^e$ | 32 | 52 |
| 119 | X | | 71 |
| 120 | 4 | | 04 |
| 121 | h $\pi$ | 35 | 73 |
| 122 | ÷ | | 81 |
| 123 | RCL A | 34 | 11 |
| 124 | g $x^2$ | 32 | 54 |
| 125 | + | | 61 |
| 126 | f$\sqrt{x}$ | 31 | 54 |
| 127 | RCL A | 34 | 11 |
| 128 | + | | 61 |
| 129 | RCL 8 | 34 | 08 |
| 130 | g $x^2$ | 32 | 54 |
| 131 | X | | 71 |
| 132 | ÷ | | 81 |
| 133 | RCL 5 | 34 | 05 |
| 134 | + | | 61 |
| 135 | RCL 9 | 34 | 09 |
| 136 | X | | 71 |
| 137 | h RTN | 35 | 22 |

Exhibit 7.2-7

INSTRUCTIONS FOR USE OF THE HP-67 PROGRAM
FOR CALCULATING LOSS-OF-LOAD PROBABILITY

1. Key the input data into the following registers:

| | | |
|---|---|---|
| I | REG 0 | (Value from Exhibit 10.1-1) |
| S | REG 1 | " |
| $I_D$ | REG 2 | (Value dependent upon application) |
| C | REG | " |

2. Depress R/S. The program will calculate $Z_1$ and stop with $Z_1$ in the X-register. Input the value of $Y_1$ corresponding to $Z_1$ from the graph in Exhibit 7.2-2. Press R/S to re-start the program. If the program encounters a value of Z less than 2, it will stop with 2.00 in the X-Register. Press h x y to display the value of Z. Input the Y value from Exhibit 7.2-2 into the X-register. Press R/S to re-start the program. (Note: Values of Z less than 2 may indicate a high loss of load probability).

3. The program will pause and display the contents of register 5 (the running sum of Y) after each day.

4. The program will halt with the loss of load probability displayed in the X-register.



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## Exhibit 7.2-8

## TYPICAL CASES FOR THE LOSS-OF-LOAD PROBABILITY

| $S/\bar{I}$ | $I_D/\bar{I}$ | Storage Capacity, C (days) 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 0.5 | 1.2-1 | 4.5-2 | 1.8-2 | 7.1-3 | 3.2-3 | 1.2-3 | 5.2-4 | 2.2-4 | 9.6-5 | 4.2-5 |
| 1.0 | 0.4 | 6.8-2 | 2.6-2 | 1.0-2 | 4.2-3 | 1.8-3 | 7.7-4 | 3.4-4 | 1.5-4 | 6.8-5 | 3.1-5 |
| 0.8 | 0.5 | 5.3-2 | 1.2-2 | 2.9-3 | 7.4-4 | 2.0-4 | 5.3-5 | 1.4-5 | 4.1-6 | 1.2-6 | 3.1-7 |
| 0.8 | 0.4 | 3.0-2 | 6.8-3 | 1.7-3 | 4.6-4 | 1.3-4 | 3.7-5 | 4.1-2 | 3.2-6 | 9.8-7 | 2.9-7 |
| 0.7 | 0.8 | 4.1-2 | 1.4-2 | 2.5-2 | 1.4-2 | 4.2-3 | 1.4-3 | 4.5-4 | 1.5-4 | | |
| 0.7 | 0.7 | 1.4-1 | 3.0-2 | 6.5-3 | 1.4-3 | 3.3-4 | 7.8-5 | 1.9-5 | 4.8-6 | 1.0-6 | 2.7-7 |
| 0.7 | 0.6 | 5.6-2 | 9.5-3 | 1.6-3 | 3.0-4 | 5.8-5 | 1.2-5 | 2.4-6 | 4.3-7 | 9.5-8 | 2.0-8 |
| 0.6 | 0.8 | | | | | | | | | | |
| 0.6 | 0.7 | 6.5-2 | 7.8-3 | 1.0-3 | 1.3-4 | 1.9-5 | 3.0-6 | 4.0-7 | 6.6-8 | 1.1-8 | 1.8-9 |
| 0.6 | 0.6 | 2.2-2 | 2.0-3 | 2.0-4 | 2.1-5 | 2.5-6 | 2.5-7 | 3.2-8 | 4.0-9 | | |
| 0.4 | 0.9 | 3.7-1 | 4.8-2 | 6.6-3 | 9.5-4 | 1.4-4 | 2.4-5 | 3.3-6 | 5.8-7 | 1.0-7 | 1.8-8 |
| 0.4 | 0.85 | 7.0-2 | 4.0-3 | 2.6-4 | 1.9-5 | 1.2-6 | 1.1-7 | 9.1-9 | | | |
| 0.3 | 0.9 | 4.7-2 | 1.4-3 | 1.4-3 | 4.7-5 | 1.6-6 | 7.3-8 | 3.4-9 | | | |
| 0.3 | 0.85 | 3.9-3 | 3.0-5 | 2.6-7 | 3.2-9 | | | | | | |
| 0.3 | 0.8 | 4.8-4 | 1.1-6 | 3.8-9 | | | | | | | |
| 0.3 | 0.7 | 1.7-5 | 6.6-7 | | | | | | | | |

Notes:

1. Read LOLP entries such as 7.2-3 as $7.2 * 10^{-3} = 0.0072 = 0.72\%$
2. The vertical lines in the table separate those cases for which the LOLP $\geqslant 0.01$ to the left from those for which LOLP $< 0.01$
3. Based on the curve fit (All Z)

$$Y = \mathrm{Exp}\,(-Z^2/2) * (1 + 0.083 * Z) / (\sqrt{2\pi} * Z + 2)$$

4. The results depend only on $S/\bar{I}$, $I_D/\bar{I}$ and C



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When evaluating several designs which involve different array sizes, and different battery capacities, but which have a constant LOLP level, the methods of life cycle cost determination discussed in Sections 6.3 and 6.4.2 should be used again to determine the optimum design which has minimum life cycle costs. Other evaluations might be performed holding the array size constant and varying storage capacity and reliability levels. The life-cycle cost differentials can then be used to evaluate the worth of any improvement in power system reliability.

## 7.3 CODES AND STANDARDS

The PV power system should conform to all of the appropriate regulations in the building industry. Nationally recognized regulations known as codes are the laws which have been developed to protect the health, safety, and welfare of the general public. Standards, manuals, and approved equipment listings have been developed to support these codes. The following subsections will discuss the codes, standards, and related documentation applicable to photovoltaic power systems, and requirements the designer should include in the overall PVPS design.

### 7.3.1 Codes

As of the writing of this handbook, there are no existing applicable electrical or building code categories into which photovoltaic modules, panels, arrays, or support equipment can be conveniently placed. Until specific codes governing PVPS components are developed, code officials will rely on existing code catageories which can be interpreted as applying to photovoltaic systems. The lack of nationally recognized codes governing photovoltaics will most likely cause problems for both designers and installers in areas where building code officials are resistant to innovative products. The only areas regarding photovoltaic systems which are addressed in the codes relate to the use of storage batteries and their special wiring/interconnections procedures. These areas are covered in the National Electric Code (NEC).

The NEC is one code which is almost universally accepted throughout the country and has been recognized by all major model codes to insure the safety of persons and property using electricity. It is expected that compliance with the NEC will be an outstanding requirement for the design installation, operation, and maintenance of PV power systems. The NEC should be fully reviewed during the system design phase.

An example of how the NEC applies directly to the installation of PV power systems is as follows: The NEC (Article 110-17(a)) requires that live parts operating at 50 volts or more shall be guarded against accidental contact during installation. This code places special requirements on the installation of photovoltaic panels, since daylight will cause these panels to become active electric generators. These types of general electrical codes can be applied to photovoltaics for wiring sizes, current ratings, grounding requirements, ground fault requirements, lightning protection, insolation of live electrical parts, and power conditioning equipment.

### 7.3.2 Standards

Standards are written to support the codes and provide ways through which the code requirements can be satisfied. There are four generic types of standards: (1) specifications, (2) test methods, (3) classifications, and (4) recommended practices.

The system design engineer should be aware that standards pertaining directly to photovoltaic power systems do not exist. The Solar Energy Research Institute (SERI) is developing documentation on performance criteria and test methods for photovoltaic systems. These documents should be available in the near future. Until such standards are available, existing general standards can be interpreted to include PV power systems.

The Federal Occupational Safety and Health Act (OSHA) of 1970 authorizes the issuance of National Health and Safety Standards for work places. This includes PV power system construction sites, and it is the responsibility of the contractor or builder to insure the health and safety of his employees. The designer of the PV power system should also be aware of OSHA requirements, for these requirements can affect system installation costs considerably.



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### 7.3.3 Manuals

Accepted practice manuals are used in industry to interpret codes and standards, as well as to allow the installer to realize the intent or purpose for specific design decisions represented on system design drawings. Accepted practice manuals are written by the building industry to describe proven procedures or techniques which are most often used, and they change rapidly as a new technology develops.

As with codes and standards, accepted practice manuals written specifically for photovoltaic power systems do not exist due to the limited use of PV power system in industry. It is advisable, therefore, that manufacturers of the PV power system's components develop their own installation, maintenance, and operation manuals which shall comply with all existing codes and standards.

The building industry has been using components which display similarities to components utilized in PV power systems. For example, there are manuals of accepted practice for the installation of wiring systems that directly relate to wiring practices utilized in PV power systems.

### 7.3.4 Approved Equipment Listings

One way to accelerate code approval is for PV power system components to be tested (or listed) by a qualified testing laboratory, such as Underwriters Laboratories, Inc. (UL). Codes like the NEC generally allow the installation of equipment bearing the label of such a nationally recognized testing facility. Most code officials feel that there is little question as to the risk involved in allowing a new and innovative piece of equipment bearing laboratory approval labels to be installed in a construction site under their jurisdiction. If unlisted components must be used, the designer should be prepared to obtain a variance to the code. This process can be very time-consuming and costly.

### 7.3.5 Notes

Most local jurisdictions have adopted nationally recognized codes and standards and are enforcing them at the local level.

Any local building official has the authority to allow or disallow any product or process if he feels that compliance with established codes and standards is not met.

It may be found that, in some instances, the planned installation of a PV power system is inhibited by local officials who are not well versed or willing to make affirmative decisions about this new technology. With this fact in mind, it is important to have a good working knowledge of photovoltaics. The system design engineer should also have the ability to convey the necessary concepts about this technology to the local code officials.

### 7.3.6 Applicable Document List

Engineers, manufacturers and installers of photovoltaic power systems should be aware of all documentation applicable for designing, manufacturing and installing of PV power systems. Appendix C contains a listing of appropriate codes and standards and the addresses of the sponsoring agencies.

## SECTION 8
## INSTALLATION, OPERATION AND MAINTENANCE

### 8.1 INTRODUCTION

PV power systems are inherently capable of unattended operation, require only a minimum of scheduled maintenance, and only rarely require unscheduled corrective maintenance. The accessibility of the PV system site to operations and maintenance personnel and the reliability, maintainability, and availability of the power provided to the load have significant impact upon the PV system design. This section sets forth the basic operation and maintenance design considerations and tradeoffs to be considered during detailed design.

### 8.2 POWER OUTAGES

The principal operational requirement is the number and duration of power outages that the load can tolerate. Exhibit 8.2-1 lists the primary causes of power losses.

Exhibit 8.2-1 Causes of Power Loss in PV Systems

| | |
|---|---|
| Natural Causes: | Consecutive cloudy days |
| | Environmental effects: |
| | Cold weather on batteries |
| | Lightning |
| System Design: | Less insolation than expected |
| | More load than designed for |
| | Scheduled maintenance shutdown |
| Equipment Malfunctions: | Array fault, or open circuit |
| | Optical degradation |
| | Electrical/electronic failure in power |
| | Conditioning and distribution equipment |
| | Batteries |

## 8.3 RELIABILITY AND MAINTAINABILITY

Since power outages, with the exception of scheduled maintenance shutdown periods, are expected to occur randomly, the preferred method of establishing operational performance requirements on power outages is to use a statistical approach. The following parameters are recommended:

Reliability -- the probability of operating "x" days without loss of power

Maintainability -- the probability that system power will be restored within "y" hours

For example, emergency loads may be required continuously. While it is impractical to build a system that can assure no outages, a requirement of a 0.99 probability of no outages in a month could be specified. Such a stiff requirement would require consideration of back-up, non-solar systems sized to handle the critical load during natural-caused outages, an auxiliary power unit to handle the load during scheduled maintenance, significant over-capacity of the energy storage coupled with load-shedding (shut-off of convenience and even essential loads) to account for less insolation than anticipated, and a redundant fail-safe design. A 0.01 probability of outages in a month can be interpreted that, on the average, a power outage will occur once every 100 months (or every 8.3 years). However, that outage can occur at any time during the 100-month period.

For essential loads, a more realistic requirement may be a 0.10 probability of an outage in a month; that is, an outage, on the average, once every 10 months.

The second parameter of operational interest is the down time following a power outage. Components of down time are:

- Delay time in reporting power outage occurrence
- Time for operation or maintenance personnel to arrive at site
- Time to restore power, either by bringing a back-up source on line, or repairing malfunction at the site
- In the case of malfunction, time to acquire spare or repair parts and materials required to effect repair

There is generally little difference in the down time limits following a power outage among the load categories. With critical power losses being very infrequent, down time requirements are based on essential loads. For example, a down time requirement for essential loads for sites in the proximity of qualified maintenance personnel would be stated as a 95% probability that system power would be restored within 4 hours. For a remote site, the time requirement would have to be extended to permit notification and travel time.

## 8.4 OPERATION AND MAINTENANCE TRADEOFFS

Operation and maintenance procedures to be implemented at each site will have a significant impact on the system design. These procedures must be included in the system design tradeoff analyses involving array sizing, battery capacity, redundant features, the degree of automatic controls, and automatic monitoring and telemetry. Major operation and maintenance factors to be considered in the design tradeoff analyses are discussed in the following paragraphs.

### 8.4.1 Operation and Preventive Maintenance

Stand-alone PV power systems do not require an on-duty operator under normal conditions of system utilization. The routine functions of an "operator" consist of inspection and preventive maintenance. Typical tasks include:

(1) Inspection Tasks:

- Site physical security — fencing intact, breach of security alarm test
- Array shading — by debris, vegetation
- Array cleanliness -- dust, bird droppings
- Cabling — damage by elements or rodents
- Grounding paths -- loose connections, corrosion
- Battery terminals -- corrosion



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- Batteries -- electrolyte leakage and corrosion of support structure
- Control equipment -- cleanliness; accumulation of dirt, bird nests, rodent damage
- Fuel/oil/water -- at or above specified storage levels for backup systems

(2) Preventive Maintenance Tasks:

- Clean array surface
- Clean battery terminals and tighten connections
- Check and refill electrolytic solution
- Read and record all metered points
- Perform operability tests to assure that all automatic switching and monitoring is functional and that standby backup and emergency generator units will start and operate
- Lubrication
- Restock stored fuel
- Record all discrepancies observed by inspection and in performing preventive maintenance

In general, the PV systems should require inspection and preventive maintenance only on a scheduled periodic basis (e.g., 30 days, 60 days, 90 days, 6 months, etc.), consistent with known system degradation rate due to dust accumulation, etc. However, backup systems of the engine/generator type should be started and run for at least one hour on a weekly basis.

Site visits by operational and preventive maintenance personnel are primarily for the purpose of fault detection, exercise of switching/controls, exercise of backup systems, and observation of abnormal deterioration conditions. All of these functions (except abnormal deterioration detection) can be performed automatically and the results monitored remotely via telemetry -- either by radio or land line. Thus the tradeoff over the life of the installation is the cost of automation and remote monitoring versus the cost of having a human perform site visits (note: as a safety precaution, site operation and preventive maintenance should be performed by a two-man team). Included in the human costs are the costs of training, transportation, site access maintenance, and the method of communication with repair facilities.

### 8.4.2 Corrective Maintenance

Maintenance is divided into preventive and corrective categories to permit separation of skill levels and training in the design tradeoff analyses. Whereas preventive maintenance of the entire site can be performed by one trained individual, corrective maintenance involves several different skills, including electrical, electronics, engine mechanics, and at times, construction training. Corrective maintenance also requires spare parts, test equipment, and documentation.

PV systems can be designed to permit scheduling of corrective maintenance by designing in a tolerance to faults -- that is, a design which is not sensitive to individual faults, thus permitting accumulation of faults between scheduled corrective maintenance site visits. The other end of the design spectrum is a system without fault tolerance -- corrected prior to reconnecting the load.

Establishing the design to corrective maintenance tradeoff requires consideration of the following:

- Frequency of site visits.
- Delay time when a system drops the load until unscheduled corrective maintenance can be performed, assuming full availability of personnel, test equipment, and spare parts.

Both the frequency of power outages and the maximum downtime requirement when an outage occurs are affected by corrective maintenance tradeoffs. If the maximum downtime limits are less than the delay time required to travel to the site, then only two alternatives are available:

(1) To design a system that is fault tolerant and capable of repair without dropping the load; i. e., mechanisms must be built in for isolating the fault and de-energizing the faulty item while leaving the remainder of the system operational.

This alternative will have the practical effect of eliminating downtime periods, thus increasing the probability of operating between scheduled corrective maintenance visits to nearly unity.

If this alternative is chosen, an additonal trade off should be performed--whether to design the system:

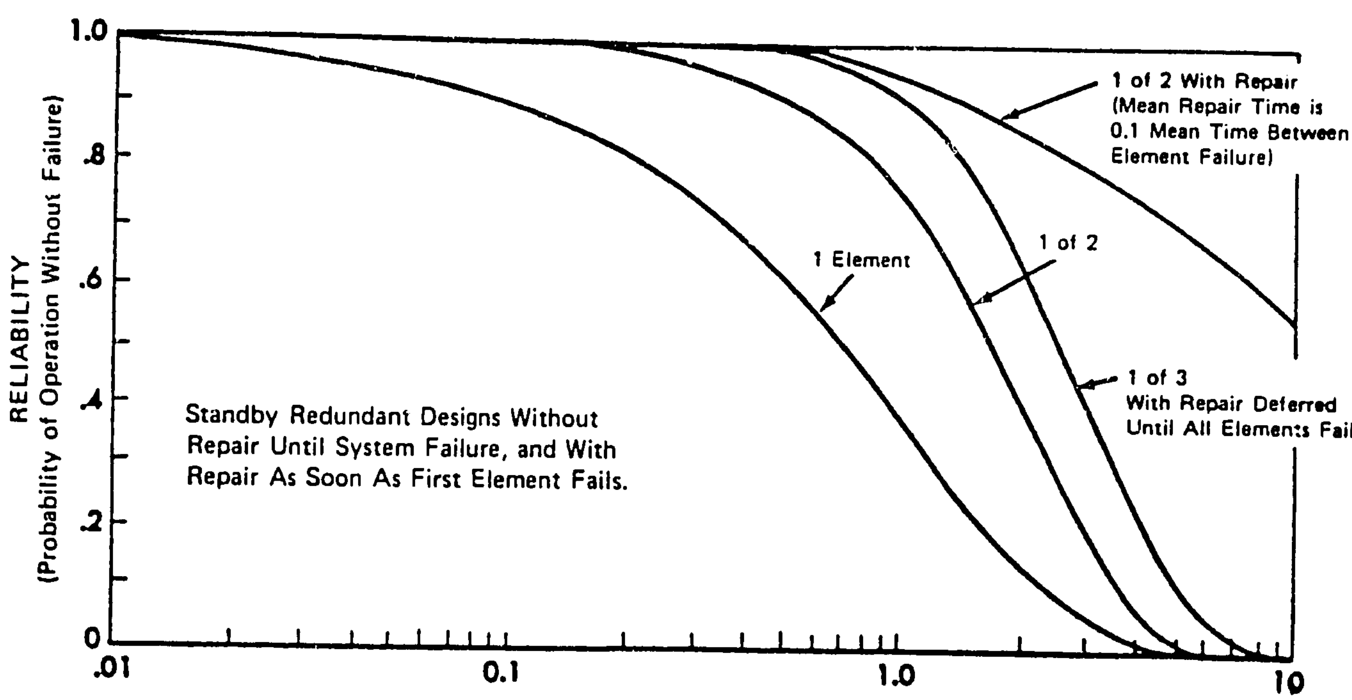
(a) With sufficient redundancy to permit deferral of maintenance until the next scheduled corrective maintenance visit; or

(b) With only sufficient redundancy to ensure system operation until a repair crew can be dispatched to the site to accomplish the corrective maintenance. This case must include: the cost of more detailed fault detection and telemetry to tell the crew prior to dispatch what has failed; the cost of maintaining a ready repair crew; and the additonal transportation and personnel-related costs of an expected larger number of unscheduled site trips rather than a predefined number of scheduled site trips. (Note: Since failures occur randomly, there is always a finite probability of having power outages between scheduled vists. This probability is a function of the fault-tolerance margin designed into the system).

(2) To design a system without fault tolerance, and to provide trained repair personnel capable of immediate reaction at or near the site, this alternative also requires adequate logistic (spare parts) support at the site. In this alternative, the system design needs only to meet the reliability requirement.

Exhibit 8.4-1 illustrates the design tradeoff advantages of initiating repair as soon as a fault occurs versus having redundant hardware to maintain a high probability of no power outage between scheduled corrective maintenance periods. The reliability functions shown in the figure are plotted as a function of system operating time ($t_o$) "normalized" to individual equipment MTBF (i.e., $t' = t_o$/MTFB). The figure depicts the case of standby redundancy; that is, the redundant element does not operate until the "ON" element has failed, the failure is sensed, and the standby element is activated. The apparent advantages of the type of redundancy can be significantly reduced if similar design consideration is not given to the failure-sensing and switching circuitry which should also be redundant, or if not, its reliability should exceed that of the sensed element by at least 10-to-1.

For small, simple systems, the most promising tradeoff against too much additonal equipment is to combine scheduled corrective maintenance with the periodic inspection and preventive maintenance site visits plus an infrequent unscheduled corrective maintenance.




Normalized System Operation Time,
t' = System Operating Time/Equipment MTBF

Exhibit 8.4-1
RELIABILITY IMPROVEMENT WITH STANDBY REDUNDANCY

## 8.5 SYSTEM MAINTENANCE

Section 8.4 identified the major tradeoffs associated with the scheduling of maintenance and identified a major component of downtime as the time from fault occurrence until arrival of the maintenance team at the site. This discussion covers the design for hands-on maintenance once the team arrives at the site.

### 8.5.1 Maintenance Concept

Maintenance planning begins with establishment of the concept to be followed; this should be done prior to detailed equipment design or site layout. Decisions required in establishing the maintenance concept include:

(1) Personnel Skill Level -- based on experience and training provisions. If skilled personnel are to be used, fault isolation can be accomplished using portable test equipment and technician interpretation of results; repair then can be accomplished at lower levels of complexity, such as part replacement on an electronic assembly instead of removal and replacement of the assembly.

(2) Level of Repair. The level of on-site repair can vary from removal and replacement of whole equipments or array panels to the replacement of parts or modules. In the case of fossil-fueled backup engine generators, this can vary from complete replacement and remote repair to on-site overhaul. The level of repair selected for the site is a function of skill of personnel, ease of handling and transporting replacement parts, and test equipment required for fault isolation. The level of repair (e. g., remove and replace level) and the built-in means for fault isolation must be compatible, whether the fault-isolation procedures consist of accessible test points or built-in automatic fault localization.

(3) On-Line Repair. This term means preventive or corrective maintenance at the site without load interruption. If the critical or essential loads cannot



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be "down" during scheduled maintenance periods, then the design must be such that portions of the system can be removed from on-line status while the remainder carry the load, or auxiliary power-generating units must be brought to the site to provide a power source while the PV system is undergoing maintenance.

(4) Faulty Item Disposition. The level of remove-and-replace is influenced by whether the replaced faulty item should be discarded or returned to a centralized repair facility (such as the original vendor) for more detailed trouble-shooting, repair, retest, and return to stock. This in turn affects the cost of stocking site spares, whether stored at the site or at the corrective maintenance facility.

The result of the maintenance concept is to provide design requirements on the location of fault isolation test points, the amount of automatic fault isolation to be built in, and the mechanical fasteners and electrical connections for ease of removal and replacement.

### 8.5.2 Maintainability Design

Maintainability, expressed as the mean time to repair (MTTR) a fault in the system, given a properly trained personnel, authorized test equipment and documentation, and the required replacement parts, is a quantitative parameter often specified to drive the physical and mechanical design of the system. Generally, MTTR should be in the range of 1.5 to 3 hours for a typical PV system. Design considerations for achieving MRRT include:

(1) Fault Isolation. This term was covered under "Maintenance Concept", in 8.5.1 above. If fault isolation is automatic, then the time required is negligible. If fault isolation is manual (i. e., using test points and portable test equipment), it may require up to 15% of the specified MRRT.

(2) Accessibility. The physical layout and packaging design for the system must assure that the equipment is accessible for each planned maintenance task and that sufficient space exists for the task to be accomplished safely. (safety involves first the safety of the maintenance personnel, and second the protection of the equipment against damage in the repair process). Accessibility involves ease

of opening or unfastening covers and doors, not locating replaceable items under other items or beyond arms reach, and providing handles or places to grip items for removal. Where solar arrays are elevated or battery storage is on elevated racks, means must be provided for accessibility by built-in catwalks, ladders, and places to setup and lay tools, or by defined portable devices such as ladders.

(3) Weight of Replacement Items. The size and weight of replacement items must be compatible with accessibility at the site and transportability to and from the site. In general, the maximum weight of a replaceable item to be handled by one person without mechanical lifting devices is 40 pounds. If the replacement area is elevated and requires ladders or various walkways, the replacement item should also be equipped with a means for carrying it with one hand (the other being used to maintain safe balance). Where two people are used or mechanical lifting and handling devices can be taken to or left at the site, the size and weight of replacement items may be increased.

(4) Maintenance Safety. The means of access to site equipment for maintenance must comply with OSHA requirements for physical safety of maintenance personnel. This includes built-in steps, walkways, and ladders. The equipment design must provide protection against inadvertent electrical, thermal, or chemical contact with maintenance personnel. Where on-line maintenance is contemplated, positive means for assuring electrical disconnections are required. System grounding must not be compromised during maintenance.

(5) Standardization. Standardization of parts, wire, connectors, sizes of nuts and bolts, and modules is an essential discipline for ease in maintenance. It reduces training, tools, and spare item inventories.

(6) Replacement Availability Warrants. Parts, modules, and assemblies used in the PV design should carry with them a replacement availability warranty which warrants that during the 20-year life of the system, replacements will be available for purchase which provide workable and consistent (not necessarily identical) form (having the same connections and attachment points), fit (capable

of fitting in the same space), and function (performs the same function and is compatible with the other items in the system). Where such warranty is not available, the design should be sufficiently simple and spacious to permit substitutes or local fabrication of replacements.

(7) Test and Checkout. Maintenance actions are not complete until the repaired system has been tested and the effectiveness of the repair has been verified. This may be accomplished automatically by built-in fault-sensing circuitry, or it may require special provisions such as a light source to verify that a replaced circuit breaker will trip on overload.

(8) Maintenance Data. An often neglected part of maintenance is documentation of the maintenance action so the owner and designer may feed back this experience into either new designs or upgrading of the existing system.

## 8.6 LOGISTICS DESIGN

The system design engineer is responsible for planning logistic elements for the operating life of the PV system, as described in the following paragraphs.

### 8.6.1 Supply Support

This logistic element has a potentially greater impact on reliability and maintenance than does the basic equipment design or maintenance transit and repair times. The lack of a spare part defeats designed-in redundancy, contributing to more power outages; once power outage occurs, the lack of a spare can keep the system down until one is obtained. The supply support planning cycle requires the following steps:

(1) Prepare a site spares list. This is a list of all items designated for removal and replacement at the site; it includes:

- Identification in an unambiguous manner and in sufficient detail to permit reordering by the identification.
- Source where replacements can be obtained.
- Statement as to whether the item should be scrapped or returned for off-site repair.

- The importance of the item to power outage for critical loads and essential loads. The importance is assessed for two levels: Major, failure of the item will cause the system to drop load: Minor, failure of the item will not cause the system to drop load although it may induce some degradation.

- The expected number of removals of the item at the site during a 12-month period.

(2) Determine recommended quantity of initial spares to be purchased and delivered with the system. The simplest method[1] is to consider each part individually on the list of Step (1), planning to provide an x% probability of having the required spares on hand throughout a one-year period or a spares procurement or repair cycle if that exceeds one year. The following tabulation provides a guide for typical x-values:

| Failure Impact | Load: Critical | Essential | Convenience |
|---|---|---|---|
| Major | 0.999 | 0.99 | 0.90 |
| Minor | 0.99 | 0.95 | 0.90 |
| Other | 0.90 | 0.90 | 0.90 |

Following is the basic formula for determining the quantity of spares:

$$\text{Prob} = \sum_{x=0}^{x=?} \frac{e^{-m} m^x}{x!}$$

Where: m = number of expected failures in 1 year, and

x = number of spares

**Examples:** GOAL is Prob = 0.99 for essential load and major failure impact

(1) m = 0.5 failures in 1 year

Prob = 0.9856 with x = 2 spares
Prob = 0.9982 with x = 3 spares

To exceed goal (Prob = 0.99) retain 3 spares

(2) m = 1.5 failures in 1 year

Prob = 0.9814 with x = 4 spares
Prob = 0.9955 with x = 5 spares

To exceed goal (Prob = 0.99) retain 5 spares

[1] More sophisticated cost optimization and system-protection level models can be developed for determining spares sets, but are beyond the scope of this handbook.



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(3) Prepare a list of consumables. This would include distilled water for batteries, array face washing compound, terminal grease, paint, fuel and lubricants for backup systems, etc. The list must clearly identify the consumable product and the estimated quantity required at each preventive maintenance period.

(4) Prepare list of common and bulk items. This is a list of screws, nuts, bolts, washers, spacers, gasket material, fasteners, and other items commonly used in maintaining the equipment; include items which can be locally purchased or fabricated at local hardware-equivalent outlets and need not be provided with the system.

(5) Prepare list of off-site repair parts. This is an optional step, depending on where and by whom off-site repair will be performed. If it is to be accomplished by facilities not specializing in the specific site equipment, a complete list of repair parts containing the same information supplied in Step (1) should be prepared.

### 8.6.2 Power System Drawings

At least two complete sets of equipment drawings, site structural drawings, and site installation drawings should be delivered to the PV system owner, one for permanent records and the other for use in corrective maintenance that requires more knowledge than is available in the operation and maintenance manuals. These drawings may be in contractor format, with completeness and legibility the overriding criteria.

### 8.6.3 Tools, Test Equipment, and Maintenance Aids

Planning for this element of logistics involves preparing a list of all the tools, test equipment, and maintenance aids, such as step ladders, array covers, etc., that are required for site inspection, preventive maintenance, and on-site corrective maintenance. The list should show which items are required for inspection and preventive maintenance and which are for corrective maintenance. Special tools, test equipment, and maintenance aids are those not readily available over the counter locally; these should be clearly identified and provided to the owner as part of the system equipment included with the system.

### 8.6.4 Technical Manuals

At least three manuals are required and should be prepared under cognizance of the system design engineer by personnel capable of writing clearly for the level of education and background of the user, and the user's language if necessary:

(1) Operation Manual. This manual provides an overview of what the system is, how it works (theory of operation), and how the major equipment groups, including backup systems, are interrelated to provide the power output. The manual must define the system-to-load interface and should discuss the impact on system performance of changing the load after installation. The Operation Manual must define the duties and responsibilities of the operator (inspection and preventive maintenance), and the duties of corrective maintenance personnel. It must also include safety warnings, notices, and emergency treatment for accidents such as chemical burns.

(2) Inspection and Preventive Maintenance Manual. This manual must contain a procedure for each inspection and preventive maintenance task, detailing step-by-step the action to be taken and observation made. The procedure must also tell the operator what to do when anomalies are detected. The manual must present the schedule for each task (weekly, monthly, or semi-annually), and repeat safety information.

(3) Corrective Maintenance Manual. This manual must contain the information needed to accomplish corrective maintenance to the level established by the maintenance concept. It must cover fault detection, fault isolation, remove-and-replace instructions, and -- most important -- verification testing to ensure that the repair was effective. Again, safety information must be included.

All three manuals may have individual sections covering different equipment in the design, such as solar array, batteries, and backup systems. This is acceptable provided introductory material puts each in perspective with respect to the total system.

8.6.5 Training

This logistic element ties all the preceding elements together into the total logistic support package. The planning for training consists of:

(1) Preparation of instructors' guide for teaching courses for both operators and corrective maintenance personnel.

(2) Determining the length of courses and the percent of hands-on training versus classroom discussions.

(3) Providing an initial training course concurrent with site installation.

The operation and maintenance manuals discussed under 8.6.4 provide the basic course text material for the students.

## 8.7 INSTALLATION DESIGN CONSIDERATIONS

This discussion is written from the operation and maintenance point of view, addressing those concerns most often leading to excessive maintenance problems.

### 8.7.1 Physical Considerations

The following physical considerations in site layout should be adequately addressed:

- Local ground cover and vegetation growth that could arise and cause unplanned array shading.
- Location of buildings and security fences that act as snow fences and actually contribute to snowdrifts in the vicinity of arrays.
- Location of buildings and security fences that act as snow fences may provide bird perches and thus contribute to fouling of the array face.
- Personnel safety, to protect personnel from accidentally coming in contact with high voltage, thermally hot arrays, or dangerous chemicals.

8.7.2 Equipment Housing and Structure Considerations

The equipment housing and structure should be designed to prevent the following problems:

- Array edges being used as bird perches, thus inducing extreme fouling of the array face.
- Rough edges, grooves, or protusions that will catch, hold, and permit build-up of airborne debris on the array faces.
- Junction boxes and cable runs which allow entry of rodents which in turn might gnaw on insulation.
- Cable insulation and coverings which provide rodent food.
- Protective structures and buildings that provide sites for bird nests and their droppings on electronic equipment.

8.7.3 Installation Checkout and Acceptance Testing

The system design engineer and owner must agree on the means of determining structural and physical compliance with drawings and specification and for performance acceptance tests of the system. Conformance to structural and physical requirements can be determined by the owner or his representative. Conformance to performance requirements requires the development of detailed test procedures and acceptable tolerances of measured parameters; these test procedures must be documented prior to the start of site installation.

# SECTION 9
# SITE SAFETY

The personnel safety design requirements for both the general public and installation, maintenance, and operating personnel, and the site safety design requirements for the facility while in operation and undergoing maintenance, shall be in accordance with applicable local codes and nationally-recognized standards. Lead-acid storage battery safety is covered separately in Section 4.3.6.

The design safety checklists, described in the following paragraphs, are divided into two areas: (1) personnel and (2) facility. These should be treated with equal importance. Portions of these will be repeated. Various items within these checklists are not covered under any local or nationally recognized codes or standards, but should be considered to increase the overall safety of the PVPS facility and personnel.

## 9.1 PERSONNEL SAFETY CHECKLIST

### 9.1.1 Safety & Health Standards

The PV modules, arrays, wiring, power distribution, power conditioning, batteries, and structures (PVPS) shall comply with the Occupational Safety & Health Administration (OSHA) Standards. OSHA standards apply primarily to the on-site construction and installation procedures of the above equipments. The manufacturers of these equipments must adhere to the OSHA standards in their design of these equipments.

Electrical materials, equipments, and their installation shall be in accordance with applicable local and nationally recognized codes and standards. Such codes shall include, but not be limited to, the National Electric Code (NFPA 70-1981), American National Standards Institute (ANSI nos. A. 58.11-1972 and Z 97.1-1975), Building Official & Code Administrators International (BOCA), and others: i. e., NEMA and UL. Electrical components shall be listed and/or approved by a nationally recognized testing laboratory. (See Appendix B for a listing of codes and standards).



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### 9.1.2 Electric Shock

The PVPS equipments and structures described in Section 9.1.1 shall be designed to prevent shock hazard during installation, normal operation, and during maintenance procedures. The life-safety hazards, which could occur as a result of a failure of any of the above equipment, shall not be greater than those imposed by conventional electrical systems. The above equipments shall be grounded in accordance with the National Electrical Code (NEC) Sections 250-72 and 250-92. These equipments shall also be designed to comply with all existing OSHA standards for installation, operation, and maintenance protection of the workers. These equipments should also be isolated from casual contact, as well as being adequately insulated, to reduce the possibility of electrical shock as a result of system anomalies.

### 9.1.3 Toxic & Flammable Materials

The materials used in the PVPS, as described in Section 9.1.1, shall not expose the installing, operating, or maintenance personnel to hazards related to toxicity or flammability. The PV system shall be designed to utilize materials which in the presence of fire do not endanger the installing, operating, or maintenance personnel with excessive levels of smoke or toxic fumes in accordance with nationally recognized codes such as NFPA 251-1972, ASTM E119, ASTM E84, and UL 263.

### 9.1.4 Fire Safety

The design, installation, operation, and maintenance of the PVPS shall provide a level of fire safety that is consistent with applicable codes and standards including, but not limited to, NFPA 256-1976 and the NEC (NFPA 70-1981). Some factors which shall be considered in assessing potential fire hazard are: potential heat, rate of heat release, smoke generation, firestopping, and ease of ignition.

The protection against auto-ignition of combustible solids used in the PVPS, especially in the PV modules, should be addressed. Combustible solids, such as plastics, shall not be exposed to elevated temperatures which may cause ignition. Exposure of these materials over an extended period of time may result in the materials reaching, and possibly surpassing, their auto-ignition temperatures.

The PVPS site shall have on-hand emergency fire extinguishing apparatus in accordance with all local fire protection ordinances.

### 9.1.5 Excessive Surface Temperatures

The PVPS shall not create a hazard to installation, operation, or maintenance personnel due to excessive exterior surface temperatures. Any component that is located in areas normally subjected to personnel or general public traffic, and which is maintained at elevated temperatures in excess of $140^{o}$ F or $60^{o}$ C, shall be isolated from casual contact with proper clearances or passageways. Any surface where isolation is impossible shall be identified with appropriate warnings.

### 9.1.6 Equipment Identification Labeling

All PVPS components should be identified as to: their function; their voltage, current, power, and temperature warnings; corrosive or toxic properties; and procedures for handling accidental contact and natural or man-made occurrences (flooding, structural damage, foreign objects); and a list of authorities and their telephone numbers to contact if such occurrences should take place.

### 9.1.7 Physical Barriers

The PVPS shall be totally enclosed by a seven-foot (minimum) barbed-wire-top security fence approximately 30 feet from any part of the array. This barrier shall be erected before construction begins, and shall remain in place throughout the PVPS life cycle and until the PVPS is totally dismantled. Warning signs shall be displayed in plain view of the general public stating the danger of active high voltage within the fenced area (in the language of the area).

Local codes should be investigated for the appropriate distance a PVPS shall be from any residential or commercial building and from public roads.

## 9.2 FACILITY SAFETY CHECKLIST

### 9.2.1 PVPS Safety Protection from Environmental Conditions

The PVPS safety requirements shall include protection from the possibility of power interruption, transients, and electrical faults caused by natural environmental conditions. The meteorological/environmental factors should be investigated for the particular site location. Historical meteorological information is available from the National Weather Service on a national or local level, such as:

- Average wind speed
- Annual rainfall and flooding data
- Average snow loads
- Annual number of days with hail
- Annual number of days with glaze (freezing rain)
- Annual number of thunderstorm days
- Seismic data

Some or all of these areas may affect the design and safety aspects of the PVPS.

Most of these areas are covered in the design consideration sections from a structural loads aspect in other works (Refs 4-5, 9-1). Due to the uniqueness of a PVPS, these areas must also be investigated from a safety aspect. The following are examples of questions that should be answered before site construction in order to increase the reliability and overall safety of the proposed PVPS site, and which may effect the system design itself:

- Is there a history of flooding or high snow accumulation in the proposed PVPS site location? If so, what are the effects of frequent flooding or high snow accumulation on the system and personnel (including the general public)? Has the design been modified to allow sufficient ground clearances for both array and battery-storage areas?

- Is the vegetation growth rate in the proposed PVPS site location high enough to become overgrown and create a shading condition if left unattended? Has the array design been modified to allow sufficient ground clearance to compensate for this potential problem?

- Is there a history of seismic activity in the proposed site location? If so, are the system's components adequately sized to withstand frequent seismic forces and remain safe?

- Is the annual number of thunderstorm days for the proposed site location high? Has the frequency of lightning strokes to earth in the proposed site location caused an unusual amount of damage to existing structures in the past? Are the array module covers plastic, which could increase the electrostatic potential between ground and air, and could induce the lightning hazard in areas of high ligtning incidence? If so, then lightning protection should definitely be a design consideration (Ref. 9-2). The NFPA Lightning Protection Code should be consulted for lightning protection procedures.

### 9.2.2 PVPS Safety Protection from Man-Made Conditions

The PVPS site design safety should include provisions for the protection from the possibility of power interruptions, transients, and electrical faulting created by man-made conditions.

The security fence described in Section 9.1.7 will protect the PVPS site from invasion of casual unauthorized personnel, but the temptation of vandalism is always present. Projectiles thrown or shot from any type of firearms at the photovoltaic arrays can cause enormous damage to the system.

Accidental penetration of the PVPS site by means of motorized vehicles (automobiles, tractors, etc.) is also possible. Although the site shall be isolated from public roads, as described in Section 9.1.7, an out-of-control vehicle can penetrate the security fence. A bunker-type knoll surrounding the fenced-in site can serve as both a way to hide the site from plain view and a way to create a double barrier.

### 9.2.3 PVPS Safety Protection from Component Failure

To prevent damage to the system from component failures, the system should be designed to eliminate excessive temperatures and reverse biasing which may occur as a result of shading or cell cracking. Examples of devices which automatically detect and isolate component failures are: high-speed fault-detection devices, fuses, circuit breakers (with adequate interrupting capacity), etc. These should be included in the detailed system design. These devices will also prevent system damage due to operator or maintenance personnel errors. This protection system should include automatic system shutdown circuitry, automatic system failure alarm, and/or telemetric failure alert system.

## 9.3 REFERENCES

An extensive list of codes and standards referenced in the section is presented in Appendix C and covers all aspects of the PVPS design, installation, operation, and maintenance.

# SECTION 10
# DESIGN EXAMPLES

## 10.1 REMOTE MULTIPLE-LOAD APPLICATION

### 10.1.1 Northern Hemisphere Location

A typical load profile for a remote village is presented in Exhibit 10.1-1, derived from data supplied by the NASA-Lewis Research Center on the Papago Indian Village of Schuchuli, Arizona (Reference 10-1). The actual installation allowed for load shedding and for tilting the collector four times per year ($3.5^{\circ}$ tilt in summer, $26^{\circ}$ in spring and fall, and $48^{\circ}$ in winter). To permit the direct use of the tables and charts presented in this report, a fixed array tilted at the latitude angle of $32.11^{\circ}$ will be considered. The methods of Section 11 could be used to compute the insolation at other tilt angles; the standard deviation of the insolation could be similarly calculated or could be estimated from Exhibit 6.1-1, based on having the same sigma ratio for any tilt. The load-shedding capability will also be ignored, although this would reduce the energy-storage requirements.

The design computations are presented in Exhibit 10.1-2 in the format of the quick-sizing procedure of Section 6.2.1. The $K_H$ values were obtained from NASA; the values are in reasonable agreement with the data of Tucson as reported by the National Weather Service (last column). The first computation of the collector area and storage capacity, for a one percent loss-of-load probability, is based on M = 0.33. Values of C were read from Exhibit 6.2-2. The array area required to meet the load is 45 square meters, as dictated by the August load. The storage capacity is 51 kWh, as determined by the August load. The collector area required for a one percent LOLP can be re-computed based on the storage capacity of 51 kWh. This capacity is converted to days of load (C') and the revised value of M (= M') is read from the battery storage chart (Exhibit 6.2-2). The collector area is computed from the formula in Note 3 of Exhibit 10.1-2. The required collector area is again 45 square meters, as determined by the August requirement.



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For the parameters chosen, the array size is 3.6 kW at 1.0 kW/m$^2$ of insolation. This figure compares favorably with the 3.5 kW actually installed. The 51 kWh battery capacity, however, represents the nominal capacity. Thus, when a depth of discharge of 50 percent and a round trip charging efficiency of 85 percent is assumed, the actual battery capacity would be 120 kWh. The difference between the installed 285 kWh battery and the calculated capacity can be attributed to the difference in LOLP calculated in the design example and that for the installed system.

### 10.1.2 Southern Hemisphere Location

The requirements for the Papago Indian Village can be applied in the Southern hemisphere as well. If we assume that the installation is at 32.11$^{o}$ South latitude and the tilt is again 32.11$^{o}$, all of the computations would be the same, although a $\pm$6 percent correction to the insolation should be made due to the seasonal variation in the earth-sun distance (Section 11). If the $K_H$ profile were the same, except with the January value for the Northern hemisphere being used in July in the Southern hemisphere and all other months shifted also by six months, the month-by-month computation would be identical. The only difference in Exhibit 10.1-2 would be the labeling in the "MONTH" column entry for July being used for the January entry in the Southern hemisphere.

Exhibit 10.1-1

MULTIPLE LOAD APPLICATION

MONTHLY LOAD SUMMARY

| Device | Load Ah/day | | | | | | |
|---|---|---|---|---|---|---|---|
| | Water Pumps 2 hp | Refrigerators 1/8 hp | Clothes Washer 1/4 hp | Sewing Machine 1/8 hp | Fluorescent Lights 20 W | Instruments | Total |
| Quantity | 1 | 15 | 1 | 1 | 44 | 1 lot | |
| Month | | | | | | | |
| January | 34.9 | 15.2 | 31.1 | 2.4 | 44.8 | 13.0 | 141.4 |
| February | 34.9 | 17.8 | 31.1 | 2.4 | 38.8 | 12.7 | 137.7 |
| March | 49.1 | 21.1 | 31.1 | 2.4 | 26.8 | 13.9 | 144.4 |
| April | 49.1 | 26.5 | 31.1 | 2.4 | 17.7 | 14.2 | 141.0 |
| May | 70.4 | 31.7 | 31.1 | 2.4 | 17.3 | 15.5 | 168.4 |
| June | 70.4 | 37.8 | 31.1 | 2.4 | 11.5 | 15.5 | 168.7 |
| July | 70.4 | 42.2 | 31.1 | 2.4 | 11.5 | 13.9 | 171.5 |
| August | 70.4 | 41.8 | 31.1 | 2.4 | 17.3 | 13.9 | 176.9 |
| September | 49.1 | 37.8 | 31.1 | 2.4 | 20.6 | 13.9 | 154.9 |
| October | 49.1 | 28.3 | 31.1 | 2.4 | 32.6 | 13.9 | 157.4 |
| November | 34.9 | 20.4 | 31.1 | 2.4 | 38.8 | 13.5 | 141.1 |
| December | 34.9 | 16.1 | 31.1 | 2.4 | 44.8 | 13.0 | 142.3 |

Exhibit 10.1-2

MULTIPLE LOAD APPLICATION EQUIPMENT SIZING

LOLP = 1 percent

Latitude = 32.11°N

Tilt = 32.11°N

| Month | Cleaness Factor $K_H$ | Average Insolation $I^{(1)}$ $\frac{kWH}{Day\text{-}m^2}$ | R - | Standard Deviation S $\frac{kWH}{Day\text{-}m^2}$ | Load (kWh/day) | Array Area $A^{(2)}$ $m^2$ | Storage Requirement C Days | Storage Requirement Q kWH | Revised Values Based on Q = 51 kWH C' Days | M' - | A' $m^2$ | $K_H^{(5)}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 0.667 | 5.48 | 0.278 | 1.53 | 17.0 | 43 | 2.6 | 44 | 3.0 | 0.29 | 42 | 0.633 |
| February | 0.667 | 5.98 | 0.264 | 1.58 | 16.5 | 38 | 2.4 | 40 | 3.1 | 0.28 | 37 | 0.665 |
| March | 0.737 | 7.17 | 0.153 | 1.10 | 17.3 | 32 | 1.1 | 19 | 2.9 | 0.23 | 31 | 0.692 |
| April | 0.758 | 7.51 | 0.115 | 0.87 | 16.9 | 29 | 1.1 | 19 | 3.0 | 0.17 | 29 | 0.744 |
| May | 0.768 | 7.47 | 0.095 | 0.71 | 20.2 | 35 | 1.0 | 20 | 2.5 | 0.16 | 34 | 0.765 |
| June | 0.711 | 6.81 | 0.154 | 1.05 | 20.2 | 39 | 1.3 | 26 | 2.5 | 0.21 | 38 | 0.755 |
| July | 0.647 | 6.24 | 0.229 | 1.43 | 20.6 | 45 | 2.3 | 47 | 2.5 | 0.25 | 44 | 0.658 |
| August | 0.651 | 6.34 | 0.238 | 1.51 | 21.2 | 45 | 2.4 | 51 | 2.4 | 0.33 | 45 | 0.657 |
| September | 0.720 | 7.00 | 0.169 | 1.19 | 18.6 | 35 | 1.6 | 30 | 2.7 | 0.21 | 34 | 0.680 |
| October | 0.681 | 6.30 | 0.237 | 1.49 | 18.9 | 41 | 2.1 | 40 | 2.7 | 0.29 | 40 | 0.671 |
| November | 0.690 | 5.90 | 0.238 | 1.41 | 16.9 | 39 | 2.1 | 36 | 3.0 | 0.28 | 38 | 0.637 |
| December | 0.690 | 5.55 | 0.246 | 1.37 | 17.1 | 42 | 2.2 | 38 | 3.0 | 0.28 | 41 | 0.612 |
| | | | | For 1% LOLP: | | 3.6 kW | | 51 kWH | | | 3.6kW | |
| | | | | Installed: | | 3.5 kW | | 121 kWH[4] | | | | |

Notes:

1. $\rho_g$ = 0.05
2. $\eta$ = 0.08
3. A = Load/$[\eta(I - MS)]$
   M = $(I - Load/A\eta)/S$ = (0.33 assumed starting value)
4. 2,380Ah battery rating chosen to operate with 50% ≤ SOC ≤ 100%, so 1,190Ah provided at 120 volts
5. $K_H$ per SOLMET for Tucson, Arizona.

SECTION 11

INSOLATION

## 11.1 INTRODUCTION

The purpose of this section is to present the calculational tools for determination of the insolation on a tilted surface. The quantity that is required for system sizing is the average daily insolation for a given month on the tilted array surface. Four numbers are needed to perform the calculation of average daily insolation. These are: the clearness index or $\overline{K}_H$ ; the latitude angle of the site; the tilt angle of the array; and the reflectance of the ground in front of the array. The clearness index is the ratio of the average monthly horizontal insolation to the extraterrestrial horizontal insolation. $\overline{K}_H$ varies from month to month with the lowest values usually occurring in the winter.

In Appendix A, monthly values of $\overline{K}_H$ are tabulated for a number of cities in the United States and throughout the world. The locations listed are grouped according to country. If there is no listing for a proposed site, then the closest listing should be used as long as the general weather conditions are similar. (Note that the values of $\overline{K}_H$ in Appendix A must be divided by 1000 before they are input to the insolation calculation programs described in the following sections).

The equations that form the basis for the insolation calculation programs are presented in Exhibit 11.1-1. A sample calculation is given in Exhibit 11.1-2. A table listing the reflectances of various types of ground covers is presented in Exhibit 11.1-3.



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Exhibit 11.1-1

INSOLATION COMPUTATION FOR A SOUTH-FACING ARRAY

A. Select Latitude (L), Day of Year (Day) Ground Reflectance ($\rho$) and Array Tilt ($\phi$) ($0^o$ for Horizontal)

B. Obtain the monthly average clearness index, $\bar{K}_H$, from Appendix A.

C. Compute the Solar Hour Angle at Sunset

$\cos \Theta_{SS}$ = $-\tan L \tan \delta$

L = Latitude

$\sin \delta$ = sin(declination angle) = $\sin (23.45) \sin (\frac{284 + day}{365} \times 360^o)$

D. Compute the Solar Hour Angle at Sunset for the Tilted Surface

$$\cos \Theta_{TS} = -\tan (L - \phi) \tan \delta$$

E. Determine which Sunset Occurs First

$$\Theta = \min (\Theta_{TS}, \Theta_{SS})$$

F. Compute the Extraterrestrial Irradiance on a Plate Held Normal to the Sun's Rays

$$S_O = 1.356 \quad (1 + 0.0167 \cos (\frac{Day}{365} * 360) )^2 \text{ kW/m}^2$$

G. Compute the Extraterrestrial Insolation on a Horizontal Surface

$$S_{OH} = S_O \frac{24}{\pi} (\cos L \cos \delta \sin \Theta_{SS} + \frac{\pi \Theta_{SS}}{180} \sin L \sin \delta) \frac{\text{kWh}}{\text{m}^2\text{-Day}}$$

H. Compute the Horizontal Insolation

$$S_H = \bar{K}_H * S_{OH}$$

I. Compute the Diffuse-Insolation Factor (Ref. 11-1) ($K_D = S_D/S_H$) for the monthly average insolation:

$$K_D = \left\{ 0.230 + \Theta_{SS}/165 - \left[ 0.095 + \Theta_{SS}/220 \right] * \cos \left[ 114.6 * (\bar{\bar{K}}_H - 0.9) \right] \right\}$$

J. Compute the daily-direct radiation factor

$$R_D = \frac{\cos (L - \phi)}{\cos L} * \left\{ \frac{\sin \theta - \frac{\pi}{180} \theta \cos \theta_{TS}}{\sin \theta_{SS} - \frac{\pi}{180} \Theta_{SS} \cos \theta_{SS}} \right\}$$

K. Compute the average daily insolation on the tilted surface

$$I_T = S_H \left\{ (1 - K_D) R_D + \tfrac{1}{2} (1+\cos \phi) K_D + \tfrac{1}{2} (1 - \cos\phi) \rho \right\}$$

where $\rho$ = ground reflectance (See exhibit 11.1-3)

Exhibit 11.1-2

INSOLATION COMPUTATION EXAMPLE: WASHINGTON, D.C.

A. Let: $L = 38.95^{\circ}$, Day = 15 (Jan), $\phi = 55^{\circ}$

B. Find from Appendix A: $\bar{K}_H = 0.417$

C. Compute: $\sin\delta = \sin(23.45) * \sin(\frac{284 + 15}{365} * 360) = -0.36094$

$$\delta = -21.16^{\circ}$$

$$\cos\theta_{SS} = -(\tan 38.95)(\tan(-21.16)) = 0.31286$$

$$\theta_{SS} = 71.77^{\circ}$$

D. Compute: $\cos\theta_{TS} = -\tan(38.95 - 55)\tan(-21.16) = -0.11134$

$$\theta_{TS} = 96.39^{\circ}$$

E. Set: $\theta = \min(71.77, 96.39) = 71.77^{\circ}$

F. Compute: $S_O = 1.356 * (1 + 0.0167 * \cos(\frac{15}{365} * 360))^2 = 1.400\ kW/m^2$

G. Compute: $S_{OH} = 1.400 * \frac{24}{\pi} * \left[\cos(38.95)\cos(-21.16)\sin(71.77) + (\frac{\pi * 71.77}{180})\sin(38.95)\sin(-21.16)\right]$

so $S_{OH} = 4.328\ kWh/m^2$ - day

H. Compute: $S = 0.417 * 4.328 = 1.805\ kWh/m^2$ - day

I. Compute: $K_D = \left\{0.230 + 71.77/165 - \left[0.095 + 71.77/220\right] * \cos\left[114.6 * (0.417 - 0.9)\right]\right\} = 0.426$

J. Compute: $R_D = \frac{\cos(38.45 - 55)}{\cos(38.95)} *$

$$\frac{\sin(71.77) - (\pi * 71.77/180) * \cos(96.39)}{\sin(71.77) - (\pi * 71.77/180) * \cos(71.77)}$$

$$= 2.416$$

K. For $\rho = 0$:

$$I_T = 1.805 * \left\{(1 - 0.426) * 2.413 + \tfrac{1}{2}(1 + \cos 55) * 0.426 + \tfrac{1}{2}(1 - \cos 55) * 0\right\}$$

so $I_T = 3.106\ kWh/M^2$ - day



\SV

Exhibit 11.1-3

GROUND REFLECTANCES FOR VARIOUS SURFACES

| | |
|---|---|
| Ocean | 0.05 |
| Bituminous concrete | 0.07 |
| Wheat field | 0.07 |
| Dark soil | 0.08 |
| Green field | 0.12 to 0.25 |
| Grass, dry | 0.20 |
| Crushed rock surface | 0.20 |
| Concrete, old | 0.24 |
| Concrete, light colored | 0.30 |
| Paved asphalt | 0.18 |
| Concrete, new | 0.32 |
| Snow, fresh | 0.87 |
| Snow, old | 0.50 |

References: (11-2, 11-3)



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## 11.2 INSOLATION CALCULATION PROGRAMS

Programs for calculating the average daily insolation on a tilted array surface have been developed for the TI-59 and HP-67 programmable calculators. The programs are based on the equations of Exhibit 11.1-1. They will enable the effects of $K_H$, tilt angle and other variables on the performance of the PV system to be analyzed.

Instructions for using the TI-59 program are given in Exhibit 11.2-1. A listing of the program is presented in Exhibit 11.2-2. The instructions for use of the HP-67 program are in Exhibit 11.2-3 with the program listing given in Exhibit 11.2-4.

Exhibit 11.2-1

INSTRUCTIONS FOR OPERATING THE

TI-59 INSOLATION-COMPUTATION PROGRAM

1. Enter the following values in the respective storage locations:

| Value | Storage Location |
|---|---|
| Latitude degrees | 00 |
| Tilt, degrees | 02 |
| Ground reflectance, decimal | 13 |

2. Depress C to start the entry of the monthly $\overline{K}_H$'s. The calculator displays the month number for which the $\overline{K}_H$ is to be entered (1.0 for January).

3. Enter the $\overline{K}_H$ for the month indicated. Depress R/S. The calculator will display the next month number for which $\overline{K}_H$ is to be entered. Repeat this step until all twelve values are entered.

4. Depress A to obtain the output. Typical output for the case of $\overline{K}_H$= 0.5 for each month is presented below. The average monthly insolation is printed for each month and for the year, in kWh/day-m$^2$, for the tilted surface.

| | |
|---|---|
| Latitude | 20$^{o}$ |
| Tilt | 30$^{o}$ |
| Ground ref. | 0.050 |
| Month | $I_T$ (kWh/day-m$^2$ |
| Jan | 4.595 |
| Feb | 4.798 |
| Mar | 4.910 |
| April | 4.832 |
| May | 4.646 |
| June | 4.512 |
| July | 4.544 |
| Aug | 4.703 |
| Sept | 4.837 |
| Oct | 4.821 |
| Nov | 4.657 |
| Dec | 4.517 |
| Average | 4.698 |



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```
000  76  LBL
001  12  B
002  43  RCL
003  01  01
004  85  +
005  02  2
006  08  8
007  04  4
008  95  =
009  55  ÷
010  03  3
011  06  6
012  05  5
013  65  x
014  03  3
015  06  6
016  00  0
017  95  =
018  38  SIN
019  65  x
020  02  2
021  03  3
022  93  .
023  04  4
024  05  5
025  38  SIN
026  95  =
027  22  INV
028  38  SIN
029  42  STO
030  04  04
031  30  TAN
032  65  x
033  43  RCL
034  00  00
035  30  TAN
036  94  +/-
037  95  =
038  22  INV
039  39  COS
040  42  STO
041  05  05
042  43  RCL
043  00  00
044  75  -
045  43  RCL
046  02  02
047  95  =
048  30  TAN
049  65  x
050  43  RCL
051  04  04
052  30  TAN
053  94  +/-
054  95  =
055  22  INV
056  39  COS
057  42  STO
058  06  06
059  32  X:T
060  43  RCL
061  05  05
062  22  INV
063  77  GE
064  32  X:T
065  32  X:T
066  76  LBL
067  32  X:T
068  42  STO
069  07  07
070  43  RCL
071  01  01
072  55  ÷
073  03  3
074  06  6
075  05  5
076  65  x
077  03  3
078  06  6
079  00  0
080  95  =
081  39  COS
082  65  x
083  93  .
084  00  0
085  01  1
086  06  6
087  07  7
088  85  +
089  01  1
090  95  =
091  33  X²
092  65  x
093  01  1
094  93  .
095  03  3
096  05  5
097  06  6
098  95  =
099  65  x
100  02  2
101  04  4
102  55  ÷
103  89  π
104  65  x
105  53  (
106  43  RCL
107  00  00
108  39  COS
109  65  x
110  43  RCL
111  04  04
112  39  COS
113  65  x
114  43  RCL
115  05  05
116  38  SIN
117  85  +
118  89  π
119  65  x
120  43  RCL
121  05  05
122  55  ÷
123  01  1
124  08  8
125  00  0
126  65  x
127  43  RCL
128  00  00
129  38  SIN
130  65  x
131  43  RCL
132  04  04
133  38  SIN
134  54  )
135  95  =
136  65  x
137  43  RCL
138  03  03
139  95  =
140  42  STO
141  10  10
142  53  (
143  53  (
144  93  .
145  02  2
146  03  3
147  85  +
148  43  RCL
149  05  05
150  55  ÷
151  01  1
152  06  6
153  05  5
154  75  -
155  53  (
156  93  .
157  00  0
158  09  9
159  05  5
160  85  +
161  43  RCL
162  05  05
163  55  ÷
164  02  2
165  02  2
166  00  0
167  54  )
168  65  x
169  53  (
170  01  1
171  01  1
172  04  4
173  93  .
174  06  6
175  65  x
176  53  (
177  43  RCL
178  03  03
179  75  -
180  93  .
181  09  9
182  54  )
183  54  )
184  39  COS
185  54  )
186  54  )
187  42  STO
188  11  11
189  43  RCL
190  00  00
191  75  -
192  43  RCL
193  02  02
194  95  =
195  39  COS
196  55  ÷
197  43  RCL
198  00  00
199  39  COS
200  65  x
201  53  (
202  43  RCL
203  07  07
204  38  SIN
205  75  -
206  89  π
207  55  ÷
208  01  1
209  08  8
210  00  0
211  65  x
212  43  RCL
213  07  07
214  65  x
215  43  RCL
216  06  06
217  39  COS
218  54  )
219  55  ÷
220  53  (
221  43  RCL
222  05  05
223  38  SIN
224  75  -
225  89  π
226  55  ÷
227  01  1
228  08  8
229  00  0
230  65  x
231  43  RCL
232  05  05
233  65  x
234  43  RCL
235  05  05
236  39  COS
237  54  )
238  95  =
239  42  STO
240  12  12
241  01  1
242  75  -
243  43  RCL
244  11  11
245  95  =
246  65  x
247  43  RCL
248  12  12
249  85  +
250  93  .
251  05  5
252  65  x
253  53  (
254  01  1
255  85  +
256  43  RCL
257  02  02
258  39  COS
259  54  )
260  65  x
261  43  RCL
262  11  11
263  85  +
264  93  .
265  05  5
266  65  x
267  53  (
268  01  1
269  75  -
270  43  RCL
271  02  02
272  39  COS
273  54  )
274  65  x
275  43  RCL
276  13  13
277  95  =
278  65  x
279  43  RCL
280  10  10
281  95  =
282  42  STO
283  14  14*
284  99  PRT
285  72  ST*
286  30  30
287  92  RTN
288  76  LBL
289  11  A
290  58  FIX
291  03  03
292  98  ADV
293  25  CLR
294  42  STO
295  28  28
296  43  RCL
297  00  00
298  99  PRT
299  43  RCL
300  02  02
```

EXHIBIT 11.2-2

LISTING OF A TI-59 INSOLATION COMPUTATION PROGRAM

*For calculators without printers, a step "R/S" should be inserted between #283 and #284.

EXHIBIT 11.2-2 (Continued)

LISTING OF A TI-59 INSOLATION COMPUTATION PROGRAM

```
301  99  PRT
302  43  RCL
303  13   13
304  99  PRT
305  98  ADV
306  01   1
307  06   6
308  42  STO
309  15   15
310  03   3
311  01   1
312  42  STO
313  30   30
314  76  LBL
315  16  A'
316  43  RCL
317  15   15
318  75   -
319  01   1
320  06   6
321  95   =
322  65   x
323  03   3
324  00   0
325  85   +
326  01   1
327  05   5
328  95   =
329  42  STO
330  01   01
331  73  RC+
332  15   15
333  42  STO
334  03   03
335  12   B
336  44  SUM
337  26   28
338  01   1
339  44  SUM
340  15   15
341  44  SUM
342  30   30
343  43  RCL
344  15   15
345  32  X:T
346  02   2
347  07   7
348  77   GE
349  16  A'
350  43  RCL
```

```
351  28   26
352  55   ÷
353  01   1
354  02   2
355  95   =
356  99  PRT
357  86  STF
358  08   08
359  91  R/S
360  00   0
361  22  INV
362  44  SUM
363  02   03
364  43  RCL
365  10   10
366  34  √X
367  61  GTO
368  11   A
369  76  LBL
370  13   C
371  01   1
372  06   6
373  42  STO
374  15   15
375  76  LBL
376  18  C'
377  43  RCL
378  15   15
379  75   -
380  01   1
381  05   5
382  95   =
383  91  R/S
384  72  ST+
385  15   15
386  01   1
387  44  SUM
388  15   15
389  61  GTO
390  18  C'
391  00   0
392  00   0
```

Exhibit 11.2-3

INSTRUCTION FOR OPERATING THE

HP-67 INSOLATION-COMPUTATION PROGRAM

1. Load the following quantities into the storage registers indicated below:

| Value | Register |
|---|---|
| $S_H$ | 0 |
| Day (Jan 1=1) | 1 |
| Latitude, L | 2 |
| Tilt Angle, | 3 |
| Reflectance | 4 |

2. Depress A to initiate the program. In approximately 45 seconds, the value of $S_T$, the average monthly insolation on the tilted surface will be displayed in the x-register. The units of $S_H$ are kWh/day-m$^2$.

3. To calculate $I_T$ for a different month, the value of $\overline{K}_H$ and the value of DAY corresponding to the middle of the month must be stored in Registers 0 and 1 respectively. Alternatively, the variation of $S_T$ with tilt angle or ground reflectance can be studied by changing these variables with the remaining ones fixed.

4. Example:

For $K_H$ = 0.5, L = 20, DAY = 15 (January)
Tilt = 20, and $\rho$ = 0.05, the calculated
value of $I_T$ = 4.595.

4. The following quantities are also calculated and stored by the program:

| Quantity* | Register |
|---|---|
| $\delta$ | 5 |
| $\theta$ ss | 6 |
| $\theta$ sr | 7 |
| $\theta$ | 8 |
| $S_{OH}$ | 9 |
| $K_D$ | A |
| $R_D$ | B |

* See Exhibit 11.1-1 for a definition of these quantities



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Exhibit 11.2-4

## LISTING OF AN HP-67 INSOLATION COMPUTATION PROGRAM

| Step Number | Key-strokes | Key Code | Step Number | Key-strokes | Key Code | Step Number | Key-strokes | Key Code |
|---|---|---|---|---|---|---|---|---|
| 001 | f LBL A | 32 25 11 | 028 | X | 71 | 055 | f cos | 31 63 |
| 002 | RCL 1 | 34 01 | 029 | CHS | 42 | 056 | . | 83 |
| 003 | 2 | 02 | 030 | g $\cos^{-1}$ | 32 63 | 057 | 0 | 00 |
| 004 | 8 | 08 | 031 | STO 6 | 33 06 | 058 | 1 | 01 |
| 005 | 4 | 04 | 032 | RCL 2 | 34 02 | 059 | 6 | 06 |
| 006 | + | 61 | 033 | RCL 3 | 34 03 | 060 | 7 | 07 |
| 007 | 3 | 03 | 034 | — | 51 | 061 | X | 71 |
| 008 | 6 | 06 | 035 | f TAN | 31 64 | 062 | 1 | 01 |
| 009 | 5 | 05 | 036 | RCL 5 | 34 05 | 063 | + | 61 |
| 010 | ÷ | 81 | 037 | f TAN | 31 64 | 064 | g $x^2$ | 32 54 |
| 011 | 3 | 03 | 038 | X | 71 | 065 | 1 | 01 |
| 012 | 6 | 06 | 039 | CHS | 42 | 066 | . | 83 |
| 013 | 0 | 00 | 040 | g $\cos^{-1}$ | 32 63 | 067 | 3 | 03 |
| 014 | X | 71 | 041 | STO 7 | 33 07 | 068 | 5 | 05 |
| 015 | f sin | 31 62 | 042 | RCL 6 | 34 06 | 069 | 6 | 06 |
| 016 | 2 | 02 | 043 | g $x<y$ | 32 81 | 070 | X | 71 |
| 017 | 3 | 03 | 044 | h $x \lessgtr y$ | 35 52 | 071 | RCL 5 | 34 05 |
| 018 | . | 83 | 045 | STO 8 | 33 08 | 072 | f sin | 31 62 |
| 019 | 4 | 04 | 046 | RCL 1 | 34 01 | 073 | RCL 2 | 34 02 |
| 020 | 5 | 05 | 047 | 3 | 03 | 074 | f sin | 31 62 |
| 021 | f sin | 31 62 | 048 | 6 | 06 | 075 | X | 71 |
| 022 | X | 71 | 049 | 0 | 00 | 076 | RCL 6 | 34 06 |
| 023 | g $\sin^{-1}$ | 32 62 | 050 | X | 71 | 077 | X | 71 |
| 024 | STO 5 | 33 05 | 051 | 3 | 03 | 078 | h$\pi$ | 35 73 |
| 025 | f TAN | 31 64 | 052 | 6 | 06 | 079 | X | 71 |
| 026 | RCL 2 | 34 02 | 053 | 5 | 05 | 080 | 1 | 01 |
| 027 | f TAN | 31 64 | 054 | ÷ | 81 | 081 | 8 | 08 |

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Exhibit 11.2-4 (Continued)

LISTING OF AN HP-67 INSOLATION COMPUTATION PROGRAM

| Step Number | Key-strokes | Key Code | Step Number | Key-strokes | Key Code | Step Number | Key-strokes | Key Code |
|---|---|---|---|---|---|---|---|---|
| 082 | 0 | 00 | 109 | X | 71 | 136 | RCL 8 | 34 08 |
| 083 | ÷ | 81 | 110 | f cos | 31 65 | 137 | X | 71 |
| 084 | RCL 6 | 34 06 | 111 | RCL 6 | 34 06 | 138 | hπ | 32 73 |
| 085 | f sin | 31 62 | 112 | 2 | 02 | 139 | x | 71 |
| 086 | RCL 5 | 34 05 | 113 | 2 | 02 | 140 | 1 | 01 |
| 087 | f cos | 31 63 | 114 | 0 | 00 | 141 | 8 | 08 |
| 088 | X | 71 | 115 | ÷ | 81 | 142 | 0 | 00 |
| 089 | RCL 2 | 34 02 | 116 | . | 83 | 143 | ÷ | 81 |
| 090 | f cos | 31 63 | 117 | 0 | 00 | 144 | CHS | 42 |
| 091 | X | 71 | 118 | 9 | 09 | 145 | RCL 8 | 34 08 |
| 092 | + | 61 | 119 | 5 | 05 | 146 | f sin | 31 62 |
| 093 | X | 71 | 120 | + | 61 | 147 | + | 61 |
| 094 | 2 | 02 | 121 | X | 71 | 148 | RCL 6 | 34 06 |
| 095 | 4 | 04 | 122 | CHS | 42 | 149 | f cos | 31 63 |
| 096 | X | 71 | 123 | RCL 6 | 34 06 | 150 | RCL 6 | 34 06 |
| 097 | hπ | 35 73 | 124 | 1 | 01 | 151 | X | 71 |
| 098 | ÷ | 81 | 125 | 6 | 06 | 152 | hπ | 32 73 |
| 099 | STO 9 | 33 09 | 126 | 5 | 05 | 153 | X | 71 |
| 100 | RCL 0 | 34 00 | 127 | ÷ | 81 | 154 | 1 | 01 |
| 101 | . | 83 | 128 | + | 61 | 155 | 8 | 08 |
| 102 | 9 | 09 | 129 | . | 83 | 156 | 0 | 00 |
| 103 | — | 51 | 130 | 2 | 02 | 157 | − | 81 |
| 104 | 1 | 01 | 131 | 3 | 03 | 158 | CHS | 42 |
| 105 | 1 | 01 | 132 | + | 61 | 159 | RCL 6 | 34 06 |
| 106 | 4 | 04 | 133 | STO A | 33 11 | 160 | f sin | 31 62 |
| 107 | . | 83 | 134 | RCL 7 | 34 07 | 161 | + | 61 |
| 108 | 6 | 06 | 135 | f cos | 31 63 | 162 | ÷ | 81 |

Exhibit 11.2-4 (Continued)

LISTING OF AN HP-67 INSOLATION COMPUTATION PROGRAM

| Step Number | Key-strokes | Key Code | | Step Number | Key-strokes | Key Code | |
|---|---|---|---|---|---|---|---|
| 163 | RCL 2 | 34 | 02 | 190 | + | | 61 |
| 164 | RCL 3 | 34 | 03 | 191 | 2 | | 02 |
| 165 | — | | 51 | 192 | ÷ | | 81 |
| 166 | f cos | 31 | 63 | 193 | RCL 4 | 34 | 04 |
| 167 | X | | 71 | 194 | X | | 71 |
| 168 | RCL 2 | 34 | 02 | 195 | + | | 61 |
| 169 | f cos | 31 | 63 | 196 | RCL 9 | 34 | 09 |
| 170 | ÷ | | 81 | 197 | X | | 71 |
| 171 | STO B | 33 | 12 | 198 | RCL O | 34 | 00 |
| 172 | RCL A | 34 | 11 | 199 | X | | 71 |
| 173 | CHS | | 42 | 200 | h RTN | 32 | 22 |
| 174 | 1 | | 01 | 201 | R/S | | 84 |
| 175 | + | | 61 | ↓ | ↓ | | ↓ |
| 176 | X | | 71 | | | | |
| 177 | RCL 3 | 34 | 03 | | | | |
| 178 | f cos | 31 | 63 | 224 | R/S | | 84 |
| 179 | 1 | | 01 | | | | |
| 180 | + | | 61 | | | | |
| 181 | 2 | | 02 | | | | |
| 182 | ÷ | | 81 | | | | |
| 183 | RCL A | 34 | 11 | | | | |
| 184 | X | | 71 | | | | |
| 185 | + | | 61 | | | | |
| 186 | RCL 3 | 34 | 03 | | | | |
| 187 | f cos | 31 | 63 | | | | |
| 188 | CHS | | 42 | | | | |
| 189 | 1 | | 01 | | | | |

## 11.3 STATISTICAL INSOLATION COMPUTATIONS

The tilted surface insolation computation using monthly averages directly, as was done in Exhibit 11.1-1 disagrees with the monthly averages computed by averaging day-by-day tilted surface insolations by as much as 30%; therefore, results of the monthly method will not agree exactly with Section 6 for which the data were generated by a day-by-day method. More accurate day-by-day data can be generated by using the following method.

The insolation for each month and for each $K_H$ ranging from 0.0 to 1.0 must be computed. The procedure is identical to that presented in Exhibit 11.1-1, with one exception: the expression for $K_D$ must be modified. The day-by-day expression for $K_D$ is:

$$K_D = 0.99 \quad \text{if } K_H \text{ is less than } 0.1557$$

$$K_D = 1.188 - K_H * (2.272 - K_H * [9.473 - K_H * (21.856 - 14.648 * K_H)]) \quad \text{if } K_H \text{ is between } 0.1557 \text{ and } 0.761$$

$$K_D = 0.2255 \quad \text{if } K_H \text{ is greater than } 0.761$$

The frequency with which each $K_H$ is encountered can be determined from Exhibit 11.3-1, which gives the (cumulative) distribution, M, for each $K_H$ as a function of the monthly average $K_H$. The average and standard deviation are computed from the formulas:

$$\text{Average insolation} = \sum_{i=1} (M_{i+1} - M_i)\,(I_{T,\,i+1} + I_{T,i})/2$$

$$\text{Standard deviation} = \sqrt{\sum_{i=1} (M_{i+1} - M_i)\left[(I_{T,\,i+1} + I_{T,i})/2 - \text{Average insolation}\right]^2}$$

This procedure is tedious and is best performed on a computer, rather than a hand-held calculator. The latter would probably require several days of computation, whereas the former requires approximately one hour on a micro computer.

Exhibit 11.3-1

GENERALIZED $K_H$ DISTRIBUTION COVERAGE, F ($K_H$)

| $K_H$ | Average $K_H$ .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 | .654 | .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 | |

## 11.4 SUN ANGLE CHARTS

In this section, charts are presented to predict the amount and duration of array shading caused by objects located in front of and to the side of the array. The determination of array shading is an important part of site selection in view of the sensitivity of array output to shadowing. This sensitivity is due to series connection of cells and of modules and can be minimized but never eliminated. Thus, it is imperative that shading be kept to a minimum especially during the hours of 0900 to 1500 solar time.

From the point of view of an observer standing on earth, the position of the sun in the sky can be specified by two angles, the altitude angle and the azimuth angle. The altitude angle is the elevation of the sun above the horizon. The azimuth angle is the angle between true south (or north in the southern hemisphere) and the projection of the sun's rays onto the horizontal surface. Exhibit 11.4-1 illustrates these angles. To estimate shading, the skyline must be plotted on the sun chart closest to the site latitude. The sun charts are presented in Exhibits 11.4-2 through 11.4-10 for latitude angles from 0 to 64 degrees in 8 degree increments. The altitude and azimuth angles of objects on the horizon can be measured directly or estimated based on the known locations and elevations of objects relative to the array site. For close objects or an extended array, the measurements should be referenced to several locations along the array. An example calculation is presented in Exhibit 11.4-11.

## 11.5 ROW TO ROW SHADING

For PV arrays arranged in multiple rows of PV modules, the largest source of shading in the winter is likely to be the adjacent row. Sufficient spacing between rows must be provided to keep the shading to a minimum. This is most important for stand-alone systems, since the months of maximum shading (winter months) are also usually the months of lowest insolation.

In Exhibit 11.5-1 a graph is presented showing the minimum spacing between rows as a function of latitude angle for no row-to-row shading between the hours of 0900 to 1500 solar time for December 21 (June 21). It is seen that the land areas taken up by the array at the higher latitudes is excessive. The technique used to overcome this is to locate the array on a slope or to artificially create a slope by raising the rear rows. This is depicted in the exhibit.

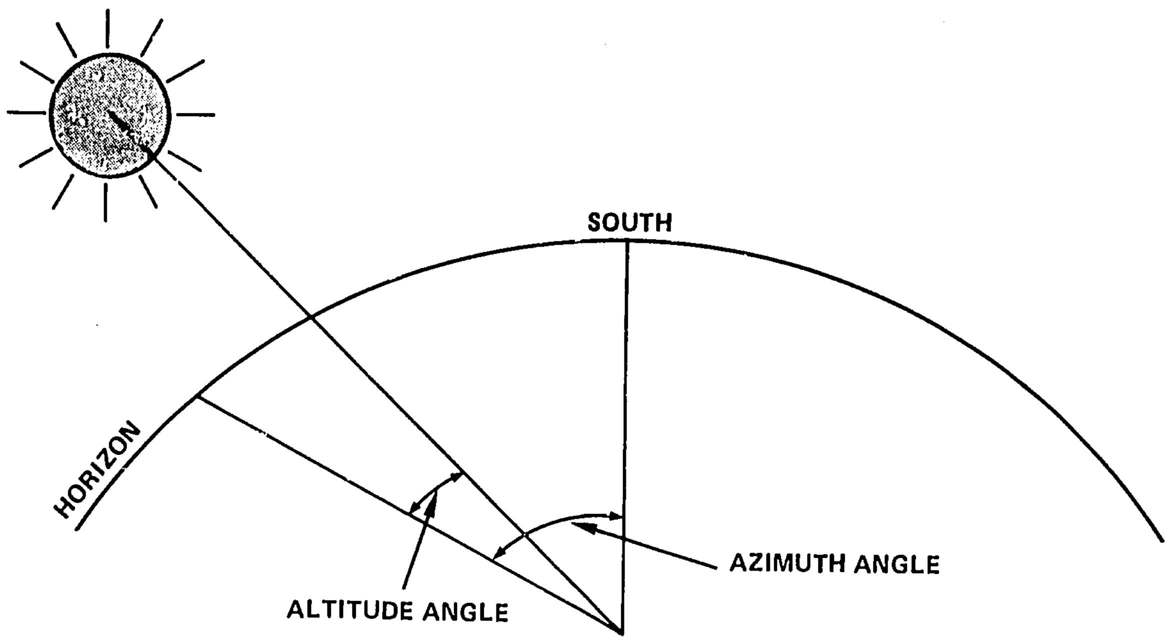
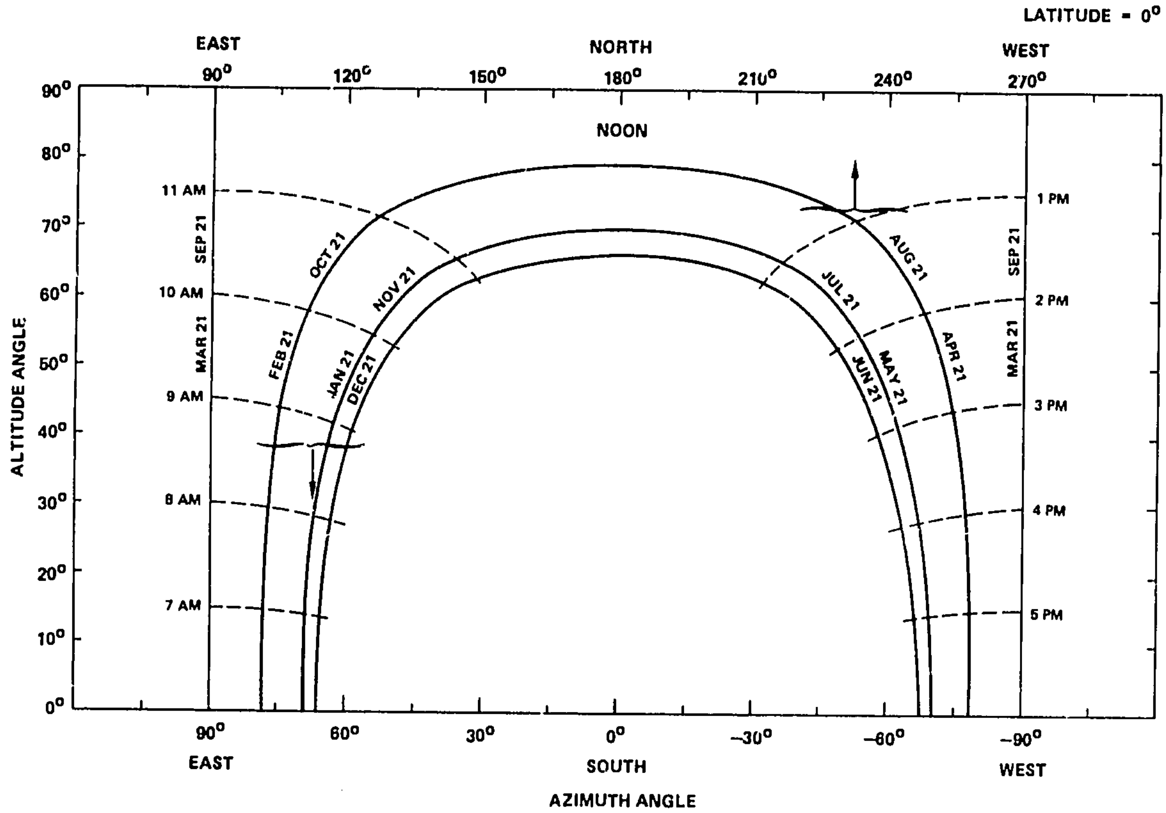



Exhibit 11.4-1

ILLUSTRATION OF SOLAR ALTITUDE AND AZIMUTH ANGLES

Exhibit 11.4-2

SUN CHART FOR 0° LATITUDE



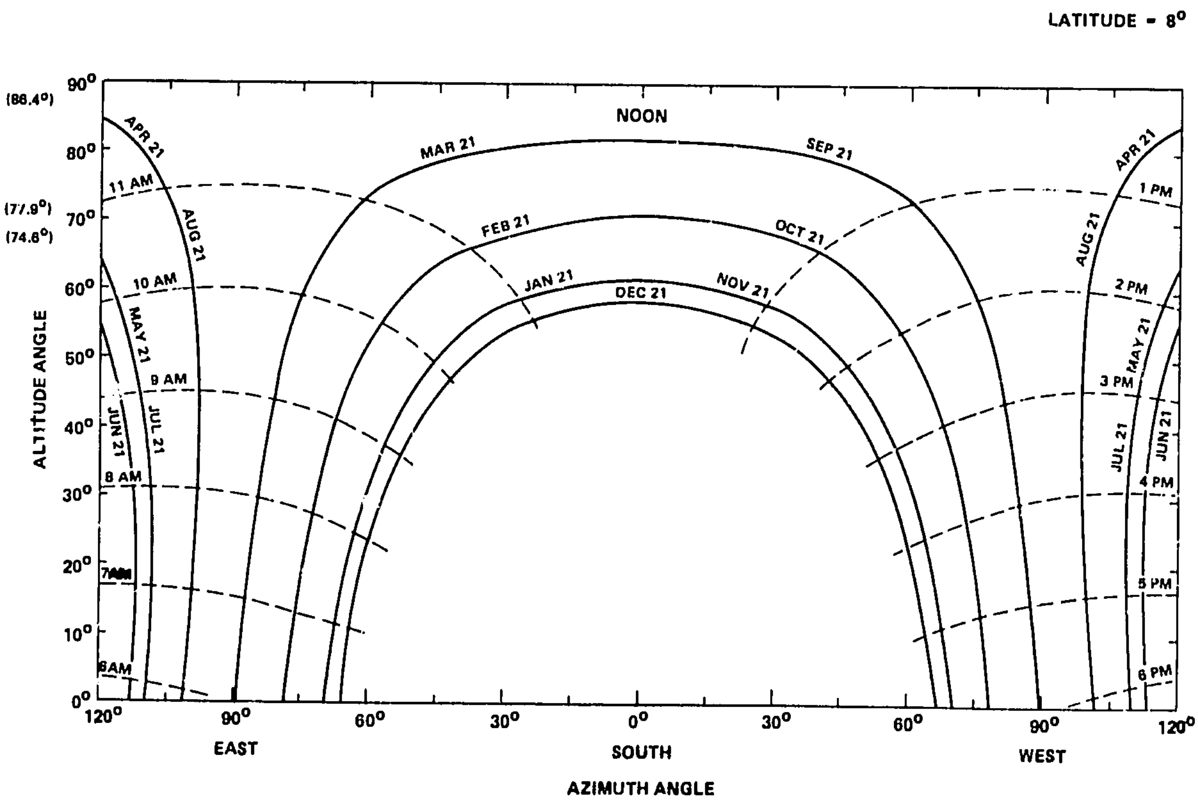
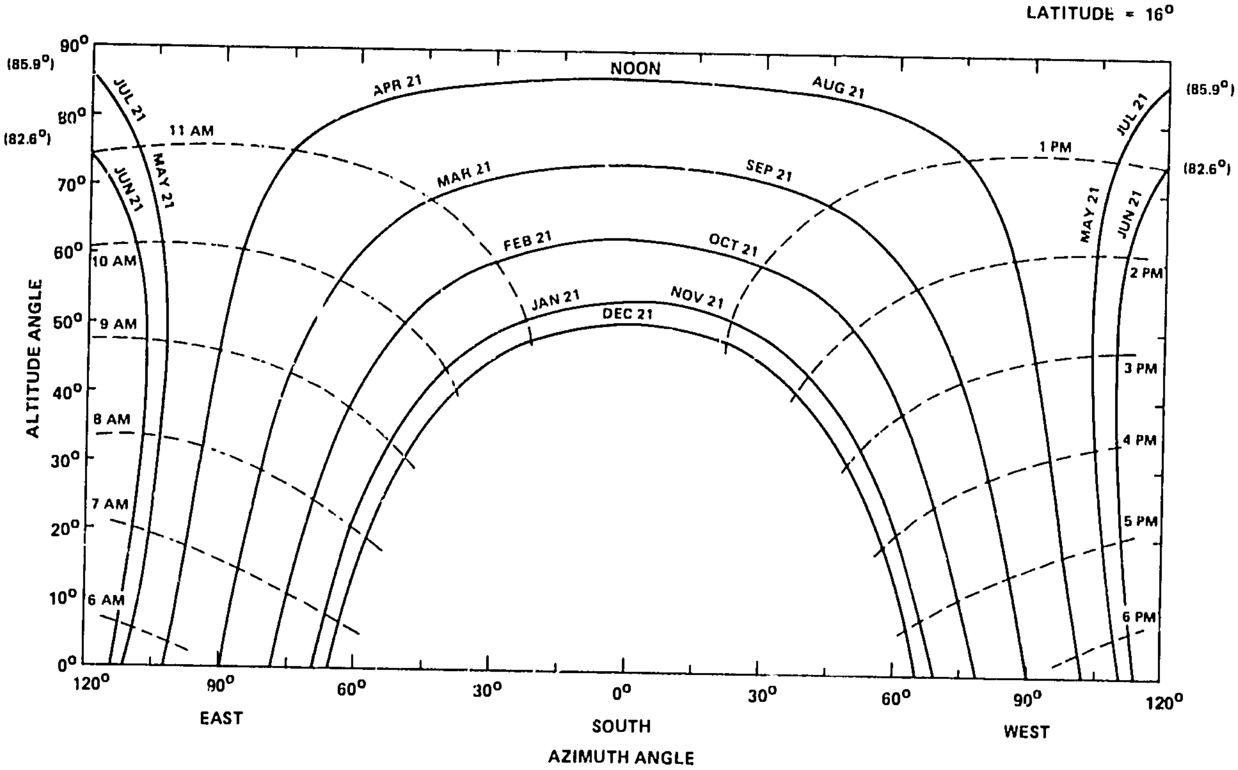




Exhibit 11.4-3

SUN CHART FOR 8° LATITUDE

Exhibit 11.4-4

SUN CHART FOR 16° LATITUDE



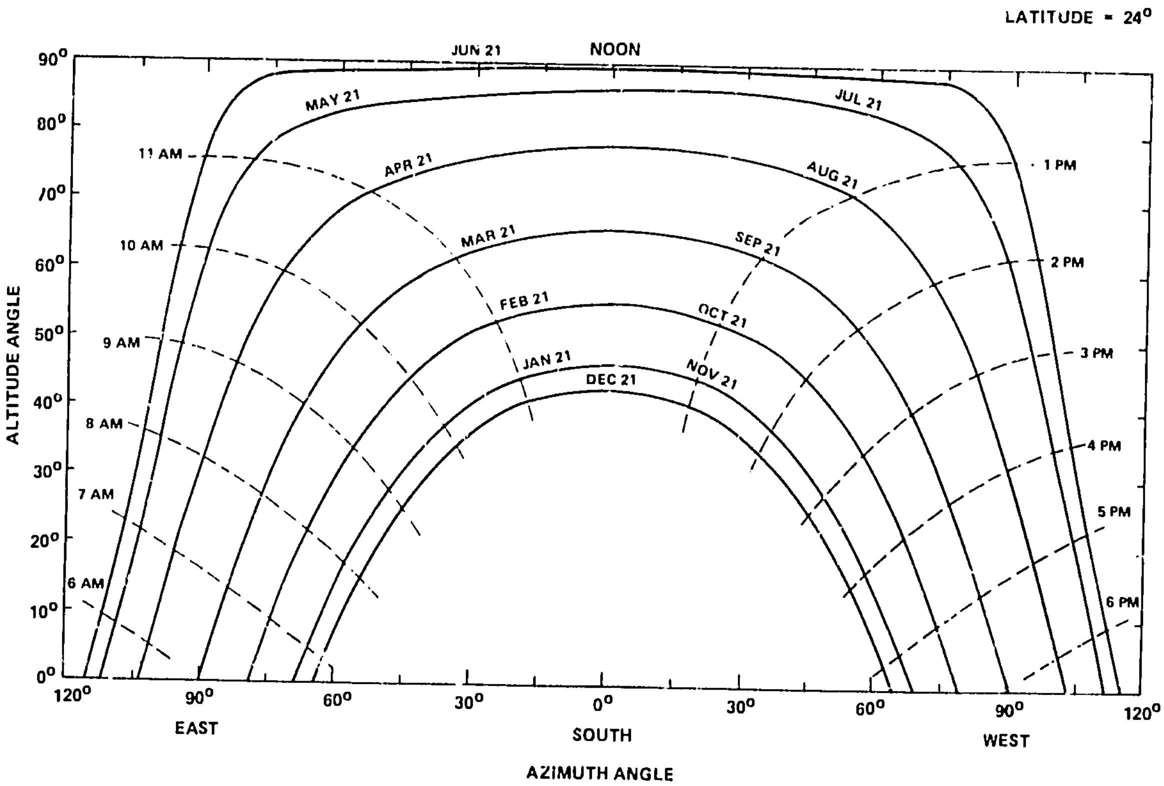
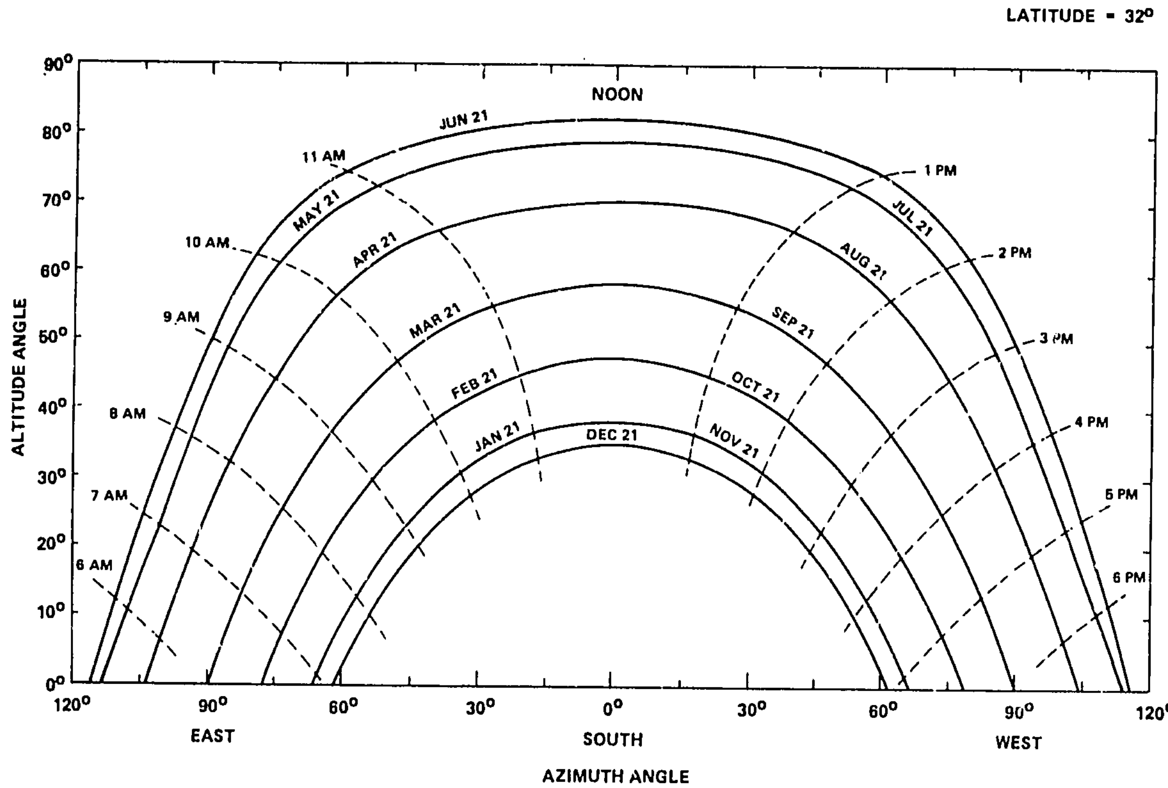




Exhibit 11.4-5

SUN CHART FOR 24° LATITUDE

Exhibit 11.4-6

SUN CHART FOR 32° LATITUDE



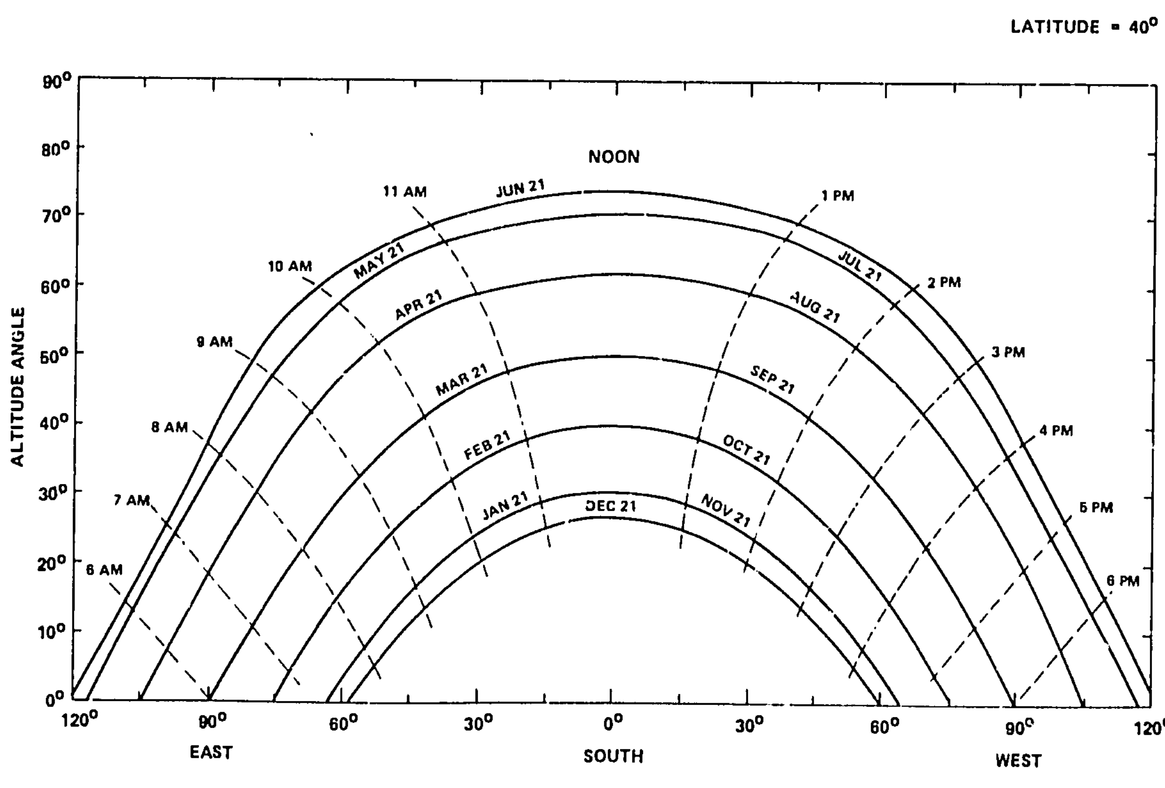
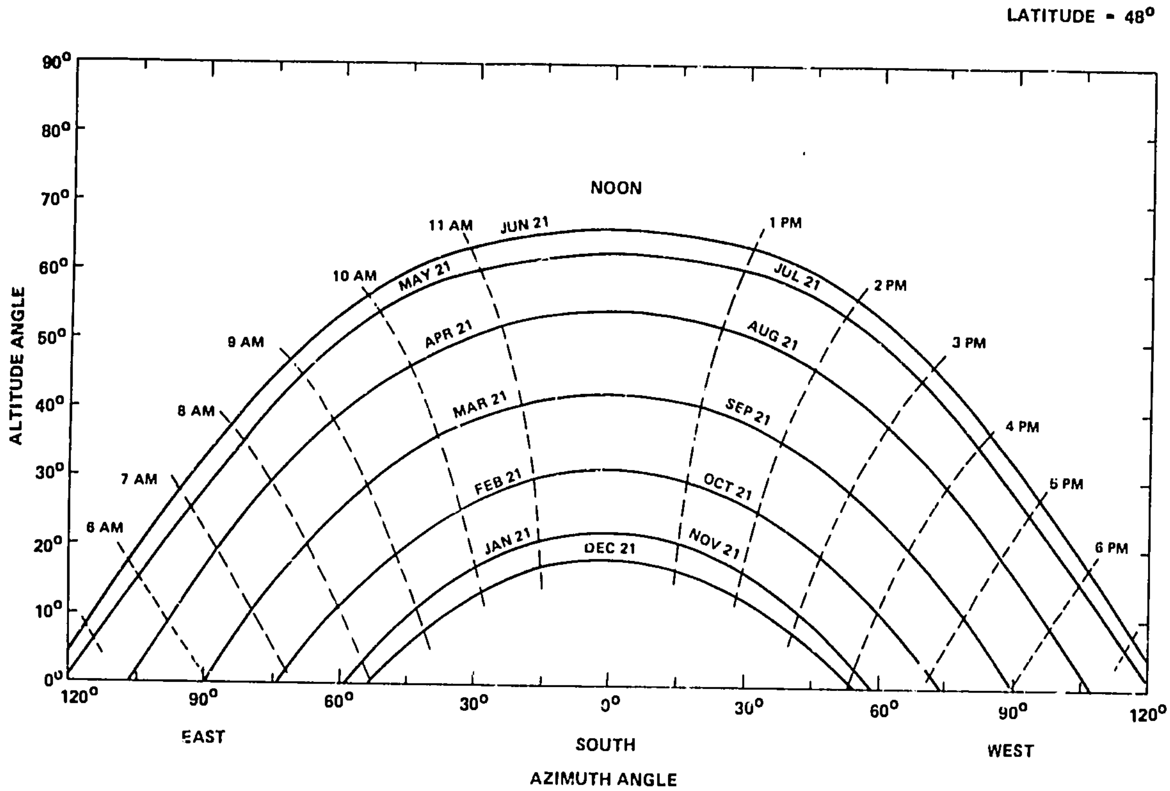




Exhibit 11.4-7

SUN CHART FOR 40° LATITUDE

Exhibit 11.4-8

SUN CHART FOR 48° LATITUDE



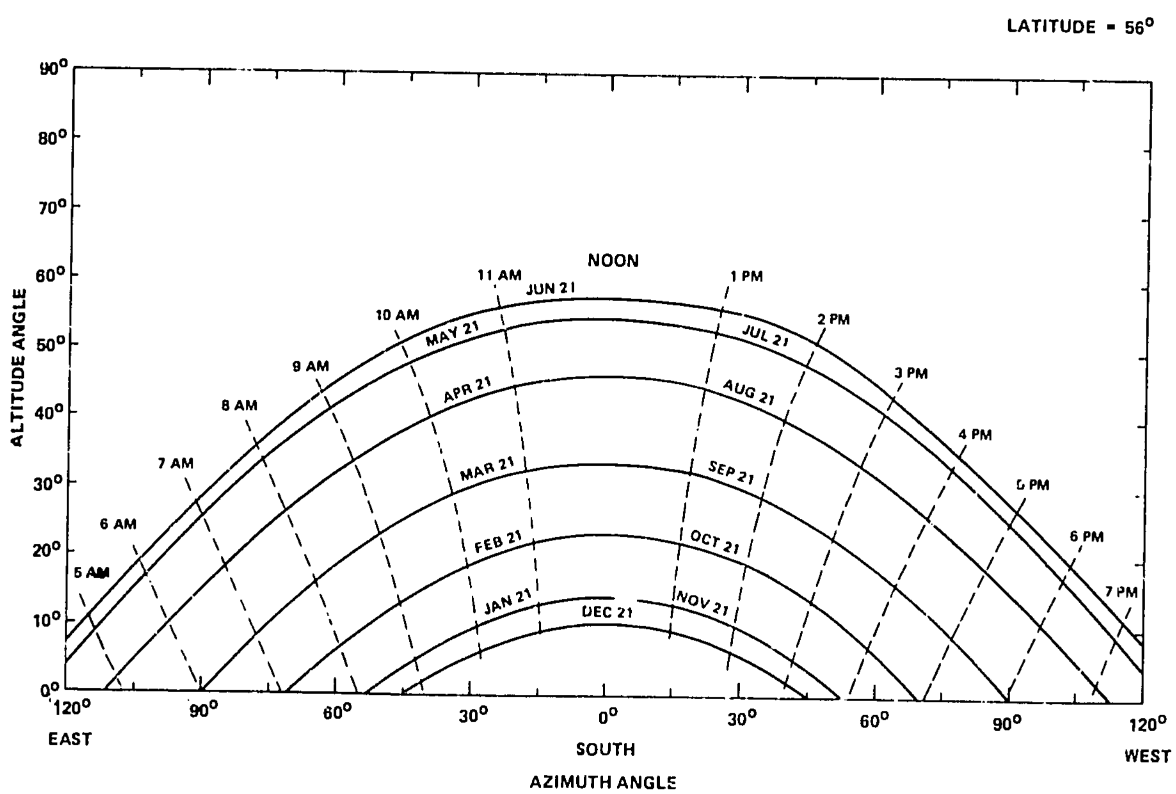




Exhibit 11.4-9

SUN CHART FOR 56° LATITUDE



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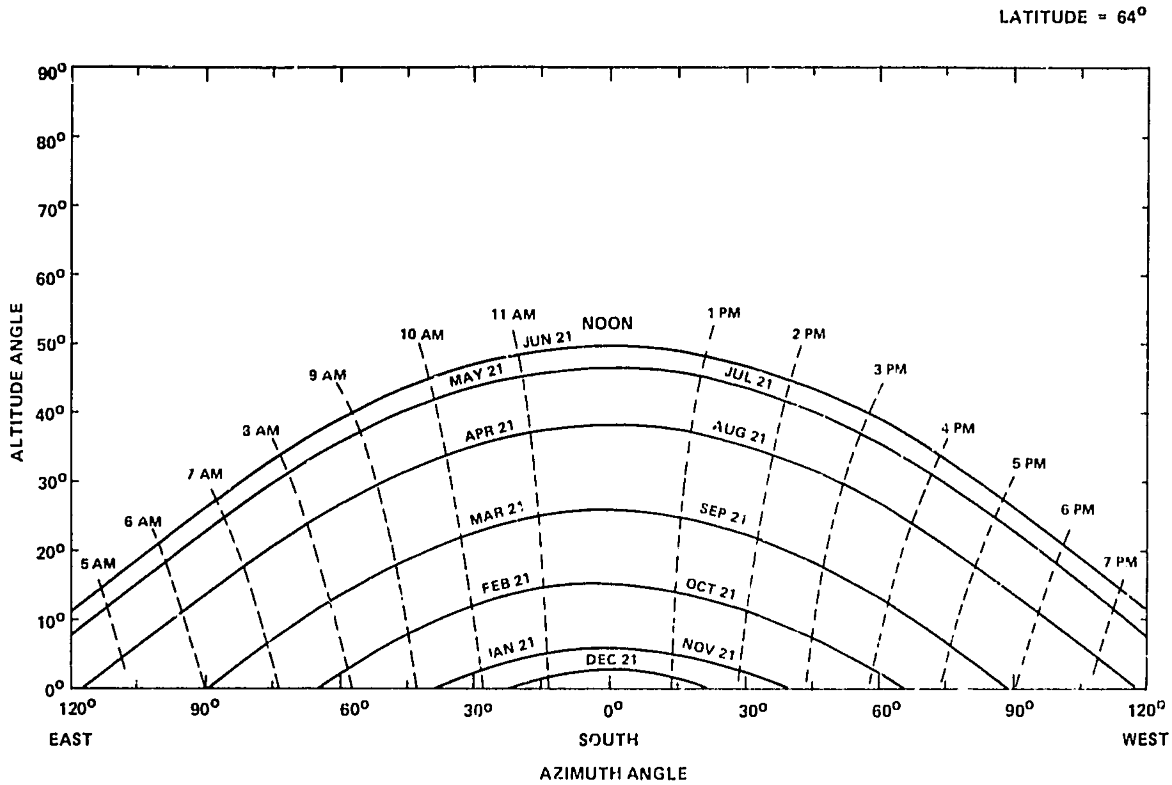
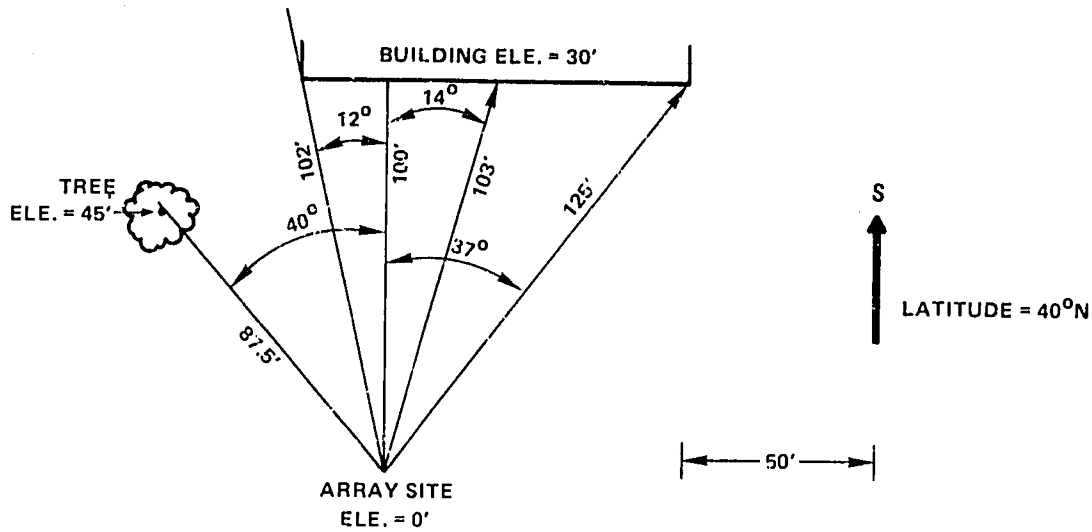



Exhibit 11.4-10

SUN CHART FOR 64° LATITUDE

## Exhibit 11.4-11
## SAMPLE SHADING CALCULATION




AZIMUTH OF TREE = 40° E

ALTITUDE OF TREE = $TAN^{-1}(\frac{45}{87.5})$ = $\underline{43.5°}$

AZIMUTH OF CENTER OF BUILDING = 14°W

ALTITUDE OF CENTER OF BUILDING = $TAN^{-1}(\frac{30}{103})$ = $\underline{16°}$

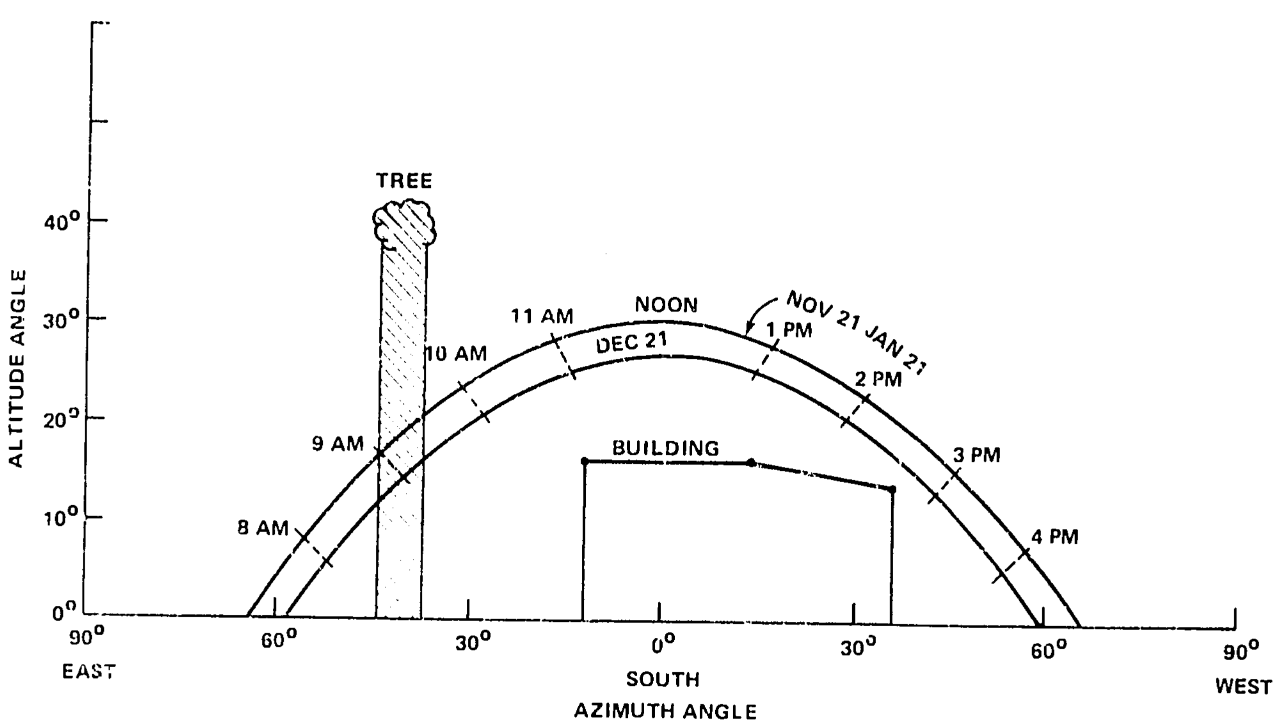
AZIMUTH OF EAST CORNER OF BUILDING = 12°E

ALTITUDE OF EAST CORNER OF BUILDING = $TAN^{-1}(\frac{30}{102})$ = $\underline{16°}$

AZIMUTH OF WEST CORNER OF BUILDING = 37°W

ALTITUDE OF WEST CORNER OF BUILDING = $TAN^{-1}(\frac{30}{125})$ = $\underline{13.5°}$

SUN CHART FOR 40°N



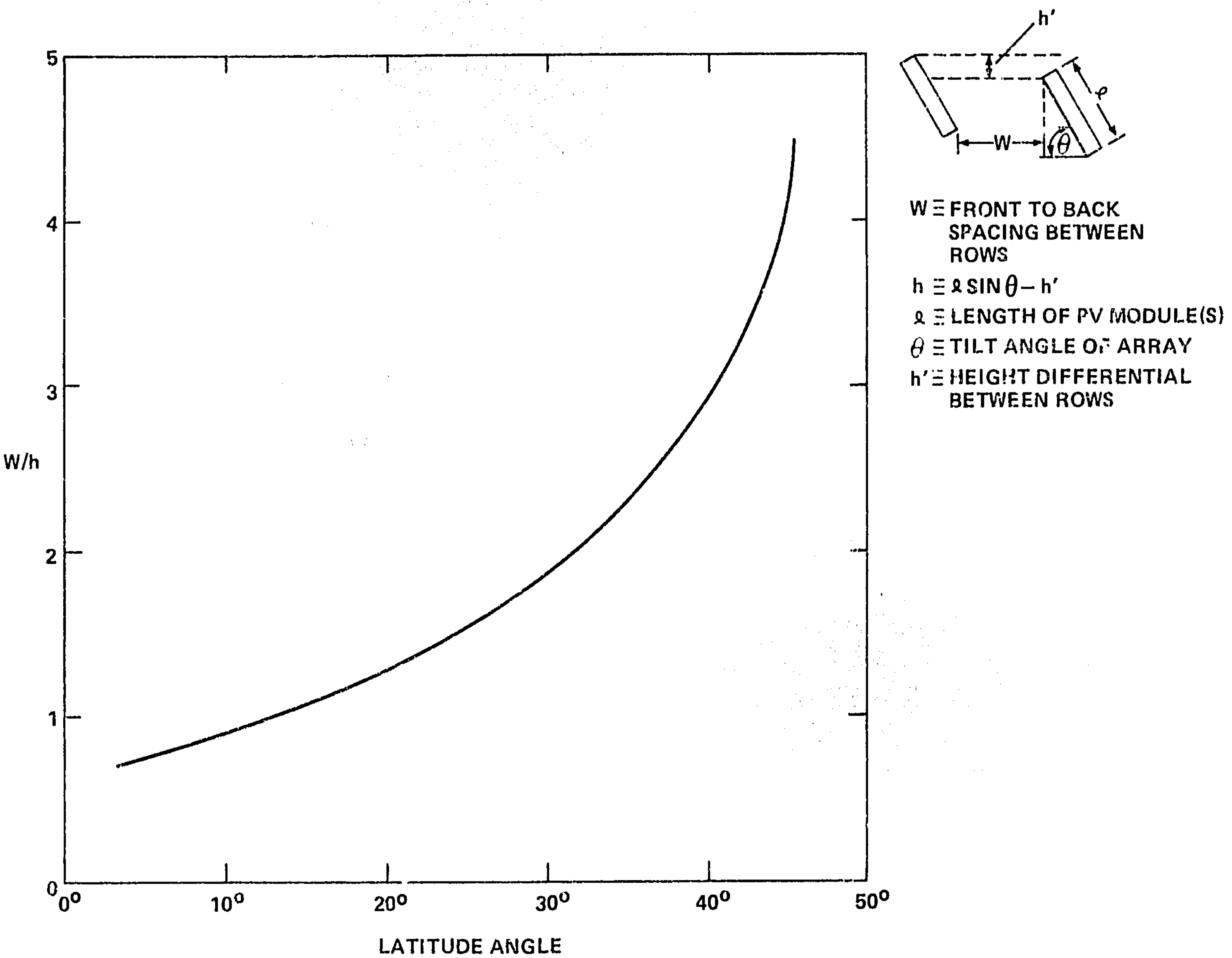



Exhibit 11.5-1

MINIMUM ROW-TO-ROW SPACING REQUIRED FOR NO SHADING BETWEEN 0900 AND 1500 HOURS ON DECEMBER 21 (JUNE 21)



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# SECTION 12
# PHOTOVOLTAIC SYSTEM COMPONENTS

A brief survey of manufacturers and standard catalogs reveals the availability and costs of the major components for photovoltaic power systems. The results of this survey are presented in the exhibits of this section. For typical systems under 1.5 kWp array sizes, there are components available off the shelf (within approximately 16 weeks). In the following subsections, each of the components will be discussed individually. The data are arranged in the order that the components appear in the system, starting with the solar array.

## 12.1 SOLAR CELL MODULES

Exhibit 12.1-1 lists data obtained from representative module manufacturers. The specifications were obtained from GSA lists, brochures and telephone calls. The prices referred to as minimum are based on small quantities, typically less than 5 kWp. Most suppliers reserve the right to determine large quantity prices at the time of the contract based on supply and demand. It should be noted that at the present, the demand exceeds the immediately available supply. Thus, some delays in delivery may be experienced. Also there are several firms not listed here which are developing new processes that will substantially effect the cost in the future. Some of these firms may enter the market as suppliers. This is meant to be a sampling of what is available and not a complete reference for these products.

The most popular modules for terrestrial power are made with silicon cells, although much research and development is being done with cadmium sulfide solar cells and other semi-conductor materials. Availability of cadmium sulfide cells is limited at present, and therefore specifications are limited too. It has been projected that the cadmium sulfide cells will become available in quantities at competitive prices (less than $8/Wp) within the year. Furthermore, an anticipated price in the range of $3/watt peak for installed dc power systems may offset the relatively low (typically 3-8 percent) efficiency posed by a cadmium silfide manufacturer.

The efficiency of silicon cells depends primarily on their purity. Lab experiments have produced samples at near theoretical maximum. Yet the variables of mass production tend to limit the efficiency of silicon cells to about 17 percent and average close to 10 percent. When the fill factor of a module or space between the cells is considered it can be understood why module sizes have not been standardized for commercial applications; however, most manufacturers supply their own structures, so standardization is of lesser importance unless it is desired to have the capability to interchange different manufacturers modules.

Although manufacturers may vary from one to another in the relativeness of their test data, some general conclusions can be drawn: photovoltage is independent of area (typically 0.5 V/cell), while current is directly related to area and light intensity. The change in current is directly proportional to the change in temperature by about 25 micro amperes per centimeter squared per degree celsius. 100 milliwatts per centimeter squared is the typical maximum intensity of sunlight. As discussed in Section 6.2 on pv arrays, the open-circuit voltage ($V_{oc}$), short-circuit current ($I_{sc}$) and series resistance ($R_{series}$) are important in combining arrays. For the same reason, the temperature coefficients are important. Arrays matched at one temperature may not be matched at another. The JPL (I-V) current per voltage tests are cited by one cell manufacturer; based on their findings a cell temperature of 28°C is standard. Yet, under nominal working conditions there is an increase in cell temperature of 15° -20° C above ambient temperature. As mentioned before, manufacturers may vary on this point.

Some arrays come with dual leads from each cell. If one should fail, the other will suffice. Few of the GSA listed arrays come with an intermediate tap that would permit the use of a partial-shunt regulator. In total, there are approximately nine manufacturers from whom modules can be bought off the shelf. At present there is a greater demand for P.V. modules than is being supplied. This is an unusual condition. Partially due to the effects of supply and demand and partially due to mass production techniques, there is a wide range in cost per watt peak from about $26/Wp to $8/Wp. Typically the mean price is about $15/Wp.



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Exhibit 12.1-1

## COMPARISON OF TYPICAL SPECIFICATIONS FOR PHOTOVOLTAIC MODULES

| Manufacturer: | | | | | |
|---|---|---|---|---|---|
| Model #: | 60-3012 | 60-3013 | 60-3014 | 60-3015 | 60-3016 |
| Price/pc. min/max:(1) | $34-41 | $62-74 | $103-124 | $83-99 | $150-180 |
| $/Watt peak:(1) | $11.81-14+ | $11.78-14+ | $9.78-11+ | $16.12-19+ | $14.25-17+ |
| Efficiency:(2) | 7.22% | 7.79% | 7.92% | 7.67% | 8.71% |
| Standard Operating Conditions:(3) | Ta:20°C Wind:1m/s NOCT:oc | same | same | same | same |
| Watts Peak: ($I_p \cdot V_p$) | 2.88 | 5.265 | 10.53 | 5.148 | 10.53 |
| Volts Peak: | 9.0 | 8.1 | 8.1 | 16.2 | 16.2 |
| Amps Peak: | 0.32 | 0.65 | 1.30 | 0.32 | 0.65 |
| V. open circuit: | | | | | |
| V. Temp. Coeff.: | | | | | |
| I. short circuit: | | | | | |
| I. Temp. Coeff.: | | | | | |
| R. series/cell: | | | | | |
| R. Temp. Coeff.: | | | | | |
| Temp. cell-Temp. air | | | | | |
| P. Temp. Coeff.: | | | | | |
| No. of Cells & Size: | 20@¼of3" | 18@½of3" | 18@ 3" | 36@¼of3" | 36@½of3" |
| Configuration: | 20s x 1p | 18s x 1p | 18s x 1p | 36s x 1p | 36s x 1p |
| Dual Leads: | | | | | |
| Intermediate Tap: | | | | | |
| Failure Rate (MTBF): | | | | | |
| Protection: | | | | | |
| Fill Factor: | | | | | |
| Panel Dimensions: | 1.75x6.87x9" | 6.87x15.25" | 6.87x30" | 6.87x15.25" | 12x15.62" |
| Front Surface Area: | 61.83"² | 104.77"² | 206.1"² | 104.77"² | 187.44"² |
| Cover Material: | Glass | Glass | Glass | Glass | Glass |
| Weight: | 2 lbs. | 3 lbs. | 5.75 lbs. | 3 lbs. | 4 lbs. |
| Ambient Temp. Limit: | | | | | |
| Insulation: | | | | | |
| Max. Snow Load: | | | | | |
| Max. Wind Load: | | | | | |
| Max. Impact: | | | | | |
| JPL Tested: | | | | | |
| GSA Listed: | yes | yes | yes | yes | yes |
| Delivery: | | | | | |

(1) Based on present 1980 $ value Domestic Price List effcective March 1, 1979

(2) Based on gross frontal area

(3) Based on 100 $mw/cm^2$, $28^o$ cell temp. (or State Other Conditions)



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Exhibit 12.1-1 (Con't)

## COMPARISON OF TYPICAL SPECIFICATIONS FOR PHOTOVOLTAIC MODULES

| | | | | | |
|---|---|---|---|---|---|
| Manufacturer:<br>Model #: | ASI16-2000 | | | | |
| Price/pc. min/max:(1) | $264-495 | | | | |
| $/Watt peak:(1) | $8 -$15 | | | | |
| Efficiency:(2) | 8.97% | | | | |
| Standard Operating Conditions:(3) | | | | | |
| Watts Peak:(4) | 33 | | | | |
| Volts Peak: | 16.1 | | | | |
| Amps Peak: | 2.05 | | | | |
| V. open circuit: | 20.3 | | | | |
| V. Temp. Coeff.: | 2.5-3mV/C/°C | | | | |
| I. short circuit: | 2.3 | | | | |
| I. Temp. Coeff.: | | | | | |
| R. series/cell: | | | | | |
| R. Temp. Coeff.: | | | | | |
| Temp. cell-Temp. air | 40°C | | | | |
| P. Temp. Coeff.: | | | | | |
| No. of Cells & Size: | 35@ 4" | | | | |
| Configuration: | 35series | | | | |
| Dual Leads: | yes | | | | |
| Intermediate Tap: | | | | | |
| Failure Rate (MTBF): | | | | | |
| Protection: | yes/op. | | | | |
| Fill Factor: | | | | | |
| Panel Dimensions: | 47.9x11.9x1.5" | | | | |
| Front Surface Area: | 570.01"² | | | | |
| Cover Material: | Glass | | | | |
| Weight: | 11 lbs. | | | | |
| Ambient Temp. Limit: | -40to+90°C | | | | |
| Insulation: | | | | | |
| Max. Snow Load: | | | | | |
| Max. Wind Load: | | | | | |
| Max. Impact: | | | | | |
| JPL Tested: | | | | | |
| GSA Listed: | | | | | |
| Delivery: | | | | | |

(1) Based on present 1980 $ value

(2) Based on gross frontal area

(3) Based on 100 mw/cm$^2$, 28$^0$ cell temp. (or State Other Conditions

(4) Recent production units have 37 watts peak which may result in a second module becoming available soon.

Exhibit 12.1-1 (Con't)

## COMPARISON OF TYPICAL SPECIFICATIONS FOR PHOTOVOLTAIC MODULES

| Manufacturer:<br>Model #: | 9200J[4] | HE50J/JG[4] | HE51J/JG[4] | HE60J/JG[4] | 4200C |
|---|---|---|---|---|---|
| Price/pc. min/max:[1] | $335.5-419+ | $499.2-624 | $504-630 | $576-720 | $219-300 |
| $/Watt peak:[1] | $13.4-16+ | $15.13-18+ | $14.82-18+ | $15.57-19+ | $10.95-15 |
| Efficiency:[2] | 7.33% | 11.60% | 11.95% | 11.38% | 7.03% |
| Standard Operating Conditions:[3] | $T_c$: 25°C ±3°C | same | same | same | same |
| Watts Peak: | 25.0 | 33.0 | 34.0 | 37.0 | 20.0 |
| Volts Peak: | | | | | |
| Amps Peak: | | | | | |
| V. open circuit: | 23 | 18/36 | 20 | 20/40 | 20 |
| V. Temp. Coeff.: | | | | | |
| I. short circuit: | | | | | |
| I. Temp. Coeff.: | | | | | |
| R. series/cell: | | | | | |
| R. Temp. Coeff.: | | | | | |
| Temp. cell-Temp. air | | | | | |
| P. Temp. Coeff.: | | | | | |
| No. of Cells & Size: | | | | | |
| Configuration: | | | | | |
| Dual Leads: | | | | | |
| Intermediate Tap: | | | | | |
| Failure Rate (MTBF): | | | | | |
| Protection: | | | | | |
| Fill Factor: | | | | | |
| Panel Dimensions: | 23x23" | 21x21" | 21x21" | 21x24" | 21x21" |
| Front Surface Area: | 529"$^2$ | 441"$^2$ | 441"$^2$ | 504"$^2$ | 441"$^2$ |
| Cover Material: | | /Glass | /Glass | /Glass | Glass |
| Weight: lbs. | 21 | 23 | 23 | 25 | 19 |
| Ambient Temp. Limit: | | | | | |
| Insulation: | | | | | |
| Max. Snow Load: | | | | | |
| Max. Wind Load: | | | | | |
| Max. Impact: | | | | | |
| JPL Tested: | | | | | |
| GSA Listed: | yes | yes | yes | yes | yes |
| Delivery: | | | | | |

(1) Based on present 1980 $ value GSA Discounts thru April 30, 1980

(2) Based on gross frontal area

(3) Based on 100 mw/cm$^2$, 28° cell temp. (or State Other Conditions)

(4) J: Integral mounting frame with junction box



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Exhibit 12.1-1 (Con't)

## COMPARISON OF TYPICAL SPECIFICATIONS FOR PHOTOVOLTAIC MODULES

| Manufacturer: | | | | | |
|---|---|---|---|---|---|
| Model #: | 1263-4G | 1294-G | 1263-S | 1203-S | 1264-S |
| Price/pc. min/max:(1) | $136-152 | $450-502 | $301-337 | $310-346 | $395-441 |
| $/Watt peak:(1) | $34-38 | $12.86-14+ | $13.68-15+ | $13.48-15+ | $12.34-13+ |
| Efficiency:(2) | 8.86% | 7.66% | 8.81% | 7.78% | 7.05% |
| Standard Operating Conditions:(3) | | | | | |
| Watts Peak: | 4 | 35 | 22 | 23 | 32 |
| Volts Peak: | | | | | |
| Amps Peak: | | | | | |
| V. open circuit: | | | | | |
| V. Temp. Coeff.: | | | | | |
| I. short circuit: | | | | | |
| I. Temp. Coeff.: | | | | | |
| R. series/cell: | | | | | |
| R. Temp. Coeff.: | | | | | |
| Temp. cell-Temp. air | | | | | |
| P. Temp. Coeff.: | | | | | |
| No. of Cells & Size: | 36@¼-3" | 39@4" | 36@3" | 42@3" | 36@4" |
| Configuration: | | | | | |
| Dual Leads: | | | | | |
| Intermediate Tap: | | | | | |
| Failure Rate (MTBF): | | | | | |
| Protection: | | | | | |
| Fill Factor: | | | | | |
| Panel Dimensions:(4) | 20x3.5 | 30x23.6 | 21.8x17.75 | 22.9x20 | 46x15.3 |
| Front Surface Area: | 70"2 | 708"2 | 386.95"2 | 458"2 | 703.8"2 |
| Cover Material: | Glass | Glass | Silicone | Silicone | Silicone |
| Weight: lbs. | 2.5 | 24.9 | 4 | 5 | 7 |
| Ambient Temp. Limit: | | | | | |
| Insulation: | | | | | |
| Max. Snow Load: | | | | | |
| Max. Wind Load: | | | | | |
| Max. Impact: | | | | | |
| JPL Tested: | | | | | |
| GSA Listed: | Yes | Yes | Yes | Yes | Yes |
| Delivery: | | | | | |

(1) Based on present 1980 $ value GSA Discount list effective thru April 30, 1980

(2) Based on gross frontal area

(3) Based on 100 mw/cm$^2$, 28$^o$ cell temp. (or State Other Conditions)

(4) Heighth: Glass-1.75", Silicone-.25"



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## 12.2 BATTERIES

A detailed analysis of various batteries has been presented in Section 4.3. Both nickel cadmium and lead-acid batteries are represented in Exhibit 4.3-1. A distinction should be made between two types of lead-acid batteries, the lead-antimony (typically useful to 5 to 10 percent maximum depth of discharge) and lead-calcium (most useful to 20 percent, some useful to 80 percent maximum depth of discharge). The specifications for depth of discharge and number of cycles per life vary widely. It is therefore difficult to compare the various types. For instance, nickel cadmium batteries are generally capable of being used to 100 percent of the maximum rated depth of discharge for thousands of cycles over many years.

The prime contenders for use with photovoltaic systems are the NiCd and lead-calcium. Some loads may not require battery storage, while some may require the storage to be displaced in a day, and others may require several days of storage or even several weeks where high dependability is demanded. In any case the battery manufacturer should always be consulted before making the final choice as to the appropriate cell for a particular application.

The actual battery size is not usually important, because battery cells, like PV cells, 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.

Exhibit 12.2-1 lists many of the characteristics and specifications of impor. ice in determining the appropriate cell and block of cells for a photovoltaic application. The information asked for here is general and battery manufacturers prefer to quote on specific applications; therefore, companies such as those listed in Section 14 and elsewhere should be referred to for exact specifications.

Exhibit 12.2-1

## TABLE OF IMPORTANT BATTERY DESIGN CHARACTERISTICS

Manufacturer:
Type:[1]
Model:
Typical Application:
Price:
- total
- $/kwh

Delivery:
Efficiency:
Input (at 5 hr. rate):
Charging:
- Max. volts
- Max. current

Overcharging:
- Max. volts
- Max. current

Output (at 8 hr. rate):
- at 20 hr. rate:
- at 7 day rate:
- at 3week rate:
- kwh
- Ah
- volts
- Max. current

Life Cycles:
- 10% depth
- 20% depth
- 50% depth
- 80% depth
- 90% depth
- 100% depth
- Shelf

Self Discharge:
Physical:
- Dimensions:
- Weight:
- Temp. Limits:
- 0% charge:
- 50% charge:
- 100% charge:

$ (cycle x kwh)*[2]
$ (years x kwh)*[2]

---

1) Nickel Cadmium Calcium or Lead Antimony, etc.
2) Based on 100% discharge except as noted.



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## 12.3 DC REGULATORS

The primary purpose of regulators is to prevent storage batteries from overcharging.

Most solar module manufacturers will supply regulators or recommend if specified. These specifications vary according to the combination of arrays and the configuration of the batteries and the load. Typical data which should be specified are listed in Exhibit 12.3-1. Costs will be on the order of $1/W.

- Manufacturer
- Model
- Price
- Delivery
- Efficiency
- Input
  - Volts
  - Amps
  - Protection
- Output
  - Waveform
  - Volts
  - Amps
  - Protection
- MTBF
- Physical
  - Dimensions
  - Weight (kg)
  - Temp. Limits
  - Cooling

Exhibit 12.3-1

DC REGULATORS SPECIFICATION REQUIREMENTS

## *12.4 DC MOTORS

Direct-Current motors are acknowledged to be unsurpassed for adjustable-speed applications and other applications with severe torque requirements.

Since dc is no longer generally available from most industrial plant buses or utility networks, the most common practice to supply dc motors has been by a solid state rectifier for each motor, or for a group of motors in a process. Manufacturers of dc motors generally offer a very limited selection of dc motors for special applications as compared to ac motors. Exhibit 12.4-1 contains some representative data on dc motors obtained from manufacturers.

Permanent magnet motors are offered in small fractional horsepower ranges, sometimes in integral ratings, but rarely above 10 hp. Wound field motors are offered with either shunt, series or compound field configurations. For efficiency data and discount multipliers against List Prices, it is recommended that the manufacturer's factory be contacted directly for the specific application at hand.

## Exhibit 12.4-1
## REPRESENTATIVE DATA ON DC MOTORS

**Permanent Magnet**

| HP | Speed RPM | Armature Volts | NEMA Frame | Encl* | Max. Peak Current | F.L. Amps | List Price | Est. Shpg. Wt. (Lbs.) |
|---|---|---|---|---|---|---|---|---|
| 1/4 | 1725 | 90 | 56C | TENV | 30 | 2.8 | $149.00 | 20 |
| 1/3 | 1725 | 90 | 56C | TENV | 40 | 3.6 | 165.00 | 26 |
| 1/2 | 1725 | 90 | 56C | TEFC | 52 | 5.5 | 181.00 | 32 |
| 3/4 | 1725 | 90 | 56C | TEFC | 70 | 8.0 | 221.50 | 40 |
| | | 180 | 56C | TEFC | 34 | 4.0 | 231.50 | 40 |
| 1 | 1725 | 90 | 56C | TEFC | 88 | 10.7 | 267.00 | 46 |
| | | 180 | 56C | TEFC | 44 | 5.2 | 279.00 | 46 |

Wound Field

## Exhibit 12.4-1 (Continued)

## REPRESENTATIVE DATA ON DC MOTORS

**120 Volts, ¾ to 15 Horsepower**

| Hp | Speed, Rpm | | ¼ Hour Rating | | ½ Hour Rating | |
|---|---|---|---|---|---|---|
| | Series Wound | Compound Wound | Frame | Basic List Price① W-26 | Frame | Basic List Price① W-26 |
| ¾ | 1050 | 1150 | 187A | $ 576 | 187A | $ 651 |
| | 750 | 850 | 187A | 744 | 187A | 772 |
| 1 | 1600 | 1750 | 187A | 580 | 187A | 604 |
| | 1050 | 1150 | 187A | 693 | 187A | 719 |
| | 750 | 850 | 187A | 817 | 187A | 847 |
| 1½ | 1600 | 1750 | 187A | 668 | 187A | 691 |
| | 1050 | 1150 | 187A | 782 | 187A | 786 |
| | 750 | 850 | 187A | 894 | 187A | 945 |
| 2 | 1600 | 1750 | 187A | 753 | 187A | 785 |
| | 1050 | 1150 | 187A | 891 | 187A | 945 |
| | 750 | 850 | 216A | 1571 | 216A | 1608 |
| 3 | 1600 | 1750 | 187A | 838 | 187A | 856 |
| | 1050 | 1150 | 216A | 1067 | 216A | 1098 |
| | 750 | 850 | 216A | 1627 | 218A | 1679 |
| 5 | 1600 | 1750 | 216A | 1053 | 216A | 1086 |
| | 1050 | 1150 | 218A | 1661 | 218A | 1669 |
| | 750 | 850 | 256A | 1938 | 256A | 2045 |
| 7½ | 1600 | 1750 | 216A | 1685 | 218A | 1730 |
| | 1050 | 1150 | 218A | 2109 | 283AT | 2142 |
| | 750 | 850 | 283AT | 2499 | 283AT | 2555 |
| 10 | 1600 | 1750 | 218A | 2008 | 256A | 2118 |
| | 1050 | 1150 | 283AT | 2516 | 283AT | 2572 |
| | 750 | 850 | 283AT | 2958 | 284AT | 3040 |
| 15 | 1600 | 1750 | 256A | 2640 | 283AT | 2686 |
| | 1050 | 1150 | 283AT | 3120 | 284AT | 3196 |
| | 750 | 850 | 284AT | 3632 | 286AT | 3822 |

① Prices shown are in U.S.A. dollars.

*Totally-Enclosed Non-Ventilated Series or Compount Wound
Single Straight Shaft, Class F Insulation, 40°C Ambient
1.00 Service Factor

## SECTION 13
## GLOSSARY OF TERMS

This section includes definitions of photovoltaic terminology and conversion factors to convert English units to SI units.

### 13.1 DEFINITIONS OF PHOTOVOLTAIC TERMINOLOGY

ALTITUDE - Angle between the horizontal plane and the direction of beam radiation.

ANGLE OF INCIDENCE - Angle between the normal to a surface and the direction of incident radiation; applies to aperture plane of a solar collector.

ARRAY - A mechanically integrated assembly of modules together with support structure, exclusive of foundation, inclusive of tracking, heat transfer, and other components, as required to form a dc power producing unit.

ARRAY FIELD SUBSYSTEM - The aggregate of all solar photvoltaic arrays and support foundations generating dc power within a photovoltaic system.

AZIMUTH (of Surface) - Angle between the North direction and the projection of the surface normal into the horizontal plane; measured clockwise from North.

BEAM - Refers to radiation received from the sun without change of direction; applied as beam irradiance or beam irradiation.

BLOCKING DIODE - A semi-conductor connected in series with a solar cell or cells and a storage battery to prevent a reverse current discharge of the battery through the cell when there is no output, or low output from the cell.

BRANCH CIRCUIT - A group of modules or paralleled modules connected in series to provide dc power at the dc voltage level of the power conditioning subsystem. A branch circuit may involve the interconnection of modules located in several arrays.

BYPASS DIODE - A semiconductor connected in parallel with a series block of parallel strings to prevent excessive current from flowing through any unfailed substring in the series block upon partial shading of another substring in the same block.

DIFFUSE - Refers to radiation received from the sun after reflection and scattering by the atmosphere; also scattered; applied as diffuse irradiance or diffuse irradiation.

ELECTRIC POWER BUS - A conductor, or group of conductors, that serve as a common connection for two or more circuits.

EQUINOX - The time when the sun in its apparent motion in the celestial sphere crosses the equator; c. March 21 is the vernal equinox (northern hemisphere) and c. September 23 is the autumnal equinox (northern hemisphere); declination is zero; vernal equinox more precisely defined as the point of intersection of the ecliptic and the equator on the celestial sphere.

FILL FACTOR - The ratio of maximum power output of a cell or array to the product of the open circuit voltage and the short circuit current.

HOUR ANGLE - The angle between the hour circle of the sun and the observer's meridian.

INSOLATION - The solar radiation incident on an area. Usually expressed in milliwatts per square centimeter or watts per square meter.

LIFE CYCLE COST - An estimate of the cost of owning and operating a system for the period of its useful life; usually expressed in terms of the present value of all lifetime costs.

MAXIMUM POWER - Refers to a photovoltaic cell; the power at the point on the current-voltage curve where the current-voltage product is a maximum.

MODULE - The smallest, complete, environmentally-protected assembly of solar cells, optics, and other components designed to generate dc power.

ORIENTATION - Placement with respect to the cardinal directions, N, S, E, W; azimuth is the measure of orientation.

PHOTOVOLTAIC CELL - A photovoltaic cell is one that generates electrical energy when light falls on it. This term distinguishes it from a photoconductive cell (photoresistor) which changes its electrical resistance when light falls on it.

PHOTOVOLTAIC SYSTEM - An installed aggregate of solar arrays and other subsystems transmitting power to a given application. A system will generally include the following sub-systems:

- Array field
- Power conditioning and control
- Storage (if required)
- Backup (if required)
- Thermal (if required, noting that portions of a thermal subsystem may be included in the fabrication of the array)
- Land, security systems and buildings
- On-site conduit/wiring
- Instrumentation
- Maintenance and repair equipment

POWER CONDITIONING - The function of a subsystem which generally renders the variable dc output of an alternate energy source to be suitable to meet the power supply requirements of more traditional loads. The power conditioning subsystem of a dc photovoltaic power system would typically include voltage regulation, energy storage and possibly a dc/dc converter interface with loads. The power conditioning subsystem of an ac photovoltaic power system may also typically include energy storage, and conversion of the dc output to an ac waveform, wave form filtering and voltage transformation to meet the requirements of the load.

SOLAR CELL - Photovoltaic cell.

SOLSTICE - The time when the sun in its apparent motion in the celestrial sphere attains the maximum distance from the equator; c. June 21 is the sumer solstice (northern hemisphere) and c. Dec. 22 is the winter solstice (northern hemisphere); declination is a maximum.

SPECTRAL - refers to reflection in which the angle of incidence is equal to and in the same plane as the angle of reflection; reflection as in a mirror.

TILT (of Surface) -Angle of inclination of collector.

## 13.2 CONVERSION FACTORS

The following tables express the definitions of miscellaneous units of measure as exact numerical multiples of coherent SI units, and provide multiplying factors for converting numbers and miscellaneous units to corresponding new numbers and SI units.

The first two digits of each numerical entry represent a power of 10. An asterisk follows each number which expresses an exact definition. For example the entry "-02 2.54*" expresses the fact that 1 inch = 2.54 x $10^{-2}$ meter, exactly, by definition. Numbers not followed by an asterisk are only approximate representations of definitions, or are the results of physical measurements. The primary source of these tables is Reference 13-1. Most of the definitions are extracted from National Bureau of Standards documents.

| To convert from | to | multiply by |
|---|---|---|
| acre | $meter^2$ | +03 4.046 856 422 4* |
| atmosphere | $newton/meter^2$ | +05 1.013 25* |
| British thermal unit (thermochemical) | joule | +03 1.054 350 |
| Btu (thermochemical)/$foot^2$ hour | $watt/meter^2$ | +00 3.152 480 8 |
| calorie (International Steam Table) | joule | +00 4.1868 |
| Celsius (temperature) | kelvin | $t_k = t_C + 273.15$ |
| circular mil | $meter^2$ | -10 5.067 074 8 |
| degree (angle) | radian | -02 1.745 329 251 994 3 |
| Fahrenheit (temperature) | kelvin | $t_K = (5/9)(t_F + 459.67)$ |
| Fahrenheit (temperature) | Celsius | $t_C = (5/9)(t_F - 32)$ |
| foot | meter | -01 3.048* |
| footcandle | $lumen/meter^2$ | +01 1.076 391 0 |
| footlambert | $candela/meter^2$ | +00 3.426 259 |
| gallon (U.S. liquid) | $meter^3$ | -03 3.785 411 784* |
| horsepower (550 foot lbf/second) | watt | +02 7.456 998 7 |
| inch | meter | -02 2.54* |
| kilocalorie (thermochemical) | joule | +03 4.184* |
| lambert | $candela/meter^2$ | +03 3.183 098 8 |
| langley | $joule/meter^2$ | +04 4.184* |

| To convert from | to | multiply by |
| --- | --- | --- |
| mil | meter | -05 2.54* |
| mile (U.S. statute) | meter | +03 1.609 344* |
| mile/hour (U.S. statute) | meter/second | -01 4.4704* |
| ounce force (aviordupois) | newton | -01 2.780 138 5 |
| ounce mass (aviordupois) | kilogram | -02 2.834 952 312 5* |
| phot | lumen/meter$^2$ | +04 1.00 |
| pound force (lbf avoirdupois) | newton | +00 4.448 221 615 260 5* |
| pound mass (lbm avoirdupois) | kilogram | -01 4.535 923 7* |
| psi (lbf/inch$^2$) | newton/meter$^2$ | +03 6.894 757 2 |
| Rankine (temperature) | kelvin | $t_k = (5/9)\ t_R$ |
| yard | meter | -01 9.144* |

## SECTION 14
## PHOTOVOLTAIC POWER SYSTEM EQUIPMENT SUPPLIERS*

### 14.1 PHOTOVOLTAIC CELLS, MODULES

APPLIED SOLAR ENERGY CORP.
15251 E. Don Julian Road
P.O. Box 1212
City of Industry, CA 91749
ATTN: George Holme III
Product Marketing Manager
(213) 968-6581

ARCO SOLAR INC.
20554 Plummer Street
Chatsworth, CA 91311
ATTN: Tim Geiser
Eastern Region Sales Manager
(213) 998-0667

MOTOROLA INC.
Solar Products Operations
5005 East McDowell Road
Phoenix, AZ 85008
ATTN: Pat Walton
Solar Product Marketing
(602) 244-6511

PHOTON POWER
10767 Gateway West
El Paso, TX 79935
ATTN: Martin F. Wenzler
(915) 593-2861

PHOTOWATT INTERNATIONAL INC.
2414 W. 14th Street
Tempe, AZ 85281
Vice President & Tec. Dir.
(602) 894-9564

SES, INC.
Tralee Industrial Park
Newark, DE 19711
ATTN: Greg T. Love
Manager, Industrial Sales
(302) 731-0990

SOLAREX CORP.
1335 Piccard Drive
Rockville, MD 20850
ATTN: Theodore Blumenstock
Director of Marketing
(301) 948-0202

SOLAR POWER CORP.
Affiliate of Exxon Enterprises
20 Cabot Road
Woburn, MA 01801
ATTN: Kurt Grice
Marketing Services
(617) 935-4600

SOLEC INTERNATIONAL, INC.
12533 Chadron Avenue
Hawthorne, CA 90250
ATTN: Ishaq Shahryar, President
(213)970-0065

SOLENERGY CORP.
23 North Avenue
Wakefield, MA 01880
ATTN: Bob Willis, President
(617) 246-1855

SOLLOS, INC.
2231 S. Carmelina
Los Angeles, CA 90064
(213) 820-5181

TIDELAND SIGNAL CORP.SES, INC.
4310 Directors Road
P.O. Box 52430
Houston, TX 77052
(713) 681-6101

*See footnote on p. 14-5

## 14.2 BATTERIES*

CHLORIDE.
Mallard Lane
North Haven, CT 06473
(203) 624-7837

C & D BATTERIES DIV.
3043 Walton Road
Plymouth Meeting, PA 19462
ATTN: Clayton J. Molnar
Sales Manager
(215) 828-9000

DELCO-REMY
Division of G.M.
2401 Columbus Avenue
Anderson, IN 46011
ATTN: Charlie Erk
(317) 646-7816

EAGLE-PICHER INDUSTRIES, INC
Department G
P.O. Box 130
(417) 776-2258

THE EXIDE CORP.
"Horsham I"
101 Gibralter Road
ATTN: Mr. Gene Cook
Specialty Battery Division
(215) 674-9500

GENERAL ELECTRIC CO.
Battery Business
Department G
P.O. Box 861
Gainesville, FL 32602
(904) 462-3911

GLOBE-UNION
Battery Division
Gel/Cell Marketing
5757 N. Green Bay Avenue
Milwaukee, WI 53201
ATTN: Fred Gruner
Reg. Marketing Manager
(414) 228-2393

KEYSTONE BATTERY CORP.
35 Holton Street
Winchester, MA 01890
ATTN: Edward J. Modest
Vice President

MC GRAW-EDISON COMPANY
Power Systems Division (Batteries)
P.O. Box 28
Bloomfield, NJ 07003
ATTN: Mr. Robert Enters
Chief Engineer

NIFE INCORPORATED
P.O. Box 100
George Washington Hwy.
Lincoln, RI 02865
ATTN: Richard V. Barone, Sc. D
Manager, Applications Engineering
(800) 556-6746

SGL BATTERY MANUFACTURING CO.
14650 Dequindre
Detroit, MI 48212
ATTN: Paul Rosser
Sales & Service Coordinator
(313) 868-6410

SURRETTE STORAGE BATTERY CO., INC.
Engineering Division
15 Park Street Tilton, NH 03276
ATTN: Archie McGowan
(603) 286-8974

*See footnote p. 14-5

## 14.3 POWER CONDITIONING EQUIPMENT*

ABACUS CONTROLS, INC.
P.O. Box 893
80 Readington Road
Somerville, NJ 08876

ADVANCE CONVERSION DEVICES CO.
109 Eighth St.
Passaic, NJ 07055

AVIONIC INSTRUMENTS, INC.
943 East Hazelwood Ave.
Rahway, NJ 07065

BEHLMAN ENGINEERING CORP.
P.O. Box 4518
Santa Barbara, CA 93103

CALIFORNIA INSTRUMENTS
5151 Convoy St.
San Diego, CA 92111

COMPUTER POWER INC.
124 West Main St.
High Bridge, NJ 08829

DELTA ELECTRONIC CONTROL CORP
2801 S.W. Main Street
Irvine, CA 92714

DELTEC CORP.
980 Buenos Ave.
San Diego, CA 92110

DUEL-LITE, INC.
Simm Lane Newton, CT
Newton, CT

ELGAR CORP.
8225 Mercury Court
San Diego, CA 92111

EMERSON ELECTRIC CO.
8100 W. Florissant Avenue
St. Louis, MO 63136

EMERSON ELECTRIC CO.
3301 Spring Forest Road
Raleigh, NC 27604

GARRETT CORP.
1 Huntington Quadrangle
Suite 4 S04
Huntington Station, NY 11746

LAMARCHE MFG. CO.
106 Bradock Drive
Des Plaines, IL 60018

LOR TEC POWER SYSTEMS, INC.
5214 Mills Industrial Parkway
North Ridgeville, OH 44305

MCGRAW EDISON CO
P.O. Box 23
Bloomfield, NJ 07003

NOVA ELECTRIC MFG., CO.
263 Hillside Avenue
Nutley, NJ 07110

PACIFIC POWER SOURCE DIV.
5219 Systems Drive
Huntington Beach, CA 92649

RATELCO, INC.
1260 Mercer Street
Seattle, WA 98109

RELIANCE ELECTRIC CO.
1130 F. Street
Lorain, OH 44052

*See footnote on p. 14-5

SOLEQ CORP.
5969 North Elston Avenue
Chicago, IL 60646

STACO ENERGY PRODUCTS CO.
301 Gaddis Blvd
Dayton, OH 45403

TELEDYNE, INC.
1901 Avenue of the Stars
Los Angeles, CA 90067

TOPAZ ELECTRONICS
3855 Ruffin Road
San Diego, CA 92123

TRIPP MANUFACTURING CO.
133 N.Jefferson St.
Chicago, IL 60606

UNITED TECHNOLOGY CORP.
Power Systems Division
P.O. Box 109
South Windsor, CT 06074

VARO, INC., POWER SYSTEMS DIV.
2201 Walnut St.
Garland, TX 75040

VERSACOUNT PRODUCTS
553 Libley Blvd.
Elk Grove Village, IL 60007

WESTINGHOUSE ELECTRIC CO.
P.O. Box 989
Lima, OH 45802

WILMORE ELECTRONICS CO., INC.
P.O. Box 1329
Hillsborough, NC 27278

WINDWORKS INC.
Route 3, Box 44 A
Mukwonago, WI 53149

## 14.4 DIRECT CURRENT MOTORS AND LOAD DEVICES*

GENERAL ELECTRIC CO.
General Purpose Motor Dept.
2000 Taylor St.
Fort Wayne, IN 46804

GOULD INC.
Electric Motor Division
1831 Chestnut St.
St. Louis, MO 63166

INLAND MOTORS
Industrial Drives Division
609 Rock Road
Radford, VA 24141

LOUIS ALLIS
Drives & Systems Division
New Berlin, WI 53151

PMI MOTORS
Division of Kollmorgen Corp.
5 Aerial Way
Syosset, NY 11791

WESTINGHOUSE ELECTRIC CORP.
Defense Group
P.O. Box 9892
Lima, OH 45802

WESTINGHOUSE ELECTRIC CORP.
Large Motor Divsion
Buffalo, NY 14240

*Note: This compendium is not intended to be an exhaustive listing of equipment suppliers for photovoltaic power systems, but rather a representative sampling of manufacturers in a dynamic and changing field. It is expected that additional firms will be developing products for the photovoltaic market in the future. This list does not in any way constitute endorsement of any manufacturer, any supplier, or any product by MONEGON, Ltd., or NASA, or the U.S. DOE, or any of their employees or subcontractors.

# APPENDIX A
# WORLDWIDE INSOLATION DATA

Note:

The data have been generated from the SOLMET (Reference A-1) and the University of Wisconsin reports (Reference A-2). The data are presented as values of monthly average $K_H$, the ratio of insolation on a horizontal surface to the insolation on an extraterrestrial horizontal surface. The values of the monthly average $K_H$ are listed in per unit (X $10^3$).

The key to the abbreviations used is as follows:

General

- \- Data Missing
- * Theory Not Applicable
- [1] The data should read as if it were preceded by a decimal point. I.e., the datum 495 is $K_H$ = 0.495.
- CFP Computed From Percent Sunshine
- PPS Data is in Percent Possible Sunshine (conversion values not available). Note [1] does not apply to these data as they are listed in percent, i.e. the datum 057 is 57% possible sunshine.

Specific

- LAT/LONG data for Hochserfaus, Switz. could not be found. Used LAT/LONG values for Hochdorf.
- All data under 'United States' comes from Input Data For Solar Systems (SOLMET data), Ref. A-1.
- New York City has two separate stations: Central Park (CN. PRK) and La Guardia (LGA).

APPENDIX A (CON'T)

| STATION | LAT | LONG | ELEV | VALUES OF MONTHLY AVG. KH * 1000 [1] JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | ADEN<br>==== | | | | | | | | | |
| ADEN | 12 50'N | 45 01'E | 4 | 573 | 607 | 627 | 656 | 634 | 592 | 562 | 597 | 618 | 663 | 668 | 632 | |
| | | | | | | | ALGERIA<br>======= | | | | | | | | | |
| ADRAR | 27 52'N | 0 17'W | 258 | 716 | 708 | 730 | 706 | 699 | 723 | 721 | 716 | 686 | 665 | 666 | 658 | |
| AIN SEFRA | 32 45'N | 0 36'W | 1072 | 693 | 694 | 690 | 700 | 687 | 703 | 704 | 701 | 702 | 672 | 672 | 672 | |
| AOULEF | 26 58'N | 1 05'E | 290 | 700 | 681 | 697 | 693 | 689 | 673 | 691 | 682 | 694 | 671 | 653 | 622 | |
| BENI ABBES | 30 08'N | 2 11'W | 498 | 702 | 690 | 668 | 690 | 666 | 656 | 666 | 664 | 661 | 629 | 610 | 639 | |
| BISKRA | 34 51'N | 5 44'E | 124 | 602 | 619 | 611 | 590 | 593 | 609 | 631 | 638 | 599 | 584 | 566 | 574 | |
| CHOTTECH CHERQUI | 34 00'N | 1 00'E | - | 505 | 577 | 672 | 622 | 612 | 638 | 634 | 663 | 586 | 719 | 651 | 566 | |
| COLOMB-BECHAR | 31 36'N | 2 13'W | - | 669 | 677 | 680 | 672 | 676 | 654 | 664 | 666 | 644 | 644 | 633 | 625 | |
| DJANET | 24 33'N | 9 29'E | - | 677 | 801 | 719 | 698 | 670 | 700 | 717 | 703 | 659 | 663 | 620 | 675 | |
| DJELFA | 34 41'N | 3 15'E | 160 | 553 | 581 | 567 | 554 | 603 | 609 | 620 | 627 | 624 | 566 | 564 | 545 | |
| EL GOLEA | 30 35'N | 2 53'E | 397 | 690 | 696 | 699 | 680 | 687 | 686 | 707 | 709 | 689 | 663 | 636 | 670 | |
| EL OUED | 33 22'N | 6 53'E | 70 | 766 | 790 | 664 | 806 | 787 | 674 | 725 | 676 | 798 | 722 | 716 | 786 | |
| FORT FLATTERS | 28 06'N | 6 49'E | 381 | 680 | 693 | 678 | 673 | 678 | 671 | 710 | 705 | 687 | 680 | 668 | 640 | |
| FORT DE POLIGNAC | 26 30'N | 8 29'E | 566 | 674 | 690 | 694 | 680 | 668 | 684 | 703 | 704 | 692 | 680 | 663 | 633 | |
| GERRYVILLE | 33 41'N | 1 01'E | 1305 | 558 | 603 | 587 | 586 | 613 | 620 | 621 | 625 | 630 | 588 | 548 | 550 | |
| GHARDAIA | 32 29'N | 3 40'E | 527 | 698 | 700 | 697 | 697 | 697 | 694 | 705 | 711 | 672 | 679 | 659 | 678 | |
| LAGHOUAT | 33 48'N | 2 53'E | 767 | 589 | 594 | 582 | 584 | 603 | 601 | 621 | 613 | 601 | 565 | 558 | 561 | |
| OUALLEN | 24 36'N | 1 14'E | 347 | 703 | 808 | 715 | 697 | 681 | 681 | 687 | 681 | 681 | 685 | 694 | 630 | |
| OUARGLA | 31 57'N | 5 20'E | 138 | 676 | 683 | 683 | 673 | 655 | 633 | 705 | 689 | 659 | 648 | 639 | 632 | |
| TAMANRASSET | 22 42'N | 5 30'E | 1376 | 716 | 717 | 723 | 709 | 691 | 658 | 687 | [illegible] | 611 | 643 | 654 | 678 | |
| TIMIMOUN | 29 15'N | 0 14'E | 284 | 704 | 710 | 715 | 699 | 698 | 699 | 708 | 696 | 694 | 664 | 597 | 643 | |
| TOUGGOURT | 33 07'N | 6 04'E | 69 | 655 | 698 | 665 | 607 | 676 | 652 | 704 | 702 | 690 | 644 | 617 | 631 | |
| | | | | | | | ANGOLA<br>====== | | | | | | | | | |
| DUNDO | 7 04'S | 20 08'E | 745 | 470 | 472 | 482 | 538 | 584 | 578 | 520 | 476 | 490 | 509 | 490 | 471 | |
| LUANDA | 8 49'S | 13 13'E | 42 | 536 | 558 | 527 | 525 | 556 | 542 | 420 | 416 | 462 | 477 | 512 | 558 | |
| LUSO | 11 08'S | 19 09'E | 1328 | 465 | 539 | 509 | 641 | 690 | 729 | 741 | 760 | 606 | 550 | 532 | 507 | |
| MALANGE | 9 33'S | 16 22'E | 1151 | 489 | 543 | 515 | 509 | 614 | 664 | 610 | 549 | 514 | 514 | 488 | 506 | |
| MOCAMEDES | 15 02'S | 12 02'E | 44 | 578 | 586 | 591 | 584 | 590 | 459 | 449 | 450 | 471 | 516 | 589 | 576 | |
| | | | | | | | ANTARCTICA<br>========== | | | | | | | | | |
| AMUNDSEN-SCOTT | 90 00'S | | 2800 | * | * | * | - | - | - | - | - | * | * | * | * | |
| BASE ROI BAUDOUIN | 70 26'S | 24 19'E | 37 | * | 651 | 532 | 438 | * | - | * | 571 | 619 | 627 | 669 | * | |
| BYRD STATION | 79 59'S | 120 01'W | 1515 | - | - | - | * | * | * | * | * | 535 | 541 | * | * | |
| CHARCOT | 69 22'S | 139 01'E | 2401 | * | 381 | - | - | - | - | * | 613 | 754 | 785 | 845 | * | |
| ELLSWORTH STATION | 77 44'S | 41 07'W | 43 | * | * | 578 | - | - | - | - | - | 617 | 646 | * | * | |
| HALLETT STATION | 72 18'S | 170 19'E | 5 | * | 449 | 384 | 383 | * | * | * | - | 675 | 680 | * | * | |
| HALLEY BAY | 75 31'S | 26 36'W | 30 | * | 528 | 550 | 543 | * | * | * | * | 582 | 669 | * | * | |
| LITTLE AMERICA V | 75 31'S | 26 36'W | 30 | * | 466 | 487 | 230 | * | * | * | * | 514 | 590 | * | * | |
| MAWSON | 67 37'S | 62 53'E | 8 | 643 | 584 | 534 | 614 | 769 | * | 882 | * | 746 | 697 | 684 | * | |
| MIRNY | 66 33'S | 93 01'E | 37 | 729 | 768 | 679 | 595 | 571 | * | * | 596 | 694 | 773 | 820 | 712 | |
| NORWAY STATION | 70 30'S | 2 32'W | 58 | * | 614 | 564 | 513 | * | * | * | 581 | 622 | 673 | 718 | * | |
| PIONERSKAJA | 69 44'S | 95 30'E | 2700 | - | 900 | 830 | 518 | 978 | - | - | 584 | 622 | 775 | 848 | * | |
| SCOTT BASE | 77 15'S | 166 48'E | 16 | * | * | 488 | 429 | - | - | - | * | 572 | 719 | * | * | |
| WILKES STATION | 66 16'S | 110 34'W | 12 | - | - | 476 | 366 | 333 | 985 | 412 | 507 | 529 | 576 | 545 | 576 | |
| | | | | | | | ARCTIC OCEAN<br>============ | | | | | | | | | |
| DRIFTING STATION A | 84 30'N | 148 00'W | 2 | - | - | - | * | - | - | - | - | - | - | - | - | |

APPENDIX A (CON'T)

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ARCTIC OCEAN (CON'T) | | | | | | | | | | |
| ICE ISLAND T-3 | 83 00'N | 102 30'W | 8 | * | * | * | * | * | * | * | * | 602 | * | * | * | |
| NP-6 | 82 18'N | 123 08'E | 0 | * | * | 642 | * | * | * | * | * | 451 | * | * | * | |
| NP-7 | 85 40'N | 24 30'W | 0 | * | * | * | * | * | * | * | * | 490 | * | * | * | |
| | | | | | | ARGENTINA | | | | | | | | | | |
| ANDALGALA | 27 36'S | 66 20'W | 1081 | 575 | 562 | 571 | 587 | 494 | 450 | 564 | 616 | 645 | 678 | 616 | 548 | CFP |
| ARGENTINE IS. | 65 15'S | 64 16'W | 10 | 466 | 459 | 358 | 413 | 431 | * | 704 | 570 | 540 | 590 | 518 | 558 | |
| BARILOCHE | 41 09'S | 71 01'W | 826 | 591 | 507 | 569 | 413 | 382 | 362 | 365 | 486 | 534 | 545 | 576 | 621 | |
| BUENOS AIRES OBS. | 34 35'S | 58 29'W | 25 | 623 | 599 | 562 | 543 | 522 | 482 | 505 | 540 | 558 | 568 | 575 | 614 | |
| CASTELAR | 34 36'S | 58 40'W | 16 | 600 | 552 | 554 | 530 | 473 | 413 | 513 | 558 | 571 | 594 | 584 | 578 | |
| CIPOLLETTI | 38 57'S | 67 59'W | 265 | 666 | 659 | 630 | 552 | 480 | 423 | 488 | 532 | 609 | 602 | 601 | 674 | CFP |
| COLONIA SARMIENTO | 45 35'S | 69 04'W | 272 | 543 | 564 | 522 | 528 | 518 | 432 | 495 | 567 | 527 | 551 | 528 | 502 | CFP |
| COMODORO RIVADAVIA | 45 47'S | 67 30'W | 61 | - | 650 | - | 478 | - | - | 329 | 438 | 537 | 501 | 632 | 604 | |
| CONCORDIA | 31 23'S | 58 02'W | 37 | 633 | 633 | 587 | - | 451 | 344 | 450 | 508 | 542 | 607 | 633 | 608 | |
| CORDOBA | 31 19'S | 64 13'W | 484 | - | - | - | - | 509 | 429 | 381 | 469 | 652 | 516 | 545 | 548 | |
| CORRIENTES | 27 28'S | 58 49'W | 52 | 590 | 581 | 570 | 549 | 535 | 527 | 524 | 550 | 565 | 566 | 590 | 573 | |
| ESQUEL | 42 54'S | 71 21'W | 568 | 585 | 579 | 500 | 479 | 409 | 403 | 432 | 495 | 559 | 577 | 552 | 562 | CFP |
| HUINCA RENANCO | 34 50'S | 64 22'W | 182 | 613 | 625 | 610 | 556 | 470 | 508 | 527 | 528 | 561 | 590 | 612 | 611 | |
| LA QUIACA | 22 06'S | 65 36'W | 3458 | - | - | 749 | 822 | 793 | 798 | 806 | 841 | 876 | 871 | 835 | 796 | |
| LABOULAYE | 34 08'S | 63 24'W | 0 | 624 | 583 | 584 | 612 | 946 | - | - | 640 | 609 | 644 | 628 | 627 | |
| LAS LAJAS | 38 32'S | 70 23'W | 713 | 674 | 676 | 639 | 586 | 497 | 448 | 522 | 549 | 626 | 636 | 618 | 691 | CFP |
| LAS LOMITAS | 24 42'S | 60 35'W | 130 | - | - | - | - | 449 | 360 | 455 | 466 | 457 | 469 | 482 | 537 | |
| LAURIE IS. | 60 00'S | 45 00'W | 8 | 177 | 171 | 151 | 181 | 145 | 165 | 211 | 274 | 312 | 211 | 178 | 196 | CFP |
| LORETO | 27 21'S | 55 30'W | 163 | 575 | 546 | 587 | 509 | 458 | 431 | 448 | 443 | 463 | 525 | 585 | 556 | |
| MAR DEL PLATA | 37 56'S | 57 35'W | 19 | 624 | 601 | 568 | 493 | - | - | 365 | 523 | 530 | 512 | - | - | |
| MAZARUCA | 33 35'S | 59 24'W | 4 | 658 | 591 | 569 | 483 | 483 | 394 | 474 | 499 | 625 | 607 | 613 | 633 | |
| MENDOZA | 32 53'S | 68 52'W | 827 | 702 | 693 | 318 | 545 | 518 | 539 | 544 | 564 | 657 | 690 | 686 | 646 | |
| NEUGUEN | 38 57'S | 68 09'W | 270 | 599 | 539 | 479 | 444 | 411 | 315 | 289 | 545 | 616 | 490 | 520 | 546 | |
| ORCADAS | 60 44'S | 44 44'W | 0 | - | - | - | - | - | - | - | - | - | 361 | 329 | 269 | |
| PASO DE LOS LIBRES | 29 43'S | 57 06'W | 66 | 617 | 594 | 556 | 568 | 545 | 518 | 557 | 575 | 538 | 572 | 580 | 521 | |
| PATAGONES | 40 48'S | 62 59'W | 34 | 584 | 587 | 571 | 556 | 519 | 514 | 473 | 552 | 553 | 544 | 567 | 579 | |
| PILAR | 31 40'S | 63 53'W | 338 | 617 | 579 | 545 | 553 | 485 | 441 | 521 | 573 | 594 | 618 | 590 | 582 | |
| POSADAS | 27 22'S | 55 56'W | 117 | 551 | 570 | 568 | 530 | 511 | 479 | 517 | 512 | 508 | 543 | 560 | 545 | |
| PUELCHES | 38 08'S | 65 66'W | 160 | - | 731 | - | - | 447 | 383 | 328 | 456 | 513 | 614 | 647 | 683 | |
| PUERTO MADRYN | 42 46'S | 65 02'W | 8 | 576 | 572 | 558 | 543 | 531 | 641 | 552 | 539 | 557 | 566 | 550 | 379 | |
| RAFAELE | 31 15'S | 61 30'W | 130 | 431 | 440 | 390 | 333 | 356 | 266 | 427 | 361 | 380 | 398 | 430 | 432 | |
| RESISTENCIA | 27 28'S | 58 29'W | 49 | 538 | 469 | 465 | 347 | 343 | 409 | 415 | 454 | 476 | 528 | 523 | 515 | |
| ROSARIO | 32 56'S | 60 42'W | 222 | 594 | 589 | 573 | 536 | 509 | 500 | 495 | 524 | 561 | 559 | 570 | 536 | |
| SAN CARLOS DE BAR LO | 41 09'S | 71 18'W | 825 | 594 | 615 | 573 | 502 | 441 | 339 | 410 | 473 | 544 | 576 | 604 | 553 | CFP |
| SAN JUAN | 31 36'S | 68 33'W | 630 | 541 | 529 | 543 | 517 | 556 | 684 | 642 | 552 | 636 | 611 | 559 | 499 | |
| SAN LUIZ | 33 16'S | 66 21'W | 716 | - | - | - | 525 | 436 | 437 | 453 | 486 | 656 | 663 | 644 | 733 | |
| SAN MIGUEL | 34 33'S | 58 42'W | 27 | 539 | 515 | 461 | 388 | 406 | 344 | 380 | 422 | 483 | 496 | 456 | 511 | |
| SANTA CRUZ | 50 01'S | 68 32'W | 11 | 348 | 580 | 524 | 456 | 372 | 360 | 280 | * | 516 | 552 | 508 | 476 | CFP |
| SANTIAGO DEL ESTERO | 27 47'S | 64 18'W | 0 | 560 | 550 | 548 | 521 | 502 | 490 | 548 | 570 | 553 | 590 | 580 | 563 | |
| TRELEW | 43 14'S | 63 18'W | 39 | 676 | 609 | 582 | 509 | 403 | 336 | 345 | 492 | 572 | 536 | 555 | 515 | |
| TRES CRUCES | 23 05'S | 65 44'W | 4580 | 802 | 565 | 720 | 934 | 913 | 907 | [illegible] | - | 942 | 860 | 782 | 753 | |
| TUCUMA'N | 26 50'S | 65 12'W | 421 | 365 | 571 | 524 | 473 | 431 | 419 | 543 | 054 | 567 | 552 | 550 | 510 | |
| | | | | | | ATLANTIC OCEAN NORTH | | | | | | | | | | |
| A | 62 00'N | 33 00'W | 6 | 256 | 408 | 266 | 327 | 414 | 240 | 347 | 433 | - | 154 | 335 | - | |
| I | 59 00'N | 19 00'W | 6 | 355 | 201 | 420 | 326 | 371 | 340 | 401 | 399 | 433 | 270 | 356 | 261 | |
| J | 52 30'N | 20 00'W | 6 | 351 | - | 419 | - | 187 | 481 | 446 | 401 | 359 | 342 | 258 | 292 | |

APPENDIX A (CON'T)

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | ATLANTIC OCEAN NORTH (CON'T) | | | | | | | | | |
| K | 45 00´N | 16 00´W | 6 | - | 484 | 434 | 482 | 555 | - | - | 600 | 525 | 442 | - | - | |
| | | | | | | | AUSTRALIA | | | | | | | | | |
| ALICE SPRINGS | 23 48´S | 133 53´E | 546 | 642 | 653 | 658 | 656 | 628 | 645 | 664 | 718 | 713 | 661 | 637 | 631 | |
| ASPENDALE | 38 02´S | 145 06´E | - | 663 | 598 | 514 | 565 | 470 | 472 | 496 | 489 | 469 | 517 | 491 | 565 | |
| BOX HILL | 37 48´S | 145 08´E | 100 | 549 | 541 | 538 | 458 | 427 | 423 | 444 | 471 | 493 | 507 | 508 | 542 | |
| BRISBANE | 27 28´S | 153 02´E | - | 551 | 550 | 546 | 549 | 553 | 549 | 564 | 567 | 565 | 566 | 560 | 554 | |
| DARWIN | 12 26´S | 130 52´E | 27 | 464 | 488 | 541 | 547 | 632 | 658 | 675 | 704 | 653 | 612 | 563 | 509 | |
| DRY CREEK S. A. | 34 50´S | 138 35´E | 4 | 672 | 648 | 632 | 717 | 521 | 526 | 524 | 559 | 586 | 565 | 612 | 632 | |
| GUILDFORD | 31 56´S | 115 57´E | 15 | 649 | 652 | 637 | 562 | 526 | 529 | 542 | 581 | 602 | 615 | 636 | 659 | |
| GARBUTT | 19 15´S | 146 46´E | 4 | 511 | 518 | 557 | 596 | 584 | 626 | 644 | 664 | 689 | 660 | 644 | 623 | |
| MELBOURNE | 37 49´S | 144 58´E | 35 | 625 | 592 | 423 | 519 | 529 | 528 | 531 | 507 | 520 | 523 | 479 | 510 | |
| MOUNT STROMLO | 35 21´S | 149 10´E | - | 611 | 598 | 587 | 594 | 609 | 567 | 590 | 610 | 643 | 606 | 615 | 616 | |
| SYDNEY | 33 52´S | 151 12´E | 42 | 428 | 537 | 527 | 529 | 522 | 542 | 559 | 573 | 554 | 551 | 540 | 535 | |
| WILLIAMTOWN | 32 49´S | 151 50´E | 4 | 513 | 483 | 559 | 507 | 526 | 513 | 550 | 615 | 551 | 620 | 593 | 527 | |
| | | | | | | | AUSTRIA | | | | | | | | | |
| GMUNDEN | 47 55´N | 13 47´E | 425 | 369 | 400 | 431 | 401 | 453 | 395 | 406 | 425 | 453 | 370 | 725 | 275 | |
| GRAFENHOF | 47 19´N | 13 10´E | 766 | 412 | 584 | 474 | 481 | 450 | 369 | 414 | 413 | 585 | 489 | 374 | 351 | |
| GUMPENSTEIN | 47 30´N | 14 06´E | 710 | 388 | 442 | 483 | 453 | 493 | 405 | 420 | 442 | 441 | 422 | 317 | 319 | |
| KLAGENFURT | 46 38´N | 14 19´E | 448 | 446 | 505 | 563 | 452 | 510 | 434 | 488 | 485 | 481 | 439 | 226 | 271 | |
| KRIPPENSTEIN | 47 32´N | 13 41´E | 2064 | 591 | 591 | 551 | 550 | 510 | 380 | 388 | 410 | 506 | 556 | 530 | 486 | |
| LUNZ-AM-SEE | 47 50´N | 15 00´E | 615 | 284 | 391 | 464 | 384 | 444 | 399 | 368 | 395 | 388 | 402 | 270 | 241 | |
| MONICHKIRCHEN | 47 32´N | 16 02´E | 978 | 498 | 418 | 464 | 415 | 469 | 378 | 415 | 449 | 446 | 495 | 395 | 454 | |
| NEUSIEDLAM SEE | 47 57´N | 16 51´E | 116 | 365 | 284 | 449 | 452 | 559 | 431 | 470 | 508 | 400 | 394 | 231 | 281 | |
| OBERGURGL | 46 52´N | 11 02´N | 1950 | 409 | 494 | 563 | 605 | 533 | 300 | 456 | 457 | 448 | 468 | 359 | 324 | |
| OBERSIEBEN-BRUHN | 48 46´N | 16 43´E | 150 | 358 | 330 | 441 | 428 | 489 | 421 | 425 | 477 | 444 | 379 | 230 | 242 | |
| PERTISAU/ACHENSEE | 47 26´N | 11 42´E | 933 | 475 | 377 | 516 | 425 | 430 | 354 | 345 | 370 | 424 | 434 | 339 | 303 | |
| RETZ | 48 46´N | 15 58´E | 243 | 262 | 347 | 379 | 402 | 493 | 445 | 433 | 459 | 454 | 679 | 183 | 211 | |
| SALZBURG | 47 48´N | 13 00´E | 437 | 395 | 431 | 446 | 420 | 452 | 387 | 396 | 274 | 434 | 423 | 260 | 311 | |
| SEMMERING | 47 39´N | 15 50´E | 995 | 326 | 359 | 362 | 386 | 454 | 368 | 381 | 422 | 383 | 450 | 299 | 243 | |
| SONNBLICK | 47 03´N | 12 57´E | 3106 | 594 | 660 | 621 | 586 | 561 | 461 | 421 | 433 | 561 | 587 | 537 | 520 | |
| STEYR | 48 04´N | 14 35´E | 309 | 368 | 392 | 427 | 463 | 456 | 417 | 417 | 457 | 451 | 385 | 225 | 240 | |
| VIENNA | 48 15´N | 16 22´E | - | 292 | 359 | 398 | 438 | 473 | 461 | 473 | 467 | 581 | 355 | 273 | 248 | |
| YBBS-PERSENBEUG | 48 11´N | 15 ´3 | 228 | 374 | 383 | 435 | 482 | 490 | 408 | 414 | 448 | 443 | 377 | 244 | 227 | |
| | | | | | | | AZORES | | | | | | | | | |
| ANGRA | 38 07´N | 27 02´W | 92 | 416 | 431 | 438 | 498 | 544 | 582 | 533 | 546 | 533 | 499 | 429 | 433 | |
| CORVO | 39 40´N | 31 07´W | 28 | 442 | 431 | 469 | 514 | 536 | 525 | 563 | 582 | 559 | 483 | 415 | 403 | |
| PONTA DELGADA | 37 45´N | 25 40´W | 36 | 488 | 497 | 514 | 507 | 554 | 520 | 570 | 610 | 616 | 586 | 479 | 488 | |
| | | | | | | | BELGIUM | | | | | | | | | |
| BRUSSEL-UCCLE | 50 48´N | 4 22´E | 100 | 290 | 323 | 353 | 392 | 422 | 402 | 402 | 403 | 390 | 344 | 277 | 241 | |
| | | | | | | | BOLIVIA | | | | | | | | | |
| LA PAZ | 16 31´S | 68 93´W | 3658 | 425 | 457 | 519 | 556 | 658 | 756 | 611 | 542 | 611 | 613 | 552 | 516 | CFP |
| | | | | | | | BRAZIL | | | | | | | | | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | BRAZIL (CON'T) | | | | | | | | | | |
| ALEGRETE | 29 47'S | 55 47'W | - | 607 | 616 | 594 | 569 | 546 | 519 | 536 | 559 | 552 | 573 | 600 | 608 | |
| ARACAJU | 10 55'S | 37 03'W | - | 625 | 588 | 515 | 454 | 384 | 353 | 374 | 418 | 483 | 550 | 609 | 649 | |
| ARAXA | 19 36'S | 46 56'W | - | 425 | 533 | 519 | 539 | 590 | 552 | 569 | 567 | 501 | 477 | 501 | 371 | CFP |
| BAGE | 31 20'S | 54 06'W | - | 586 | 576 | 552 | 553 | 548 | 521 | 516 | 541 | 521 | 543 | 580 | 586 | |
| BARBACENA | 21 15'S | 43 46'W | - | 464 | 490 | 482 | 514 | 561 | 608 | 622 | 592 | 472 | 453 | 418 | 377 | CFP |
| BARRA CORDA | 5 30'S | 45 16'W | - | 404 | 400 | 393 | 414 | 441 | 526 | 550 | 509 | 496 | 491 | 465 | 473 | CFP |
| BAURU | 22 19'S | 49 04'W | - | 489 | 473 | 516 | 607 | 595 | 591 | 605 | 609 | 523 | 512 | 554 | 505 | |
| BELEM | 1 28'S | 48 29'W | - | 518 | 459 | 456 | 495 | 576 | 652 | 682 | 682 | 672 | 673 | 652 | 642 | |
| BELO HORIZONTE | 19 56'S | 43 57'W | - | 504 | 516 | 521 | 550 | 585 | 612 | 626 | 617 | 550 | 509 | 495 | 451 | |
| BLUMENAU | 26 55'S | 49 04'W | - | 470 | 489 | 511 | 479 | 460 | 477 | 434 | 437 | 398 | 430 | 433 | 458 | CFP |
| CABO FRIO | 22 52'S | 42 01'W | - | 488 | 516 | 517 | 514 | 518 | 543 | 540 | 538 | 462 | 446 | 471 | 455 | |
| CAMPINAS | 22 53'S | 47 05'W | - | 558 | 558 | 565 | 584 | 602 | 599 | 613 | 600 | 564 | 568 | 563 | 544 | |
| CAMPOS | 21 45'S | 41 20'W | - | 480 | 515 | 479 | 493 | 523 | 529 | 545 | 528 | 444 | 422 | 441 | 437 | |
| CAMPOS DE JORDAO | 22 52'S | 43 22'W | - | 438 | 442 | 470 | 473 | 518 | 543 | 558 | 569 | 487 | 457 | 440 | 405 | |
| CANANEIA | 25 01'S | 47 56'W | 5 | 502 | 477 | 446 | 446 | 426 | 448 | 449 | 421 | 342 | 374 | 462 | 453 | |
| CATALAO | 18 10'S | 47 57'W | - | 488 | 506 | 539 | 591 | 613 | 640 | 637 | 644 | 567 | 540 | 518 | 476 | |
| CAXIAS | 4 52'S | 43 22'W | - | 504 | 506 | 500 | 515 | 543 | 584 | 615 | 624 | 608 | 589 | 559 | 543 | |
| CAXIAS | 29 10'S | 51 12'W | - | 529 | 530 | 529 | 518 | 519 | 532 | 540 | 534 | 521 | 525 | 539 | 531 | |
| CORRENTES | 9 06'S | 36 21'W | - | 540 | 492 | 472 | 446 | 396 | 444 | 394 | 428 | 574 | 577 | 626 | 568 | CFP |
| CORUMBA | 19 00'S | 57 39'W | - | 405 | 411 | 415 | 424 | 435 | 429 | 448 | 449 | 422 | 419 | 424 | 413 | |
| CRUZ ALTA | 28 38'S | 53 37'W | - | 559 | 561 | 539 | 528 | 531 | 502 | 540 | 546 | 504 | 547 | 570 | 571 | |
| CUIABA | 15 36'S | 56 06'W | - | 396 | 391 | 402 | 490 | 527 | 518 | 541 | 484 | 445 | 483 | 474 | 422 | CFP |
| CURITIBA | 25 26'S | 49 16'W | - | 504 | 506 | 502 | 504 | 511 | 519 | 536 | 530 | 500 | 506 | 510 | 509 | |
| DIAMANTINA | 18 15'S | 43 36'W | - | 458 | 580 | 512 | 459 | 514 | 538 | 536 | 620 | 528 | 477 | 405 | 374 | CFP |
| FLORINOPOLIS | 27 36'S | 48 34'W | - | 513 | 523 | 545 | 521 | 537 | 502 | 502 | 488 | 466 | 472 | 485 | 509 | CFP |
| FORTALEZA | 3 46'S | 38 31'W | - | 565 | 520 | 500 | 489 | 525 | 577 | 582 | 607 | 618 | 624 | 608 | 606 | |
| GOIANIA | 16 40'S | 49 15'W | - | 491 | 507 | 353 | 569 | 613 | 637 | 635 | 631 | 549 | 528 | 500 | 450 | |
| GOIAS | 15 56'S | 50 08'W | - | 483 | 486 | 512 | 552 | 591 | 628 | 595 | 611 | 546 | 528 | 501 | 462 | |
| GRAJAU | 5 49'S | 46 09'W | - | 387 | 366 | 402 | 439 | 492 | 560 | 609 | 569 | 530 | 474 | 482 | 456 | CFP |
| GUANABARA OBS. | 22 54'S | 43 10'W | - | 498 | 505 | 506 | 514 | 518 | 524 | 541 | 523 | 462 | 446 | 471 | 474 | |
| GUARAMIRANGA | 4 16'S | 39 01'W | - | 468 | 426 | 389 | 405 | 442 | 449 | 490 | 479 | 482 | 498 | 491 | 483 | CFP |
| IGUATU | 6 22'S | 39 18'W | - | 550 | 523 | 534 | 545 | 581 | 587 | 604 | 623 | 612 | 609 | 595 | 577 | |
| ILHEUS | 14 48'S | 39 02'W | - | 590 | 565 | 543 | 544 | 555 | 587 | 553 | 627 | 569 | 590 | 524 | 549 | CFP |
| JUIZ DE FORA | 21 46'S | 43 21'W | - | 430 | 452 | 444 | 466 | 474 | 511 | 492 | 498 | 419 | 411 | 411 | 387 | |
| JOAO PESSOA | 7 06'S | 34 52'W | - | 589 | 586 | 568 | 561 | 562 | 554 | 558 | 579 | 591 | 596 | 601 | 593 | |
| LAGES | 27 49'S | 50 20'W | - | 521 | 508 | 511 | 492 | 502 | 490 | 528 | 537 | 499 | 522 | 529 | 524 | |
| LAGUNA | 28 29'S | 48 47'W | - | 521 | 508 | 554 | 560 | 613 | 601 | 554 | 520 | 525 | 497 | 546 | 541 | CFP |
| LORENA | 22 42'S | 45 05'W | - | 459 | 473 | 470 | 485 | 500 | 485 | 538 | 521 | 435 | 445 | 471 | 435 | |
| MACEIO | 9 34'S | 35 47'W | - | 602 | 581 | 569 | 568 | 562 | 557 | 560 | 564 | 572 | 595 | 594 | 594 | |
| MANAUS | 3 08'S | 60 02'W | - | 418 | 398 | 400 | 407 | 462 | 525 | 556 | 571 | 538 | 513 | 473 | 446 | |
| NATAL | 5 46'S | 35 12'W | - | 588 | 580 | 556 | 553 | 562 | 566 | 570 | 593 | 610 | 621 | 621 | 605 | |
| NITEROI HORTO BOTANI | 22 54'S | 43 07'W | - | 478 | 484 | 494 | 501 | 485 | 487 | 505 | 523 | 449 | 446 | 450 | 445 | |
| OLINDA | 8 01'S | 34 51'W | - | 624 | 531 | 526 | 527 | 512 | 519 | 468 | 568 | 620 | 616 | 600 | 625 | CFP |
| OURO PRETO | 20 23'S | 43 30'W | - | 398 | 487 | 418 | 467 | 472 | 538 | 519 | 552 | 452 | 417 | 379 | 339 | CFP |
| PALMAS | 26 29'S | 51 56'W | - | 522 | 528 | 530 | 526 | 523 | 534 | 569 | 557 | 519 | 530 | 540 | 526 | |
| PARANAGUA | 25 31'S | 48 31'W | - | 453 | 455 | 502 | 479 | 503 | 545 | 477 | 445 | 441 | 421 | 425 | 433 | CFP |
| PASSO FUNDO | 28 16'S | 52 25'W | - | 550 | 540 | 537 | 525 | 526 | 518 | 535 | 542 | 515 | 534 | 549 | 542 | |
| PESQUERIA | 8 24'S | 36 46'W | - | 568 | 535 | 547 | 517 | 436 | 474 | 479 | 557 | 631 | 684 | 631 | 629 | CFP |
| PERTOPOLIS | 22 31'S | 43 11'W | - | 449 | 410 | 469 | 484 | 514 | 538 | 536 | 535 | 460 | 434 | 430 | 416 | |
| PIRACICABA | 21 43'S | 47 38'W | - | 489 | 541 | 601 | 556 | 553 | 617 | 648 | 677 | 566 | 538 | 546 | 471 | CFP |
| POCOS DE CALDAS | 21 47'S | 46 33'W | - | 407 | 478 | 495 | 561 | 557 | 581 | 604 | 612 | 520 | 553 | 507 | 433 | CFP |
| PORTO NACIONAL | 10 42'S | 48 25'W | - | 510 | 482 | 493 | 539 | 615 | 645 | 645 | 652 | 577 | 528 | 492 | 490 | |
| RIO GRANDE | 32 02'S | 52 06'W | - | 585 | 577 | 555 | 559 | 538 | 533 | 504 | 531 | 469 | 556 | 580 | 595 | |
| SALVADOR | 12 56'S | 38 31'W | - | 616 | 582 | 586 | 569 | 521 | 579 | 553 | 618 | 603 | 616 | 575 | 583 | CFP |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | BRAZIL (CON'T) | | | | | | | | | | |
| SAN PAULO | 23 33'S | 46 38'W | - | 467 | 484 | 461 | 491 | 474 | 514 | 476 | 466 | 490 | 491 | 481 | 463 | |
| SANTA CRUZ | 22 56'S | 43 22'W | - | 478 | 494 | 506 | 501 | 519 | 544 | 541 | 538 | 449 | 435 | 461 | 445 | |
| SANTA MARIA | 29 41'S | 53 49'W | - | 548 | 552 | 531 | 522 | 506 | 495 | 513 | 505 | 497 | 526 | 549 | 559 | |
| SANTAREM | 2 45'S | 54 43'W | - | 434 | 400 | 389 | 405 | 433 | 466 | 498 | 530 | 525 | 515 | 499 | 474 | |
| SANTOS | 23 56'S | 46 20'W | - | 437 | 453 | 462 | 465 | 495 | 519 | 480 | 469 | 402 | 425 | 439 | 403 | |
| SAO LUIZ | 2 32'S | 44 18'W | - | 468 | 434 | 411 | 428 | 457 | 517 | 536 | 530 | 513 | 503 | 511 | 520 | |
| SOURE | 0 44'S | 48 31'W | - | 548 | 473 | 456 | 493 | 582 | 657 | 674 | 701 | 705 | 699 | 693 | 686 | |
| TEREZINA | 5 05'S | 42 49'W | - | 522 | 515 | 511 | 542 | 587 | 619 | 583 | 655 | 621 | 599 | 588 | 560 | |
| TERE-ZOPOLIS | 22 27'S | 42 56'W | - | 449 | 463 | 446 | 470 | 481 | 500 | 500 | 504 | 447 | 412 | 420 | 396 | |
| UAUPES | 0 08'S | 67 05'W | - | 454 | 473 | 456 | 436 | 437 | 442 | 462 | 499 | 500 | 484 | 484 | 461 | |
| UBERABA | 19 45'S | 47 56'W | - | 484 | 516 | 520 | 562 | 630 | 592 | 606 | 615 | 549 | 531 | 526 | 482 | |
| URUGUAIANA | 29 45'S | 57 05'W | - | 587 | 595 | 569 | 553 | 546 | 519 | 557 | 558 | 552 | 538 | 580 | 502 | |
| VASSOURAS | 22 24'S | 43 40'W | - | 459 | 484 | 481 | 484 | 513 | 537 | 535 | 488 | 460 | 445 | 451 | 446 | |
| VITORIA | 20 19'S | 40 19'W | - | 503 | 526 | 510 | 512 | 525 | 423 | 528 | 546 | 489 | 454 | 453 | 460 | |
| | | | | | | BRITISH GUIANA | | | | | | | | | | |
| GEORGETOWN | 7 45'N | 58 04'W | - | 495 | 512 | 498 | 504 | 470 | 469 | 513 | 536 | 555 | 538 | 521 | 480 | |
| MAZARUNI | 5 58'N | 59 37'W | - | 433 | 421 | 427 | 416 | 453 | 442 | 451 | 437 | 419 | 427 | 437 | 455 | |
| | | | | | | BULGARIA | | | | | | | | | | |
| KARDJALI | 41 39'N | 25 22'E | 231 | 379 | 446 | 393 | 382 | - | 436 | 418 | 463 | 447 | 390 | 270 | 206 | |
| POLIANOVGRAD | 42 31'N | 26 51'E | 196 | 484 | 626 | 504 | 532 | 592 | 557 | 607 | 603 | 612 | 555 | 461 | 520 | |
| SOFIA OBS. | 42 49'N | 23 23'E | 582 | 342 | 521 | 442 | 041 | 460 | 503 | 574 | 555 | 485 | 436 | 321 | 324 | |
| SOMMET STALIN | 42 11'N | 23 35'E | 2925 | 335 | 524 | 550 | 491 | 409 | 344 | 439 | 490 | 481 | 495 | 490 | 450 | |
| TCHERNI-VRAH | 42 34'N | 23 17'E | 2286 | 670 | 813 | 665 | 603 | 539 | 523 | 669 | 664 | 617 | 718 | 650 | 632 | |
| TCHIRPAN | 42 12'N | 25 20'E | 170 | 425 | 626 | 539 | 484 | 598 | 569 | 642 | 647 | 601 | 575 | 474 | 396 | |
| VARNA | 43 12'N | 27 55'E | 51 | 429 | 520 | 458 | 420 | 447 | 475 | 488 | 594 | 554 | * | 365 | 388 | |
| | | | | | | BURMA | | | | | | | | | | |
| RANGOON | 17 00'N | 96 00'E | 30 | 727 | 743 | 701 | 678 | 576 | 424 | 414 | 386 | 405 | 595 | 697 | 708 | |
| | | | | | | CANADA | | | | | | | | | | |
| AKLAVIK | 68 14'N | 135 00'W | 9 | * | 612 | 719 | 697 | 622 | * | 482 | 432 | 386 | 381 | 441 | * | |
| CHURCHILL | 58 45'N | 94 04'W | 35 | 697 | 704 | 731 | 676 | 587 | 543 | 541 | 499 | 427 | 383 | 435 | 515 | |
| DARTMOUTH | 44 36'N | 63 28'W | 31 | 414 | 444 | 467 | 478 | 491 | 454 | 498 | 498 | 512 | 474 | 354 | 387 | |
| DEPARTURE BAY | 49 13'N | 123 57'W | - | 359 | 370 | 418 | 429 | 560 | 320 | 640 | 597 | 457 | 438 | 360 | - | |
| EDMONTON | 53 34'N | 113 31'W | 676 | 551 | 611 | 640 | 582 | 570 | 522 | 556 | 512 | 506 | 503 | 529 | 497 | |
| FORT SIMPSON | 61 52'N | 121 21'W | 129 | 534 | 534 | 615 | 623 | 586 | 534 | 497 | 502 | 451 | 431 | 309 | 290 | |
| GOOSE BAY | 53 19'N | 60 25'W | 44 | 424 | 548 | 591 | 534 | 492 | 437 | 443 | 412 | 406 | 371 | 375 | 441 | |
| GUELPH | 43 33'N | 80 16'W | 320 | 475 | 475 | 531 | 473 | 495 | 529 | 570 | 530 | 512 | 461 | 367 | 384 | |
| KAPUSKASING | 49 25'N | 82 28'W | 229 | 500 | 546 | 573 | 496 | 451 | 486 | 502 | 484 | 425 | 371 | 297 | 422 | |
| KNOB LAKE | 54 48'N | 66 49'W | 512 | 414 | 518 | 658 | 602 | 451 | 438 | 381 | 418 | 366 | 336 | 364 | 429 | |
| LETHBRIDGE | 49 38'N | 112 48'W | 920 | 553 | 609 | 632 | 564 | 572 | 587 | 638 | 631 | 585 | 560 | 526 | 483 | |
| MONCTON | 46 07'N | 64 41'W | 76 | 374 | 455 | 499 | 491 | 477 | 454 | 488 | 485 | 463 | 441 | 347 | 381 | |
| MONTREAL | 45 30'N | 73 37'W | 133 | 398 | 495 | 543 | 514 | 509 | 494 | 530 | 519 | 459 | 413 | 307 | 326 | |
| MOOSONEE | 51 16'N | 80 39'W | 10 | 490 | 529 | 589 | 541 | 449 | 477 | 457 | 424 | 439 | 369 | 309 | 427 | |
| NANAIMO | 49 00'N | 123 00'W | - | 363 | 359 | 434 | 570 | 594 | 526 | 680 | 390 | 460 | 444 | 389 | 292 | |
| NORMANDIN | 48 51'N | 72 32'W | 137 | 504 | 842 | 648 | 473 | 504 | 470 | 475 | 470 | 445 | 387 | 378 | 456 | |
| OTTAWA | 45 27'N | 75 37'W | 98 | 519 | 563 | 568 | 518 | 538 | 563 | 568 | 553 | 525 | 456 | 377 | 443 | |
| RESOLUTE BAY | 74 43'N | 94 59'W | 64 | * | * | * | 766 | * | * | * | 413 | 397 | 443 | * | * | |

APPENDIX A (CON'T)

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CANADA (CON'T)** | | | | | | | | | | | | | | | | |
| ST. JOHN'S WEST | 47 31'N | 52 47'W | 114 | 324 | 400 | 425 | 420 | 436 | 434 | 458 | 406 | 428 | 372 | 270 | 324 | |
| SASKATOON | 52 08'N | 106 38'W | 515 | 551 | 631 | 632 | 575 | 556 | 538 | 589 | 557 | 537 | 507 | 456 | 493 | |
| SUFFIELD | 50 16'N | 111 11'W | 775 | 553 | 700 | 605 | 623 | 582 | 546 | 634 | 605 | 521 | 498 | 517 | 535 | |
| SUMMERLAND | 49 34'N | 119 39'W | 454 | 367 | 405 | 501 | 577 | 539 | 536 | 586 | 582 | 521 | 419 | 374 | 320 | |
| TORONTO | 43 40'N | 79 24'W | 116 | 399 | 430 | 478 | 470 | 515 | 524 | 546 | 506 | 496 | 441 | 349 | 350 | |
| VANCOUVER | 49 33'N | 123 30'W | - | 349 | 300 | 347 | 460 | 515 | 488 | 570 | 482 | 398 | 372 | 355 | 298 | |
| WINNIPEG | 49 54'N | 97 14'W | 240 | 615 | 659 | 679 | 592 | 562 | 532 | 595 | 574 | 507 | 482 | 454 | 504 | |
| **CANTON ISLAND** | | | | | | | | | | | | | | | | |
| CANTON ISLAND | 2 46'S | 171 43'W | 9 | 674 | 690 | 698 | 699 | 694 | 706 | 699 | 715 | 729 | 730 | 685 | 670 | |
| **CAPE VERDI ISLANDS** | | | | | | | | | | | | | | | | |
| MINDELO | 16 52'N | 25 00'W | 2 | 634 | 669 | 739 | 752 | 745 | 689 | 637 | 581 | 629 | 617 | 612 | 582 | |
| PRAIA | 14 54'N | 23 31'W | 27 | 666 | 686 | 738 | 746 | 703 | 684 | 590 | 548 | 590 | 635 | 614 | 575 | |
| **CAROLINE ISLANDS** | | | | | | | | | | | | | | | | |
| TRUK | 7 23'N | 151 54'E | 110 | 057 | 063 | 056 | 058 | 050 | 056 | 055 | 050 | 056 | 052 | 050 | 048 | PPS |
| YAP | 9 30'N | 138 07'E | 35 | 056 | 065 | 067 | 061 | 058 | 056 | 042 | 041 | 048 | 055 | 055 | 056 | PPS |
| **CENTRAL AFRICA** | | | | | | | | | | | | | | | | |
| BANGUI | 4 22'N | 18 34'E | - | 474 | 516 | 562 | 552 | 549 | 496 | 460 | 462 | 496 | 521 | 480 | 467 | |
| **CEYLON** | | | | | | | | | | | | | | | | |
| BATTICALOA | 7 43'N | 81 42'E | 3 | 558 | 607 | 622 | 605 | 619 | 598 | 606 | 604 | 611 | 584 | 583 | 545 | |
| COLOMBO | 6 54'N | 79 52'E | 7 | 589 | 625 | 620 | 595 | 565 | 556 | 576 | 573 | 589 | 558 | 589 | 589 | |
| **CHAD** | | | | | | | | | | | | | | | | |
| FORT LAMY | 12 08'N | 15 02'E | 297 | 689 | 711 | 725 | 668 | 666 | 649 | 605 | 556 | 625 | 699 | 729 | 713 | |
| **CHILE** | | | | | | | | | | | | | | | | |
| ATACAMA DESERT | 23 40'S | 69 45'W | - | 757 | 755 | 748 | 765 | 749 | 718 | 809 | 849 | 818 | 801 | 779 | 780 | |
| SANTIAGO | 33 27'S | 70 40'W | 520 | 662 | 708 | 652 | 607 | 473 | 432 | 455 | 473 | 478 | 608 | 591 | 669 | |
| **CHINA** | | | | | | | | | | | | | | | | |
| AIGUN | 50 15'N | 127 29'E | 131 | 529 | 595 | 547 | 487 | 485 | 506 | 482 | 500 | 479 | 476 | 505 | 506 | |
| CHANGCHUN | 43 52'N | 125 20'E | 215 | 533 | 562 | 543 | 519 | 506 | 504 | 497 | 502 | 521 | 514 | 515 | 521 | |
| CHEFOO | 37 34'N | 121 31'E | 27 | 510 | 526 | [illegible] | 553 | 531 | 516 | 496 | 498 | 522 | 531 | 501 | 498 | |
| CHINCHOW | 41 08'N | 121 07'E | 52 | 558 | 559 | 548 | 531 | 513 | 504 | 496 | 494 | 530 | 537 | 515 | 551 | |
| CHINKIANG | 32 10'N | 119 40'E | 12 | 362 | 411 | 397 | 442 | 433 | 398 | 446 | 478 | 444 | 495 | 506 | 477 | |
| DARIEN | 38 54'N | 121 14'E | 97 | 550 | 557 | 566 | 569 | 525 | 540 | 498 | 463 | 539 | 553 | 528 | 524 | |
| HANKOW | 30 35'N | 114 17'E | 36 | 487 | 448 | 457 | 484 | 507 | 502 | 478 | 520 | 476 | 467 | 505 | 454 | |
| HARBIN | 44 50'N | 126 38'E | 145 | 559 | 580 | 536 | 511 | 497 | 504 | 498 | 505 | 499 | 507 | 507 | 510 | |
| HULUN | 49 13'N | 119 44'E | 619 | 539 | 598 | 552 | 508 | 516 | 516 | [illegible] | 508 | 487 | 507 | 661 | 520 | |
| KHINGAN | 48 50'N | 121 40'E | 984 | 526 | 589 | 565 | 519 | 493 | 496 | 491 | 506 | 484 | 478 | 576 | 556 | |
| KOSHAN | 48 04'N | 125 52'E | 223 | 543 | 571 | 538 | 502 | 492 | 505 | 490 | 492 | 493 | 511 | 519 | 528 | |
| LUSKAING | 47 20'N | 123 56'E | 147 | 560 | 582 | 476 | 511 | 501 | 505 | 458 | 501 | 503 | 522 | 501 | 548 | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CHINA (CON'T)** | | | | | | | | | | | | | | | | |
| MANCHOULI | 49 35'N | 117 26'E | 641 | 552 | 607 | 575 | 524 | 495 | 506 | 513 | 497 | 490 | 536 | 674 | 534 | |
| MUKDEN | 41 47'N | 123 24'E | 43 | 544 | 548 | 538 | 509 | 514 | 504 | 496 | 508 | 521 | 564 | 527 | 501 | |
| NAIJUMATU | 50 28'N | 120 06'E | - | 537 | 601 | 549 | 516 | 508 | 496 | 503 | 488 | 465 | 503 | 472 | 515 | |
| SHANGHAI | 31 17'N | 121 28'E | 3 | 477 | 387 | 461 | 474 | 497 | 429 | 540 | 577 | 541 | 518 | 476 | 464 | |
| SUIFENHO | 44 23'N | 131 09'E | - | 546 | 548 | 532 | 509 | 475 | 484 | 498 | 492 | 481 | 521 | 497 | 497 | |
| TAILEN | 38 54'N | 121 38'E | 96 | 536 | 525 | 543 | 534 | 521 | 515 | 475 | 501 | 530 | 528 | 524 | 498 | |
| TIENTSIN | 39 09'N | 117 09'E | 3 | 542 | 528 | 530 | 523 | 532 | 515 | 506 | 501 | 518 | 531 | 528 | 503 | |
| TSINAN | 36 40'N | 116 58'E | - | 543 | 514 | 525 | 525 | 498 | 516 | 516 | 507 | 530 | 538 | 531 | 508 | |
| TSINGTAU | 36 04'N | 120 19'E | 77 | 580 | 544 | 549 | 535 | 509 | 506 | 527 | 529 | 514 | 565 | 544 | 548 | |
| **COLOMBIA** | | | | | | | | | | | | | | | | |
| BOGOTA | 4 38'N | 74 05'N | 2560 | 554 | 517 | 469 | 423 | 441 | 474 | 487 | 478 | 470 | 408 | 464 | 500 | |
| **CONGO** | | | | | | | | | | | | | | | | |
| ALBERTVILLE | 5 53'S | 29 11'E | 790 | 486 | 527 | 522 | 527 | 672 | 642 | 644 | 588 | 612 | 537 | 471 | 531 | |
| BAMBESA | 3 27'N | 25 43'E | 621 | 483 | - | 506 | 507 | 543 | 504 | 433 | 465 | 496 | 524 | 554 | 531 | |
| BOENDE | 0 13'S | 20 51'E | 370 | 467 | 489 | 476 | 500 | 480 | 494 | 429 | 455 | 500 | 471 | 450 | 424 | |
| BUKAVU | 2 31'S | 28 51'E | 1635 | - | - | 487 | 509 | 561 | 575 | 551 | 530 | 427 | 508 | 487 | 481 | |
| BUNIA-RUAMPARA | 1 32'N | 30 10'E | 1225 | 516 | 549 | 544 | 575 | 554 | 520 | 479 | 515 | 524 | 507 | 525 | 550 | |
| COQUILHATVILLE | 0 03'N | 18 16'E | 325 | 441 | 489 | 497 | 490 | 503 | 460 | 434 | 439 | 466 | 472 | 479 | 459 | |
| ELIZABETHVILLE-KARAV | 11 39'S | 27 25'E | 1260 | 468 | 439 | 509 | 571 | 659 | 691 | 690 | 684 | 650 | 620 | 515 | 464 | |
| GANDAJIKA | 6 45'S | 23 57'E | 780 | 481 | 467 | 513 | 624 | 586 | 568 | 542 | 502 | 501 | 505 | 513 | 517 | |
| KAMINA-BAKA | 8 38'S | 25 15'E | 1085 | 459 | 415 | 524 | 615 | 721 | 684 | 701 | 597 | 557 | 512 | 508 | 477 | |
| KINDU | 2 57'S | 25 55'E | 475 | - | - | - | - | - | 417 | 350 | 435 | 463 | 459 | 421 | 405 | |
| KIYAKA-PLATEAU | 5 16'S | 18 57'E | 735 | - | - | - | 480 | 559 | 536 | 509 | 503 | 477 | 506 | 501 | 476 | |
| LEOPOLDVILLE | 4 22'S | 15 15'E | 445 | 422 | 464 | 498 | 505 | 466 | 423 | 377 | 416 | 421 | 425 | 464 | 438 | |
| LULUABOURG | 5 53'S | 22 25'E | 670 | 488 | 508 | 512 | 530 | 605 | 551 | 531 | 510 | 543 | 522 | 515 | 486 | |
| LWIRO | 2 03'S | 28 08'E | 1680 | 515 | 502 | 528 | 528 | 497 | 492 | 520 | 496 | 536 | 514 | 538 | 536 | |
| RUBONA | 2 29'S | 29 46'E | 1706 | 497 | 495 | 531 | 504 | 557 | 589 | 573 | 580 | 550 | 526 | 513 | 545 | |
| SIMAMA | 9 37'S | 27 01'E | 852 | - | - | - | 575 | 662 | 666 | 640 | 606 | 551 | 451 | 461 | 450 | |
| STANLEYVILLE | 0 31'N | 25 11'E | 415 | 459 | 496 | 507 | 513 | 509 | 468 | 424 | 419 | 481 | 486 | 491 | 461 | |
| YANGAMBI | 0 49'N | 24 29'E | 500 | 478 | 508 | 510 | 511 | 530 | 499 | 438 | 433 | 464 | 462 | 489 | 442 | |
| **CONGO REPUBLIC** | | | | | | | | | | | | | | | | |
| BRAZZAVILLE | 4 15'S | 15 14'E | 320 | 479 | 486 | 509 | 544 | 472 | 445 | 387 | 430 | 446 | 443 | 504 | 474 | |
| **CZECHOSLAVAKIA** | | | | | | | | | | | | | | | | |
| BRATISLAVA | 48 10'N | 17 06'E | 289 | 378 | 393 | 429 | 481 | 551 | 498 | 509 | 563 | 489 | 426 | 258 | 232 | |
| DOKSANY | 50 27'N | 14 10'E | 158 | 331 | 405 | 441 | 494 | 525 | 510 | 461 | 498 | 500 | 374 | 228 | 217 | |
| HURBANOVO | 47 52'N | 18 12'E | 120 | 392 | 410 | 486 | 539 | 593 | 544 | 539 | 576 | 539 | 488 | 312 | 308 | |
| LOMNICKY STIT | 49 12'N | 20 13'E | 2638 | 637 | 646 | 662 | 594 | 526 | 407 | 453 | 438 | 527 | 596 | 576 | 587 | |
| MILESOVKA | 50 33'N | 13 56'E | 835 | 417 | 497 | 475 | 482 | 516 | 500 | 459 | 491 | 517 | 433 | 285 | 299 | |
| NOVY HRADEC KRALOVE | 50 11'N | 15 50'E | 280 | 359 | 409 | 463 | 480 | 523 | 489 | 454 | 496 | 472 | 385 | 256 | 257 | |
| PODERSAM | 50 13'N | 13 24'E | 320 | 254 | 351 | 397 | 390 | 450 | 409 | 428 | 441 | 402 | 309 | 233 | 230 | |
| PRAHA-KARLOV | 50 04'N | 14 26'E | 254 | 271 | 336 | 398 | 424 | 468 | 455 | 420 | 455 | 446 | 329 | 215 | 200 | |
| SKALNATE PLESO | 49 11'N | 20 15'E | 1783 | 564 | 609 | 546 | 496 | 444 | 352 | 376 | 397 | 427 | 501 | 491 | 477 | |
| **EQUADOR** | | | | | | | | | | | | | | | | |
| AMBATO | 1 15'S | 78 44'W | 2621 | 395 | 362 | 286 | 419 | 344 | 306 | 309 | 337 | 279 | 374 | 408 | 419 | CFP |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EQUADOR (CON'T)** | | | | | | | | | | | | | | | | |
| QUITO | 0 17'S | 78 32'W | 2851 | 505 | 490 | 397 | 428 | 437 | 476 | 505 | 584 | 449 | 467 | 484 | 487 | CFP |
| **EL SALVADOR** | | | | | | | | | | | | | | | | |
| SAN SALVADOR | 13 34'N | 89 13'W | 698 | 696 | 692 | 653 | 609 | 582 | 499 | 589 | 664 | 519 | 621 | 688 | 727 | |
| **FALKLAND ISLANDS** | | | | | | | | | | | | | | | | |
| PORT STANLEY | 51 42'S | 57 52'W | - | 455 | 431 | 468 | 431 | 421 | 384 | 401 | 453 | 504 | 515 | 491 | 459 | |
| **FINLAND** | | | | | | | | | | | | | | | | |
| HELSINGFORS | 60 10'N | 24 57'E | 40 | 250 | 358 | 485 | 443 | 456 | 480 | 474 | 397 | 359 | 293 | 185 | 230 | |
| HELSINKI | 60 12'N | 24 55'E | 60 | 305 | 432 | 561 | 536 | 500 | 519 | 518 | 484 | 432 | 337 | 219 | 174 | |
| JOKIONEN | 60 49'N | 23 28'E | 104 | 279 | 397 | 530 | 493 | 475 | 501 | 487 | 441 | 415 | 266 | 190 | 221 | |
| LUONETJARVI | 62 25'N | 25 39'E | 145 | 340 | 436 | 558 | 485 | 448 | 509 | 472 | 482 | 418 | 263 | 189 | 239 | |
| SODANKYLA | 67 22'N | 26 39'E | 180 | 833 | 473 | 527 | 548 | 459 | * | 481 | 419 | 344 | 325 | 300 | * | |
| **FORMOSA** | | | | | | | | | | | | | | | | |
| KOSHUN | 22 00'N | 120 45'E | 22 | 538 | 554 | 505 | 499 | 500 | 530 | 405 | 382 | 475 | 472 | 487 | 535 | |
| KWARENKO | 23 58'N | 121 37'E | 176 | 475 | 394 | 342 | 397 | 472 | 601 | 571 | 587 | 550 | 558 | 490 | 485 | |
| SHINCHIKU | 24 48'N | 120 58'E | - | 461 | 369 | 291 | 473 | 484 | 633 | 507 | 512 | 561 | - | - | - | |
| TAICHU | 24 09'N | 120 41'E | - | 461 | 474 | 363 | 435 | 483 | 439 | 464 | 417 | 489 | 486 | 468 | 446 | |
| TAINAN | 23 00'N | 120 13'E | 13 | 649 | 623 | 496 | 495 | 522 | 520 | 425 | 435 | 532 | 590 | 590 | 672 | |
| TAIPEI | 25 02'N | 121 31'E | 23 | 327 | 323 | 331 | 352 | 405 | 410 | 421 | 453 | 410 | 472 | 488 | 416 | |
| TAITO | 22 45'N | 121 09'E | 10 | 524 | 468 | 416 | 436 | 514 | 681 | 599 | 527 | 560 | 615 | 557 | 524 | |
| **FRANCE** | | | | | | | | | | | | | | | | |
| AGEN | 44 10'N | 0 40'E | - | 372 | 426 | 496 | 508 | 485 | 504 | 560 | 550 | 494 | 459 | 377 | 302 | |
| ALENCON | 48 25'N | 0 05'E | - | 341 | 414 | 452 | 477 | 482 | 475 | 501 | 493 | 434 | 427 | 352 | 295 | |
| ANGERS | 47 30'N | 0 35'W | - | 364 | 426 | 478 | 538 | 491 | 495 | 531 | 526 | 473 | 459 | 370 | 369 | |
| ANGOULEME | 45 40'N | 0 10'E | - | 438 | 448 | 511 | 541 | 509 | 525 | 561 | 543 | 505 | 477 | 402 | 371 | |
| AUXXERRE | 47 15'N | 3 35'E | - | 358 | 422 | 493 | 523 | 501 | 505 | 541 | 525 | 487 | 456 | 366 | 318 | |
| BAGNERES-DE-BIGORRE | 43 05'N | 0 05'E | - | 417 | 434 | 470 | 440 | 419 | 434 | 455 | 453 | 430 | 466 | 444 | 357 | |
| BAUGE | 47 35'N | 0 05'W | - | 365 | 427 | 461 | 552 | 491 | 495 | 531 | 526 | 474 | 438 | 338 | 325 | |
| BERGERAC | 44 50'N | 0 30'E | - | 384 | 411 | 503 | 511 | 475 | 504 | 539 | 517 | 484 | 446 | 388 | 353 | |
| BESANCON | 47 20'N | 6 02'E | - | 360 | 397 | 512 | 498 | 501 | 525 | 552 | 537 | 503 | 479 | 367 | 320 | |
| BREST | 48 35'N | 4 30'W | - | 345 | 389 | 472 | 465 | 471 | 455 | 470 | 494 | 435 | 429 | 355 | 348 | |
| CHATEAU-CHINON | 47 09'N | 0 13'E | - | 396 | 394 | 492 | 497 | 479 | 495 | 531 | 500 | 471 | 476 | 397 | 316 | |
| CHATEAU ROUX | 46 50'N | 1 40'E | - | 389 | 415 | 489 | 482 | 468 | 495 | 531 | 499 | 469 | 450 | 359 | 310 | |
| CLERMONT-FD | 49 25'N | 2 25'E | - | 364 | 460 | 499 | 496 | 473 | 496 | 544 | 521 | 488 | 487 | 408 | 422 | |
| DIJON | 47 20'N | 5 02'E | - | 360 | 423 | 529 | 524 | 512 | 535 | 562 | 549 | 518 | 479 | 367 | 320 | |
| LA MOTHE-ACHARD | 46 44'N | 0 17'W | - | 425 | 440 | 505 | 547 | 533 | 505 | 562 | 535 | 483 | 470 | 390 | 396 | |
| LE MANS | 48 00'N | 0 10'E | - | 375 | 380 | 483 | 541 | 492 | 495 | 532 | 503 | 462 | 444 | 380 | 334 | |
| LE PUY | 45 05'N | 3 50'E | - | 389 | 463 | 522 | 512 | 497 | 545 | 591 | 553 | 530 | 490 | 422 | 398 | |
| LIMOGES | 48 50'N | 1 15'E | - | 438 | 449 | 511 | 519 | 482 | 496 | 543 | 531 | 515 | 523 | 432 | 405 | |
| LILLE | 50 04'N | 3 03'E | - | 380 | 413 | 432 | 473 | 463 | 466 | 461 | 450 | 414 | 426 | 308 | 333 | |
| LYON | 45 45'N | 4 50'E | - | 366 | 399 | 529 | 541 | 531 | 545 | 592 | 567 | 520 | 458 | 341 | 331 | |
| LUXEMBOURG-VILLE | 49 35'N | 6 08'E | - | 322 | 376 | 464 | 470 | 473 | 466 | 481 | 473 | 427 | 419 | 300 | 321 | |
| MARSEILLE | 43 20'N | 5 20'E | - | 454 | 506 | 521 | 541 | 516 | 585 | 642 | 593 | 575 | 488 | 476 | 434 | |
| MONTELIMAR | 44 33'N | 4 47'E | - | 413 | 575 | 550 | 573 | 540 | 605 | 664 | 609 | 599 | 524 | 442 | 386 | |
| MONTPELLIER | 43 35'N | 3 50'E | - | 493 | 557 | 556 | 581 | 560 | 635 | 704 | 629 | 605 | 511 | 481 | 440 | |



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VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | FRANCE (CON'T) | | | | | | | | | | |
| MONTPELLIER | 43 15'N | 3 50'E | - | 485 | 528 | 488 | 528 | 516 | 605 | 663 | 570 | 545 | 468 | 475 | 432 | |
| NANTES | 47 15'N | 1 35'W | - | 398 | 422 | 440 | 497 | 501 | 495 | 531 | 501 | 441 | 434 | 366 | 363 | |
| NICE | 43 42'N | 7 18'E | - | 545 | 559 | 539 | 558 | 567 | 637 | 671 | 663 | 567 | 530 | 489 | 494 | |
| NIMES | 43 50'N | 4 20'E | - | 499 | 528 | 542 | 569 | 538 | 615 | 684 | 607 | 579 | 494 | 486 | 445 | |
| PARIS-ST. MAUR | 48 49'N | 2 30'E | 50 | 328 | 367 | 452 | 449 | 472 | 486 | 476 | 461 | 454 | 387 | 306 | 313 | |
| PERPIGNAN | 42 45'N | 2 50'E | - | 505 | 565 | 548 | 551 | 526 | 565 | 621 | 580 | 570 | 519 | 520 | 456 | |
| POITIERS | 46 40'N | 2 50'E | - | 385 | 439 | 504 | 546 | 511 | 515 | 562 | 535 | 513 | 491 | 388 | 350 | |
| REIMS | 49 20'N | 4 02'E | - | 362 | 401 | 461 | 495 | 483 | 465 | 491 | 472 | 441 | 416 | 333 | 315 | |
| ROUEN | 49 30'N | 1 05'E | - | 320 | 375 | 444 | 483 | 473 | 466 | 481 | 460 | 426 | 395 | 336 | 319 | |
| ST. QUENTIN | 49 50'N | 3 20'E | - | 327 | 380 | 429 | 471 | 451 | 445 | 461 | 437 | 413 | 399 | 304 | 327 | |
| ST. RAPHAEL | 43 25'N | 6 50'E | - | 489 | 577 | 587 | 605 | 581 | 645 | 725 | 664 | 647 | 548 | 534 | 472 | |
| STRASBOURG | 48 40'N | 7 00'E | - | 347 | 390 | 454 | 452 | 493 | 506 | 522 | 518 | 451 | 453 | 321 | 300 | |
| SUR SEINE | 48 48'N | 0 06'W | - | 358 | 423 | 439 | 496 | 556 | 524 | 482 | 494 | 463 | 477 | 356 | 237 | |
| TARARE | 45 55'N | 4 25'E | - | 370 | 402 | 480 | 490 | 477 | 515 | 561 | 532 | 507 | 460 | 375 | 334 | |
| TOULON | 43 05'N | 5 55'E | - | 513 | 571 | 567 | 590 | 580 | 645 | 714 | 651 | 630 | 543 | 527 | 499 | |
| TOULOUSE | 43 40'N | 0 45'E | - | 396 | 465 | 524 | 518 | 495 | 504 | 559 | 560 | 534 | 492 | 426 | 368 | |
| TOURS | 47 20'N | 0 45'E | - | 360 | 423 | 476 | 537 | 480 | 485 | 531 | 501 | 472 | 457 | 334 | 320 | |
| VICHY | 46 10'N | 3 25'E | - | 375 | 405 | 482 | 518 | 499 | 525 | 561 | 545 | 494 | 463 | 380 | 339 | |
| VILLEFRANCHE-DE-ROUE | 44 20'N | 3 25'E | - | 375 | 404 | 498 | 508 | 485 | 504 | 560 | 538 | 510 | 461 | 379 | 343 | |
| | | | | | | GERMANY | | | | | | | | | | |
| BOCHUM | 51 29'N | 7 13'E | 118 | 205 | 258 | 317 | 378 | 356 | 362 | 341 | 357 | 335 | 288 | 217 | 187 | |
| BRAUNLAGE | 51 43'N | 10 37'E | - | 262 | 359 | 416 | 435 | 399 | 408 | 372 | 396 | 358 | 368 | 250 | 260 | |
| BRAUNSCHWEIG-VOLKENR | 52 18'N | 10 27'E | 97 | 385 | 378 | 420 | 434 | 459 | 455 | 447 | 422 | 473 | 396 | 246 | 247 | |
| COLLM OBS. | 51 19'N | 13 00'E | 247 | 326 | 427 | 439 | 422 | 461 | 506 | 426 | 469 | 505 | 368 | 248 | 251 | |
| DRESDEN | 51 07'N | 13 41'E | 271 | 306 | 328 | 398 | 435 | 441 | 441 | 432 | 442 | 430 | 392 | 270 | 265 | |
| FICHTELBERG | 50 26'N | 12 57'E | 1214 | 307 | 573 | 479 | 460 | 422 | 433 | 421 | 413 | 534 | 436 | 318 | 268 | |
| FREIBURG | 48 01'N | 7 52'E | 285 | 237 | 304 | 457 | 413 | 446 | 494 | 471 | 482 | 474 | 408 | 249 | 306 | |
| GOTHA | 50 57'N | 10 41'E | 335 | 353 | 414 | 403 | 433 | 440 | 466 | 450 | 441 | 466 | 380 | 222 | 232 | |
| GRIEFSWALD | 54 06'N | 13 23'E | 23 | 246 | 317 | 424 | 460 | 509 | 525 | 493 | 493 | 448 | 385 | 257 | 223 | |
| HAMBURG-FUHLSBUTTEL | 53 38'N | 10 00'E | 14 | 317 | 355 | 405 | 449 | 462 | 439 | 425 | 423 | 434 | 367 | 263 | 250 | |
| HANNOVER-LANGENHAGEN | 52 28'N | 9 42'E | - | 254 | 362 | 382 | 448 | 429 | 403 | 392 | 418 | 394 | 444 | 284 | 264 | |
| HEILIGENDAMM | 54 09'N | 11 51'E | 21 | 280 | 300 | 363 | 475 | 566 | 535 | 487 | 456 | 519 | 415 | 218 | 240 | |
| HOEFCHEN | 51 06'N | 7 06'E | - | 250 | 259 | 339 | 390 | 413 | 379 | 409 | 402 | 393 | 321 | 175 | 205 | |
| HOHENPEISSENBERG | 47 48'N | 11 01'E | 1005 | 498 | 512 | 535 | 473 | 479 | 456 | 467 | 502 | 494 | 485 | 414 | 438 | |
| KARLSRUHE | 49 01'N | 8 25'E | 130 | 301 | 418 | 440 | 456 | 551 | 524 | 549 | 447 | 473 | 462 | 251 | 267 | |
| KONIGSTEIN-TAUNUS | 50 11'N | 8 29'E | - | 325 | 356 | 435 | 469 | 472 | 464 | 465 | 471 | 452 | 397 | 271 | 235 | |
| LEIPZIG | 51 18'N | 12 28'E | 146 | 259 | 349 | 387 | 438 | 494 | 479 | 452 | 463 | 479 | 380 | 211 | 202 | |
| LINDENBERG | 52 13'N | 14 07'E | 98 | 360 | 387 | 305 | 402 | 453 | 473 | 418 | 441 | 417 | 372 | 231 | 252 | |
| MUNCHEN-RIEM | 48 08'N | 11 42'E | 528 | 474 | 491 | 488 | 476 | 500 | 471 | 482 | 490 | 460 | 459 | 264 | 357 | |
| OBERSTDORF | 47 24'N | 10 17'E | - | 341 | 358 | 401 | 409 | 386 | 373 | 397 | 400 | 390 | 371 | 312 | 321 | |
| POTSDAM | 52 23'N | 13 04'E | 105 | 326 | 341 | 421 | 443 | 461 | 478 | 464 | 451 | 455 | 366 | 269 | 269 | |
| QUICKBORN | 33 44'N | 9 53'E | 14 | 116 | 220 | 289 | 372 | 392 | 417 | 365 | 389 | 326 | 204 | 102 | 089 | |
| SAARBRUCKEN | 49 13'N | 7 01'E | - | 229 | 293 | 392 | 427 | 464 | 430 | 435 | 445 | 416 | 355 | 272 | 244 | |
| TRIER-PETRISBERG | 49 45'N | 6 40'E | 276 | - | - | 510 | 502 | - | 419 | 450 | 420 | 385 | 361 | 242 | 276 | |
| TUBINGEN | 48 31'N | 9 03'E | - | 249 | 324 | 388 | 360 | 380 | 372 | 387 | 380 | 345 | 363 | 298 | 233 | |
| WURZBURG-STEIN | 49 48'N | 9 54'E | 262 | 420 | 391 | 442 | 450 | 438 | 432 | 477 | 472 | 539 | 401 | 212 | 250 | |
| WYK/FOHR | 54 43'N | 8 35'E | - | 343 | 387 | 436 | 520 | 513 | 460 | 433 | 450 | 460 | 400 | 310 | 280 | |
| | | | | | | GHANA | | | | | | | | | | |
| ACCRA | 5 36'N | 0 10'W | 65 | 445 | 509 | 543 | 559 | 558 | 461 | 432 | 427 | 473 | 542 | 558 | 506 | |
| HO | 6 00'N | 0 00' | - | 437 | 475 | 543 | 559 | 558 | 487 | 364 | 317 | 431 | 499 | 592 | 540 | CFP |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GHANA (CON'T)** | | | | | | | | | | | | | | | | |
| KUMASI | 6 43'N | 1 36'W | 287 | 292 | 356 | 441 | 465 | 413 | 308 | 254 | 206 | 278 | 355 | 371 | 328 | CFP |
| TAFO | 6 00'N | 0 00' | - | 420 | 450 | 492 | 517 | 481 | 393 | 313 | 283 | 295 | 397 | 456 | 455 | CFP |
| TAKORADI | 4 53'N | 1 46'W | 4 | 437 | 509 | 552 | 551 | 499 | 402 | 432 | 376 | 362 | 474 | 541 | 481 | CFP |
| TAMALE | 9 25'N | 0 53'W | 183 | 600 | 582 | 570 | 580 | 565 | 552 | 505 | 463 | 499 | 569 | 623 | 602 | |
| **GREECE** | | | | | | | | | | | | | | | | |
| ATHENS | 37 58'N | 23 43'E | 107 | 466 | 543 | 496 | 551 | 548 | 563 | 591 | 564 | 532 | 477 | 432 | 453 | |
| **GREENLAND** | | | | | | | | | | | | | | | | |
| THULE | 76 00'N | 70 00'W | - | * | * | 664 | 711 | * | * | * | * | - | - | * | * | |
| **GUINEA** | | | | | | | | | | | | | | | | |
| BOKE | 10 56'N | 14 19'W | 69 | 067 | 074 | 078 | 075 | 060 | 047 | 030 | 020 | 039 | 054 | 059 | 062 | PPS |
| CONAKRY | 9 34'N | 13 37'W | 46 | 041 | 056 | 066 | 057 | 042 | 029 | 016 | 013 | 027 | 044 | 047 | 028 | PPS |
| LABE | 11 19'N | 12 18'W | 1025 | 079 | 079 | 075 | 067 | 055 | 044 | 036 | 025 | 041 | 052 | 061 | 070 | PPS |
| **HONG KONG** | | | | | | | | | | | | | | | | |
| HONG KONG | 22 18'N | 114 10'E | 65 | 528 | 449 | 382 | 367 | 417 | 438 | 506 | 441 | 443 | 623 | 621 | 566 | |
| **HUNGARY** | | | | | | | | | | | | | | | | |
| BEKESCSABA | 46 41'N | 21 05'E | 88 | 401 | 369 | 487 | 471 | 537 | 501 | 531 | 524 | 538 | 495 | 337 | 311 | |
| BUDAPEST | 47 26'N | 19 11'E | 140 | 382 | 393 | 492 | 526 | 580 | 495 | 566 | 578 | 563 | 515 | 292 | 280 | |
| DEBRECEN | 47 30'N | 21 38'E | 113 | 384 | 357 | 524 | 500 | 610 | 568 | 590 | 595 | 597 | 544 | 381 | 328 | |
| KALOCSA | 46 32'N | 18 59'E | 108 | 428 | 401 | 507 | 535 | 600 | 522 | 583 | 581 | 594 | 534 | 331 | 339 | |
| KECSKEMET | 46 54'N | 19 46'E | 116 | 398 | 409 | 507 | 511 | 585 | 533 | 566 | 578 | 572 | 548 | 357 | 364 | |
| KEKESTETO | 47 52'N | 20 01'E | 991 | 413 | 502 | 486 | 469 | 581 | 511 | 562 | 589 | 587 | 563 | 377 | 336 | |
| KESZTHELY | 46 46'N | 17 14'E | 143 | 426 | 425 | 560 | 643 | 631 | 541 | 602 | 619 | 608 | 548 | 328 | 335 | |
| KISVARDA | 48 14'N | 22 07'E | 114 | 312 | 348 | 527 | 548 | 494 | 492 | 489 | 456 | 460 | 480 | 321 | 204 | |
| MARTONVASAR | 47 21'N | 18 49'E | 150 | 409 | 410 | 575 | 528 | 633 | 513 | 557 | 579 | 521 | 481 | 284 | 283 | |
| PECS | 46 04'N | 18 12'E | 124 | 403 | 427 | 512 | 551 | 570 | 501 | 551 | 556 | 530 | 468 | 299 | 321 | |
| SIOFOK | 46 54'N | 18 03'E | 112 | 425 | 432 | 542 | 571 | 617 | 533 | 620 | 594 | 581 | 524 | 321 | 293 | |
| SOPRON | 47 41'N | 16 35'E | 234 | 343 | 340 | 469 | 486 | 543 | 456 | 492 | 549 | 490 | 486 | 268 | 285 | |
| SZEGED | 46 15'N | 20 06'E | 83 | 354 | 389 | 479 | 466 | 535 | 497 | 541 | 531 | 529 | 487 | 324 | 320 | |
| TISZAORS | 47 32'N | 20 50'E | 99 | 389 | 346 | 501 | 482 | 556 | 495 | 537 | 534 | 542 | 514 | 310 | 278 | |
| **ICELAND** | | | | | | | | | | | | | | | | |
| KEFLAVIK | 64 00'N | 22 40'W | - | 238 | 375 | 449 | 491 | 431 | 506 | 463 | 526 | 434 | 312 | 424 | 704 | |
| REYKJAVIK | 64 08'N | 21 54'W | 56 | 371 | 410 | 405 | 439 | 470 | 375 | 440 | 414 | 360 | 297 | 260 | 343 | |
| **INDIA** | | | | | | | | | | | | | | | | |
| ADARTAL | 23 05'N | 79 56'E | - | 722 | 709 | 684 | 695 | 672 | 526 | 445 | 406 | 571 | 691 | 729 | 633 | |
| ADUTHURAI | 11 01'N | 79 32'E | - | 658 | 692 | 724 | 667 | 670 | 634 | 577 | 594 | 648 | 553 | 626 | 649 | |
| AGRA | 27 10'N | 78 02'E | - | 592 | 574 | 569 | 568 | 551 | 507 | 482 | 473 | 525 | 572 | 586 | 567 | |
| AHMEDABAD | 23 02'N | 72 38'E | - | 738 | 738 | 721 | 740 | 715 | 642 | 488 | 439 | 642 | 731 | 744 | 668 | |
| AKOLA | 20 45'N | 77 00'E | - | 751 | 740 | 720 | 714 | 729 | 606 | 460 | 484 | 599 | 698 | 743 | 733 | |
| ALLAHBAD | 25 28'N | 81 52'E | - | 728 | 708 | 674 | 700 | 690 | 573 | 515 | 495 | 579 | 699 | 731 | 728 | |
| BABBUR | 13 57'N | 76 37'E | - | 760 | 754 | 758 | 722 | 715 | 587 | 499 | 534 | 584 | 591 | 746 | 697 | |

APPENDIX A (CON'T)

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | VALUES OF MONTHLY AVG. KH * 1000 [1] | | | | | | | | | | | | |
| **INDIA (CON'T)** | | | | | | | | | | | | | | | | |
| BANGALORE | 12 58'N | 77 35'E | - | 706 | 707 | 731 | 688 | 663 | 513 | 446 | 513 | 525 | 549 | 669 | 699 | |
| BARODA | 22 15'N | 73 15'E | - | 742 | 743 | 716 | 728 | 737 | 633 | 479 | 439 | 639 | 630 | 748 | 724 | |
| BOMBAY | 18 56'N | 72 50'E | - | 708 | 708 | 698 | 679 | 680 | 494 | 421 | 407 | 536 | 659 | 734 | 721 | |
| CALCUTTA | 22 30'N | 88 20'E | - | 630 | 602 | 607 | 594 | 577 | 506 | 457 | 461 | 521 | 565 | 611 | 607 | |
| CALCUTTA/DUM DUM | 22 39'N | 88 27'E | 10 | * | 613 | 604 | 579 | 579 | 483 | 450 | 475 | 463 | 508 | 635 | 630 | |
| CHINSURA | 22 52'N | 88 25'E | - | 735 | 721 | 695 | 695 | 683 | 516 | 478 | 505 | 570 | 635 | 694 | 718 | |
| COIMBATORE | 11 00'N | 76 55'E | - | 685 | 692 | 712 | 667 | 659 | 544 | 486 | 583 | 637 | 589 | 599 | 676 | |
| DELHI | 28 40'N | 77 15'E | - | 693 | 686 | 671 | 663 | 666 | 628 | 522 | 552 | 555 | 702 | 714 | 714 | |
| DHARWAR | 15 27'N | 75 00'E | - | 751 | 741 | 729 | 666 | 645 | 461 | 396 | 443 | 529 | 574 | 722 | 747 | |
| HAGARI | 15 10'N | 77 04'E | - | 704 | 752 | 740 | 710 | 679 | 571 | 506 | 565 | 586 | 597 | 746 | 743 | |
| JAIPUR | 26 55'N | 75 50'E | - | 736 | 726 | 723 | 715 | 710 | 590 | 471 | 484 | 645 | 727 | 738 | 718 | |
| JALGAON | 21 03'N | 75 34'E | - | 755 | 730 | 722 | 726 | 729 | 595 | 460 | 495 | 588 | 714 | 732 | 738 | |
| JODHPUR | 26 18'N | 73 01'E | - | 743 | 734 | 718 | 714 | 721 | 706 | 556 | 528 | 655 | 721 | 745 | 726 | |
| JULLUNDAR | 31 25'N | 75 35'E | - | 666 | 692 | 652 | 706 | 697 | 674 | 550 | 577 | 668 | 718 | 726 | 710 | |
| KARJAT | 18 55'N | 73 18'E | | 739 | 735 | 722 | 723 | 723 | 526 | 410 | 407 | 547 | 646 | 734 | 736 | |
| KODAIKANAL | 10 14'N | 77 28'E | - | 664 | 675 | 675 | 635 | 640 | 524 | 421 | 484 | 523 | 490 | 529 | 654 | |
| KOILPATTI | 9 12'N | 77 53'E | - | 652 | 667 | 695 | 636 | 644 | 587 | 562 | 576 | 658 | 557 | 635 | 655 | |
| LABANDHE | 21 20'N | 81 45'E | - | 744 | 704 | 674 | 659 | 664 | 530 | 448 | 418 | 554 | 663 | 705 | 709 | |
| LAHORE | 31 35'N | 74 18'E | - | 669 | 694 | 694 | 707 | 697 | 664 | 571 | 632 | 694 | [illegible] | 748 | 691 | |
| MADRAS | 13 05'N | 80 15'E | - | 708 | 721 | 719 | 700 | 663 | 569 | 513 | 524 | 583 | 586 | 643 | 687 | |
| MADRAS | 13 11'N | 80 11'E | 16 | 661 | 704 | 706 | 637 | 627 | 540 | 481 | 508 | 608 | 485 | 478 | 530 | |
| NAGPUR | 21 09'N | 79 07'E | - | 741 | 717 | 698 | 681 | 675 | 509 | 427 | 418 | 565 | 662 | 733 | 706 | |
| NEW DELHI | 28 35'N | 77 12'E | 210 | 676 | 752 | 738 | 688 | 687 | 624 | 416 | 531 | 582 | 697 | 730 | 684 | |
| NIPHAD | 20 06'N | 74 07'E | - | 757 | 747 | 728 | 725 | 731 | 629 | 451 | 484 | 621 | 706 | 749 | 739 | |
| PATTAMBI | 10 48'N | 76 12'E | - | 736 | 716 | 700 | 667 | 660 | 477 | 464 | 516 | 648 | 576 | 676 | 715 | |
| PEDEGAON | 18 12'N | 74 10'E | - | 744 | 741 | 718 | 701 | 703 | 582 | 455 | 540 | 581 | 666 | 725 | 726 | |
| POONA | 18 32'N | 73 51'E | 559 | 735 | 771 | 739 | 735 | 718 | 571 | 436 | 441 | 551 | 636 | 678 | 686 | |
| POWERKHERA | 22 50'N | 78 00'E | - | 752 | 735 | 695 | 706 | 704 | 589 | 456 | 439 | 546 | 702 | 757 | 734 | |
| RAICHUR | 16 12'N | 77 12'E | - | 746 | 748 | 732 | 711 | 665 | 524 | 503 | 553 | 553 | 641 | 730 | 727 | |
| SAKHARNAGAR | 18 39'N | 77 45'E | - | 751 | 732 | 721 | 701 | 691 | 548 | 443 | 463 | 535 | 657 | 745 | 732 | |
| SAMALKOT | 17 03'N | 82 13'E | - | 743 | 730 | 701 | 700 | 673 | 543 | 523 | 486 | 520 | 621 | 697 | 724 | |
| SHOLAPUR | 17 40'N | 76 00'E | - | 752 | 736 | 740 | 700 | 693 | 530 | 434 | 474 | 522 | 663 | 762 | 749 | |
| SRINAGAR | 34 05'N | 74 50'E | 1593 | 456 | 396 | 439 | 520 | 595 | 571 | 648 | 598 | 652 | 651 | 646 | 334 | CFP |
| SURAT | 21 12'N | 72 52'E | - | 742 | 745 | 723 | 726 | 728 | 626 | 481 | 462 | 647 | 728 | 734 | 724 | |
| TRIVANDRUM | 8 29'N | 76 58'E | - | 683 | 709 | 670 | 558 | 603 | 464 | 462 | 544 | 555 | 518 | 540 | 686 | |
| VIRANGAM | 23 02'N | 72 07'E | - | 755 | 728 | 709 | 740 | 725 | 705 | 520 | 472 | 701 | 731 | 744 | 668 | |
| **INDONESIA** | | | | | | | | | | | | | | | | |
| DJAKARTA | 6 11'S | 106 50'E | 8 | 397 | 416 | 445 | 469 | 482 | 493 | 520 | 531 | 520 | 467 | 437 | 411 | |
| SOEMOBITO | 7 32'S | 112 20'E | 16 | 461 | 455 | 426 | 460 | 519 | 539 | 547 | 515 | 530 | 510 | 469 | 388 | |
| **IRAN** | | | | | | | | | | | | | | | | |
| BABOLSAR | 36 43'N | 52 39'E | -21 | 043 | 043 | 034 | 075 | 034 | 054 | 058 | 048 | 034 | 041 | 044 | 034 | PPS |
| ESFAHAN | 32 37'N | 51 40'E | 1590 | 067 | 073 | 075 | - | 059 | 070 | 083 | 083 | 081 | 087 | 070 | 061 | PPS |
| KERMANSHAH | 34 19'N | 47 07'E | 1298 | 071 | 047 | 054 | 074 | 057 | 061 | 078 | 086 | 093 | 077 | 063 | 057 | PPS |
| MESHHAD | 36 16'N | 59 38'E | 985 | 058 | 059 | 028 | 070 | 056 | 082 | 086 | 084 | 087 | 075 | 054 | 044 | PPS |
| PAHLAVI | 38 05'N | 46 17'E | 1405 | 034 | 032 | 022 | 050 | - | 047 | 059 | 042 | 028 | 023 | 032 | 032 | PPS |
| SHIRAZ | 29 36'N | 52 32'E | 1530 | 070 | 068 | 077 | 069 | 070 | 084 | 083 | 080 | 087 | 090 | 077 | 071 | PPS |
| TEHERAN | 35 41'N | 51 19'E | 1191 | 065 | 050 | 054 | 074 | 049 | 072 | 080 | 079 | 083 | 075 | 066 | 063 | PPS |

IRELAND

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APPENDIX A (CON'T)

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | VALUES OF MONTHLY AVG. KH * 1000 [1] | | | | | | | | | | | | |
| | | | | | | IRELAND (CON'T) | | | | | | | | | | |
| VALENTIA | 51 56'N | 10 15'W | 14 | 407 | 378 | 411 | 486 | 505 | 479 | 403 | 430 | 403 | 353 | 330 | 343 | |
| | | | | | | | ISRAEL | | | | | | | | | |
| DEAD SEA | 31 15'N | 35 25'E | - | 584 | 597 | 638 | 659 | 673 | 716 | 720 | 716 | - | 678 | 620 | 583 | |
| JERUSALEM | 31 46'N | 35 15'E | 789 | 610 | 614 | 622 | 680 | 712 | 752 | 750 | 749 | 732 | 698 | 620 | 588 | |
| LOD | 32 00'N | 34 54'E | 40 | 580 | 668 | 681 | 676 | 713 | 739 | 722 | 713 | 701 | 684 | 628 | 635 | |
| | | | | | | | ITALY | | | | | | | | | |
| ALGHERO | 40 38'N | 8 17'E | 40 | 472 | 420 | 433 | 475 | 565 | 575 | 655 | 618 | 581 | 483 | 379 | 373 | |
| ANCONA | 43 37'N | 13 31'E | 105 | 299 | 386 | 375 | 472 | 513 | 516 | 562 | 533 | 505 | 436 | 295 | 301 | |
| BARI | 41 07'N | 16 52'E | 28 | 432 | 563 | 460 | 488 | 509 | 540 | 566 | 527 | 493 | 448 | 340 | 356 | |
| BOLOGNA | 44 31'N | 11 18'E | 43 | 313 | 388 | 346 | 461 | 518 | 488 | 534 | 504 | 479 | 423 | 279 | 281 | |
| BOLZANO | 46 28'N | 11 19'E | 237 | 381 | 425 | 450 | 480 | 507 | 456 | 470 | 466 | 490 | 460 | 369 | 337 | |
| BRINDISI | 40 39'N | 17 57'E | 21 | 455 | 515 | 422 | 455 | 508 | 513 | 564 | 540 | 523 | 483 | 387 | 415 | |
| CAGLIARI | 39 14'N | 9 03'E | 12 | 416 | 422 | 456 | 494 | 549 | 580 | 611 | 589 | 532 | 481 | 400 | 392 | |
| CAMPO IMPER. M. | 42 27'N | 13 34'E | 2138 | 290 | 316 | 477 | 462 | 558 | 502 | 593 | 596 | 522 | 512 | 379 | 418 | |
| CAPO-PALINURO | 40 01'N | 15 16'E | 185 | 463 | 516 | 488 | 504 | 562 | 573 | 591 | 508 | 582 | 531 | 428 | 458 | |
| COZZO SPADARO | 36 41'N | 15 09'E | 46 | - | - | - | 677 | 572 | 656 | 675 | 665 | 578 | - | - | 433 | |
| CROTONE | 39 00'N | 17 05'E | 154 | 428 | 502 | 438 | 443 | 556 | 551 | 573 | 583 | 520 | 471 | 337 | 412 | |
| ETNA C. C. M. | 37 42'N | 15 00'E | 1884 | 476 | 457 | 589 | 401 | 565 | 605 | 699 | 602 | 544 | 469 | 451 | 468 | |
| FIRENZE | 43 48'N | 11 12'E | 48 | 285 | 332 | 365 | 483 | 545 | 557 | 574 | 545 | 487 | 411 | 300 | 263 | |
| FOGGIA | 41 26'N | 15 33'E | 62 | 405 | 490 | 415 | 433 | 454 | 468 | 506 | 507 | 478 | 418 | 341 | 368 | |
| GENOVA | 44 24'N | 8 58'E | 98 | 345 | 365 | 382 | 440 | 444 | 493 | 557 | 525 | 497 | 459 | 351 | 322 | |
| GRAPPA M. | 45 53'N | 11 48'E | 1776 | 517 | 547 | 633 | 677 | 489 | 441 | 528 | 486 | 495 | 447 | 496 | 492 | |
| MARSALA | 37 49'N | 12 27'E | 2 | 425 | 427 | 498 | 515 | 582 | 634 | 693 | 630 | 553 | 503 | 416 | 411 | |
| MESSINA | 38 12'N | 15 33'E | 54 | 394 | 440 | 470 | 477 | 544 | 576 | 613 | 584 | 522 | 461 | 388 | 387 | |
| MILANO | 45 28'N | 9 17'E | 120 | 224 | 329 | 373 | 470 | 534 | 503 | 535 | 507 | 481 | 388 | 257 | 191 | |
| MODENA | 44 39'N | 10 44'E | 64 | 447 | 490 | 391 | 393 | 526 | 575 | 623 | 565 | 553 | 525 | 314 | 353 | |
| MONTE CIMONE | 44 12'N | 10 42'E | 2173 | 599 | - | 409 | - | 504 | 414 | 478 | 489 | 452 | 409 | 380 | - | |
| MONTE TERMINILLO | 42 28'N | 12 59'E | 1875 | 505 | 511 | 381 | 387 | 444 | 428 | 526 | 491 | 490 | 503 | 360 | 373 | |
| NAPOLI | 40 53'N | 14 17'E | 110 | 628 | 389 | 427 | 488 | 517 | 556 | 586 | 552 | 487 | 466 | 362 | 368 | |
| NAPOLI (I. U. N.) | 40 50'N | 14 15'E | 25 | 342 | 369 | 448 | 527 | 534 | 573 | 571 | 561 | 530 | 487 | 397 | 393 | |
| OLBIA | 40 56'N | 9 30'E | 2 | 449 | 458 | 432 | 460 | 511 | 519 | 567 | 540 | 512 | 418 | 371 | 388 | |
| PALLANZA | 45 55'N | 8 33'E | 222 | 577 | 532 | 411 | 515 | 512 | 520 | 551 | 499 | 511 | 483 | 382 | 426 | |
| PANTELLERIA | 36 49'N | 11 57'E | 254 | 432 | 428 | 424 | 445 | 474 | 477 | 502 | 486 | 469 | 410 | 414 | 403 | |
| PESCARA | 42 26'N | 14 13'E | 16 | 417 | 492 | 388 | 450 | 534 | 533 | 616 | 552 | 511 | 445 | 319 | 349 | |
| PIANOSA | 42 35'N | 10 06'E | 17 | 445 | 449 | 435 | 538 | 579 | 576 | 591 | 489 | 532 | 508 | 400 | 414 | |
| PIAN ROSA'M. | 45 56'N | 7 42'E | 3448 | 477 | 580 | 586 | 639 | 612 | 575 | 570 | 528 | 532 | 548 | 491 | 477 | |
| PISA | 43 41'N | 10 24'E | 11 | 469 | 452 | 380 | 480 | 530 | 508 | 542 | 530 | 537 | 534 | 429 | 390 | |
| PROCIDA | 40 45'N | 14 02'E | 80 | 416 | 400 | 407 | 396 | 489 | 504 | 518 | 475 | 431 | 440 | 355 | 350 | |
| ROMA CIAMPINO | 41 48'N | 12 36'E | 131 | 445 | 452 | 407 | 462 | 516 | 551 | 578 | 557 | 511 | 493 | 404 | 395 | |
| SAN REMO | 43 49'N | 7 50'E | 113 | 455 | 484 | 452 | 526 | 563 | 531 | 584 | 550 | 537 | 520 | 414 | 427 | |
| SASSARI | 40 43'N | 8 33'E | 512 | 289 | 346 | 401 | 518 | 566 | 573 | 624 | 577 | 565 | 471 | 406 | 352 | |
| SERPEDDI M. | 39 22'N | 9 18'E | 1048 | 290 | 301 | 378 | 466 | 576 | 621 | 708 | 670 | 521 | 420 | 343 | 323 | |
| SIRACUSA | 37 04'N | 15 17'E | 15 | 405 | 415 | 428 | 447 | 488 | 492 | 500 | 505 | 455 | 407 | 365 | 380 | |
| SORATTE M. | 42 15'N | 12 30'E | 660 | 355 | 376 | 439 | 615 | 620 | 687 | 665 | 635 | 576 | 488 | 416 | 362 | |
| STROMBOLI | 38 48'N | 15 15'E | 5 | 366 | 338 | 479 | 541 | 602 | 623 | 646 | 575 | 508 | 462 | 365 | 356 | |
| TARANTO | 40 28'N | 17 17'E | 41 | 374 | 420 | 498 | 566 | 647 | 645 | 683 | 664 | 598 | 521 | 410 | 455 | |
| TORINO | 45 12'N | 7 39'E | 282 | 374 | 419 | 378 | 468 | 469 | 469 | 512 | 471 | 460 | 428 | 321 | 329 | |
| TRIESTE | 45 39'N | 13 46'E | 12 | 346 | 383 | 378 | 387 | 414 | 475 | 524 | 480 | 466 | 417 | 362 | 333 | |
| UDINE | 46 02'N | 13 11'E | 92 | 439 | 419 | 441 | 414 | 477 | 432 | 523 | 502 | 493 | 488 | 396 | 379 | |
| USTICA | 38 42'N | 13 11'E | 259 | 484 | 518 | 492 | 498 | 562 | 565 | 548 | 576 | 542 | 489 | 444 | 430 | |

APPENDIX A (CON'T)

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | VALUES OF MONTHLY AVG. KH * 1000 [1] | | | | | | | | | | | | |
| | | | | | | ITALY (CON'T) | | | | | | | | | | |
| VENEZIA | 45 26'N | 12 23'E | 17 | 328 | 375 | 407 | 466 | 534 | 504 | 538 | 515 | 493 | 456 | 337 | 288 | |
| VIESTE | 41 53'N | 16 11'E | 67 | 292 | 312 | 411 | 574 | 671 | 662 | 673 | 678 | 593 | 501 | 360 | 413 | |
| VIGNA DI VALLE | 42 05'N | 12 13'E | 270 | 383 | 383 | 388 | 496 | 584 | 610 | 654 | 612 | 540 | 477 | 371 | 353 | |
| | | | | | | JAPAN | | | | | | | | | | |
| ABASHIRI | 44 01'N | 144 17'E | - | 530 | 569 | 594 | 531 | 486 | 455 | 465 | 389 | 486 | 532 | 539 | 540 | |
| AKITA | 39 43'N | 140 06'E | 9 | 413 | 469 | 483 | 508 | 502 | 465 | 450 | 501 | 484 | 495 | 426 | 370 | |
| AOMORI | 40 49'N | 140 47'E | 4 | 467 | 496 | 529 | 496 | 491 | 470 | 459 | 490 | 473 | 520 | 455 | 418 | |
| ASAHIKAWA | 43 46'N | 142 22'E | - | 351 | 401 | 489 | 463 | 417 | 436 | 434 | 383 | 429 | 411 | 348 | 348 | |
| ASHIZURI | 32 43'N | 133 01'E | - | 597 | 609 | 408 | 499 | 364 | 396 | 466 | 525 | 422 | 422 | 555 | 588 | |
| ASOSAN | 32 52'N | 131 05'E | - | 400 | 480 | 420 | 422 | 397 | 314 | 377 | 379 | 363 | 464 | 504 | 472 | |
| ESASHI | 41 52'N | 140 08'E | - | 310 | 391 | 441 | 465 | 424 | 373 | 454 | 494 | 476 | 433 | 381 | 359 | |
| FIUKUOKA | 33 35'N | 130 23'E | 2 | 378 | 396 | 417 | 417 | 389 | 338 | 358 | 408 | 386 | 458 | 463 | 410 | |
| FUKUSHIMA | 37 45'N | 140 28'E | - | 503 | 536 | 484 | 503 | 438 | 369 | 365 | 466 | 397 | 450 | 490 | 558 | |
| HACHIJO-JIMA | 33 06'N | 139 47'E | - | 370 | 341 | 372 | 329 | 345 | 260 | 373 | 441 | 407 | 360 | 361 | 366 | |
| HACHINOHE | 40 32'N | 141 32'E | - | 490 | 459 | 423 | 461 | 410 | 383 | 397 | 414 | 389 | 453 | 458 | 450 | |
| HAKODATE | 41 49'N | 140 45'E | - | 633 | 637 | 608 | 544 | 492 | 470 | 446 | 437 | 493 | 551 | 560 | 676 | |
| HAMADA | 34 54'N | 132 04'E | - | 320 | 407 | 425 | 464 | 442 | 381 | 420 | 498 | 413 | 488 | 481 | 420 | |
| HAMAMATSU | 34 42'N | 137 43'E | - | 544 | 436 | 436 | 404 | 353 | 279 | 329 | 394 | 342 | 330 | 363 | 427 | |
| HIKONE | 35 16'N | 136 15'E | - | 486 | 532 | 483 | 521 | 524 | 411 | 453 | 510 | 469 | 499 | 571 | 496 | |
| HIROSHIMA | 34 22'N | 132 26'E | - | 497 | 533 | 474 | 484 | 441 | 404 | 430 | 501 | 435 | 512 | 558 | 544 | |
| HOFU | 34 03'N | 131 32'E | - | 512 | 572 | 497 | 507 | 448 | 382 | 434 | 543 | 485 | 581 | 623 | 630 | |
| IIDA | 35 31'N | 137 50'E | 482 | 512 | 537 | 509 | 488 | 464 | 403 | 430 | 519 | 443 | 450 | 488 | 529 | |
| INAWASHIRO | 37 34'N | 140 07'E | - | 599 | 639 | 603 | 517 | 555 | 472 | 512 | 552 | 487 | 538 | 522 | 540 | |
| ISHIGAKI-JIMA | 24 20'N | 124 10'E | - | 406 | 368 | 361 | 358 | 415 | 395 | 456 | 466 | 580 | 501 | 518 | 457 | |
| ISHINOMAKI | 38 23'N | 141 18'E | - | 513 | 516 | 444 | 529 | 419 | 402 | 322 | 438 | 413 | 371 | 545 | 487 | |
| IZUHARA | 34 12'N | 129 18'E | - | 508 | 538 | 417 | 503 | 487 | 404 | 429 | 481 | 389 | 539 | 624 | 597 | |
| KAGOSHIMA | 31 34'N | 130 33'E | 20 | 458 | 493 | 454 | 431 | 400 | 342 | 437 | 490 | 471 | 493 | 525 | 528 | |
| KOBE | 34 41'N | 135 11'E | 58 | 426 | 415 | 399 | 384 | 376 | 319 | 367 | 404 | 353 | 382 | 409 | 417 | |
| KOCHI | 33 34'N | 133 33'E | - | 562 | 557 | 469 | 471 | 383 | 355 | 393 | 483 | 437 | 498 | 578 | 570 | |
| KUMAMOTO | 32 49'N | 130 43'E | 38 | 449 | 459 | 464 | 430 | 411 | 358 | 386 | 453 | 440 | 491 | 505 | 483 | |
| KUSHIRO | 43 59'N | 144 24'E | - | 576 | 590 | 579 | 594 | 527 | 495 | 464 | 427 | 512 | 562 | 621 | 632 | |
| KUTCHAN | 42 54'N | 140 45'E | - | 582 | 577 | 585 | 578 | 502 | 465 | 483 | 467 | 521 | 572 | 523 | 537 | |
| MAEBASHI | 36 24'N | 139 04'E | - | 555 | 458 | 464 | 379 | 437 | 293 | 274 | 440 | 418 | 492 | 562 | 627 | |
| MAIZURU | 35 28'N | 135 23'E | - | 412 | 429 | 387 | 472 | 435 | 411 | 454 | 487 | 416 | 407 | 508 | 485 | |
| MINAMI-DAITO-ZIMA | 25 50'N | 131 14'E | 15 | 321 | 291 | 274 | 300 | 296 | 325 | 369 | 334 | 359 | 320 | 317 | 285 | |
| MITO | 36 23'N | 140 28'E | 29 | 532 | 482 | 428 | 405 | 402 | 320 | 369 | 386 | 354 | 368 | 437 | 502 | |
| MIYAKO | 39 39'N | 141 58'E | - | 580 | 561 | 482 | 510 | 434 | 383 | 367 | 419 | 443 | 467 | 574 | 581 | |
| MIYAZAKI | 31 55'N | 131 25'E | - | 595 | 578 | 473 | 453 | 394 | 388 | 416 | 520 | 487 | 509 | 551 | 600 | |
| MIZUSAWA | 39 08'N | 141 08'E | - | 457 | 494 | 454 | 460 | 432 | 366 | 379 | 407 | 426 | 453 | 458 | 432 | |
| MORIOKA | 39 42'N | 141 10'E | - | 720 | 720 | 642 | 601 | 495 | 455 | 478 | 486 | 510 | 586 | 641 | 643 | |
| MURORAN | 42 19'N | 140 59'E | - | 514 | 584 | 579 | 631 | 521 | 432 | 482 | 465 | 496 | 586 | 573 | 569 | |
| MUROTOMISAKI | 33 15'N | 134 11'E | - | 695 | 706 | 574 | 599 | 511 | 486 | 568 | 666 | 593 | 577 | 706 | 882 | |
| NAGANO | 36 40'N | 138 12'E | 418 | 533 | 537 | 533 | 510 | 488 | 432 | 450 | 494 | 435 | 471 | 518 | 534 | |
| NAGASAKI | 32 44'N | 129 53'E | - | 329 | 403 | 402 | 381 | 401 | 372 | 456 | 551 | 421 | 473 | 498 | 431 | |
| NAGOYA | 35 10'N | 136 58'E | - | 583 | 617 | 522 | 526 | 436 | 398 | 427 | 466 | 432 | 474 | 612 | 611 | |
| NAZE | 28 23'N | 129 30'E | - | 329 | 332 | 338 | 355 | 311 | 401 | 486 | 461 | 466 | 390 | 351 | 336 | |
| NEMURO | 43 30'N | 145 35'E | 26 | 556 | 585 | 547 | 493 | 450 | 411 | 387 | 399 | 435 | 498 | 525 | 540 | |
| OBIHIRO | 42 55'N | 143 13'E | - | 576 | 600 | 595 | 532 | 450 | 423 | 369 | 397 | 456 | 524 | 598 | 598 | |
| OITA | 33 14'N | 131 37'E | 5 | 525 | 481 | 464 | 443 | 419 | 364 | 402 | 452 | 428 | 471 | 487 | 530 | |
| OKI-DAITO-ZIMA | 24 24'N | 137 17'E | 25 | 537 | 470 | 504 | 522 | 510 | 539 | 550 | 547 | 526 | 499 | 499 | 400 | |
| ONAHAMA | 36 57'N | 140 54'E | - | 578 | 533 | 376 | 424 | 361 | 348 | 357 | 424 | 386 | 352 | 474 | 594 | |
| OSAKA | 34 39'N | 135 32'E | - | 490 | 455 | 398 | 396 | 314 | 253 | 355 | 385 | 345 | 393 | 425 | 446 | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **JAPAN (CON'T)** | | | | | | | | | | | | | | | | |
| OSHIMA | 34 46'N | 139 23'E | - | 386 | 496 | 417 | 388 | 389 | 253 | 260 | 438 | 406 | 347 | 418 | 415 | |
| OWASHI | 34 04'N | 136 12'E | - | 510 | 433 | 438 | 399 | 388 | 327 | 376 | 439 | 372 | 424 | 416 | 458 | |
| RUMOI | 43 57'N | 141 38'E | - | 358 | 343 | 402 | 400 | 334 | 360 | 352 | 292 | 342 | 355 | 322 | 321 | |
| SAGA | 33 15'N | 130 18'E | - | 453 | 518 | 459 | 459 | 403 | 328 | 388 | 495 | 447 | 550 | 597 | 537 | |
| SAIGO | 36 12'N | 133 20'E | - | 489 | 538 | 547 | 592 | 604 | 484 | 528 | 617 | 551 | 626 | 624 | 540 | |
| SAKATA | 38 54'N | 139 50'E | - | 367 | 396 | 395 | 467 | 420 | 407 | 452 | 412 | 495 | 412 | 405 | 381 | |
| SAPPORO | 43 03'N | 141 20'E | 17 | 407 | 445 | 457 | 451 | 436 | 415 | 404 | 405 | 428 | 436 | 413 | 413 | |
| SENDAI | 38 16'N | 140 54'E | - | 618 | 619 | 572 | 591 | 514 | 419 | 412 | 495 | 460 | 528 | 587 | 619 | |
| SHIMIZU | 32 47'N | 132 58'E | - | 512 | 547 | 439 | 424 | 393 | 338 | 383 | 491 | 459 | 465 | 564 | 606 | |
| SHIMONOSEKI | 33 57'N | 130 56'E | - | 308 | 375 | 390 | 392 | 353 | 317 | 348 | 459 | 374 | 447 | 425 | 365 | |
| SHIONOMISAKI | 33 27'N | 135 46'E | - | 560 | 598 | 482 | 480 | 418 | 394 | 449 | 543 | 489 | 443 | 556 | 605 | |
| SHIRAKAWA | 37 07'N | 140 13'E | - | 597 | 605 | 483 | 540 | 417 | 363 | 337 | 413 | 400 | 387 | 656 | 650 | |
| TADOTSU | 34 17'N | 133 46'E | - | 414 | 350 | 378 | 387 | 429 | 368 | 401 | 440 | - | - | - | - | |
| TAKAMATSU | 34 19'N | 134 03'E | 9 | 496 | 498 | 479 | 465 | 452 | 390 | 426 | 485 | 421 | 426 | 442 | 462 | |
| TATENO | 36 03'N | 140 08'E | 6 | 599 | 529 | 523 | 515 | 514 | 448 | 407 | 493 | 420 | 439 | 485 | 569 | |
| TOHOKU UNIV | 38 15'N | 140 52'E | 48 | 471 | 452 | 439 | 471 | 419 | 355 | 291 | 314 | 295 | 389 | 436 | 399 | |
| TOKYO | 35 41'N | 139 46'E | 4 | 443 | 420 | 385 | 363 | 356 | 301 | 340 | 372 | 327 | 327 | 389 | 427 | |
| TOMIE | 32 37'N | 128 46'E | - | 270 | 315 | 356 | 288 | 245 | 224 | 229 | 315 | 289 | 463 | 447 | 381 | |
| TORISHIMA | 30 29'N | 140 18'E | 81 | 407 | 382 | 350 | 336 | 299 | 326 | 396 | 441 | 483 | 453 | 394 | 433 | |
| TOTTORI | 35 31'N | 134 11'E | 17 | 336 | 337 | 367 | 410 | 418 | 374 | 392 | 452 | 401 | 432 | 419 | 363 | |
| TOYAMA | 36 42'N | 137 12'E | - | 373 | 434 | 420 | 448 | 472 | 383 | 396 | 473 | 412 | 360 | 426 | 337 | |
| TSUKUBASAN | 36 13'N | 140 06'E | - | 624 | 525 | 489 | 471 | 496 | 396 | 368 | 414 | 377 | 435 | 515 | 622 | |
| URUKAWA | 42 10'N | 142 47'E | - | 381 | 373 | 395 | 364 | 359 | 348 | 310 | 331 | 375 | 402 | 369 | 330 | |
| UTSUNOMIYA | 36 33'N | 139 52'E | 120 | 619 | 569 | 518 | 474 | 454 | 358 | 370 | 415 | 393 | 438 | 523 | 593 | |
| WAKAMATSU | 37 29'N | 139 55'E | - | 562 | 624 | 537 | 548 | 505 | 488 | 515 | 535 | 524 | 515 | 495 | 524 | |
| WAKKANAI | 45 25'N | 141 41'E | - | 356 | 392 | 495 | 479 | 456 | 410 | 390 | 382 | 494 | 476 | 267 | 341 | |
| YAKUSHIMA | 30 27'N | 130 30'E | - | 311 | 347 | 293 | 419 | 351 | 410 | 510 | 533 | 528 | 311 | 352 | 329 | |
| YAMAGATA | 38 15'N | 140 21'E | - | 523 | 543 | 506 | 488 | 450 | 417 | 440 | 520 | 467 | 458 | 487 | 479 | |
| YONAGO | 35 26'N | 133 21'E | 6 | 418 | 432 | 457 | 496 | 511 | 434 | 455 | 535 | 471 | 515 | 499 | 443 | |
| **KENYA** | | | | | | | | | | | | | | | | |
| FORT ESSEX | 00 42'S | 36 42'E | 2463 | 662 | 662 | 621 | 552 | 473 | 496 | 355 | 364 | 571 | 583 | 558 | 590 | |
| KERICHO | 00 19'S | 35 28'E | 2042 | 657 | 666 | 663 | 544 | 554 | 574 | 503 | 496 | 530 | 501 | 530 | 612 | |
| MARIGAT | 00 35'N | 36 00'E | 1219 | 795 | 776 | 784 | 726 | 760 | 767 | 642 | 754 | 793 | 789 | 699 | 742 | |
| MUGUGUA | 01 12'S | 36 38'E | 2073 | 535 | 585 | 557 | 499 | 457 | 490 | 427 | 443 | 581 | 468 | 550 | 554 | |
| NAIROBI | 01 18'S | 36 45'E | 1799 | 642 | 665 | 622 | 560 | 510 | 509 | 410 | 439 | 529 | 552 | 555 | 608 | |
| **KOREA** | | | | | | | | | | | | | | | | |
| INCHON | 37 29'N | 126 38'E | 69 | 534 | 544 | 516 | 504 | 510 | 506 | 475 | 498 | 508 | 530 | 523 | 524 | |
| KANGNUNG | 37 45'N | 128 54'E | 26 | 590 | 529 | 518 | 505 | 478 | 455 | 465 | 498 | 550 | 516 | 527 | 530 | |
| PUZAN | 35 06'N | 129 02'E | 71 | 696 | 634 | 604 | 580 | 569 | 489 | 464 | 539 | 554 | 561 | 632 | 670 | |
| PYONGYANG | 39 01'N | 125 49'E | - | 566 | 547 | 544 | 522 | 500 | 485 | 454 | 455 | 503 | 530 | 526 | 530 | |
| SEOUL | 37 34'N | 126 58'E | 86 | 535 | 526 | 517 | 505 | 510 | 506 | 465 | 475 | 509 | 531 | 501 | 498 | |
| TAIKYU | 35 53'N | 128 37'E | 61 | 804 | 726 | 619 | 580 | 540 | 488 | 460 | 491 | 514 | 603 | 638 | 744 | |
| UNGGI | 42 19'N | 130 24'E | 88 | 588 | 579 | 543 | 499 | 461 | 424 | 424 | 440 | 496 | 533 | 511 | 515 | |
| WONSAN | 39 11'N | 127 26'E | 35 | 597 | 570 | 530 | 523 | 490 | 464 | 423 | 433 | 477 | 532 | 529 | 534 | |
| YOGAMPO | 39 56'N | 124 22'E | 12 | 503 | 540 | 537 | 514 | 512 | 505 | 475 | 503 | 523 | 540 | 518 | 551 | |
| **LEBANON** | | | | | | | | | | | | | | | | |
| KSARA OBSEVATORY | 33 49'N | 35 53'E | 927 | 486 | 562 | 580 | 628 | 679 | 737 | 741 | 732 | 709 | 642 | 558 | 481 | |
| **MACAU** | | | | | | | | | | | | | | | | |



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| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | VALUES OF MONTHLY AVG. KH * 1000 [1] | | | | | | | | | | | | |
| **MACAU (CON'T)** | | | | | | | | | | | | | | | | |
| MACAU | 22 12'N | 113 33'E | 65 | 445 | 280 | 337 | 419 | 441 | 482 | 564 | 561 | 550 | 635 | 642 | 579 | |
| **MADEIRA ISLANDS** | | | | | | | | | | | | | | | | |
| FUNCHAL | 32 38'N | 16 54'W | 58 | 531 | 521 | 571 | 564 | 571 | 537 | 578 | 583 | 599 | 566 | 489 | 543 | |
| PORTO SANTO | 33 01'N | 16 03'W | 45 | 548 | 527 | 612 | 574 | 630 | 642 | 648 | 588 | 618 | 581 | 526 | 512 | |
| **MALIGASY** | | | | | | | | | | | | | | | | |
| TANANARIVE | 18 54'S | 47 32'E | 1310 | 520 | 539 | 564 | 617 | 630 | 624 | 631 | 682 | 697 | 683 | 645 | 585 | |
| **MALAYA** | | | | | | | | | | | | | | | | |
| SINGAPORE | 1 19'N | 103 49'E | 36 | 432 | 428 | 420 | 422 | 417 | 456 | 389 | 363 | 519 | 520 | 408 | 473 | |
| **MALI** | | | | | | | | | | | | | | | | |
| GAO | 16 16'N | 0 03'W | 270 | 645 | 617 | 603 | 611 | 599 | 567 | 580 | 575 | 588 | 603 | 633 | 607 | |
| TESSALIT | 20 12'N | 0 59'E | 496 | 790 | 748 | 729 | 714 | 698 | 661 | 697 | 682 | 691 | 707 | 691 | 691 | |
| **MALTA** | | | | | | | | | | | | | | | | |
| QRENDI | 35 50'N | 14 26'E | 135 | 549 | 511 | 623 | 594 | 654 | 689 | 712 | 726 | 649 | 604 | 520 | 556 | |
| **MARIANA ISLANDS** | | | | | | | | | | | | | | | | |
| SAIPAN | 15 14'N | 145 46'E | 212 | 561 | 597 | 658 | 688 | 646 | 637 | 517 | 532 | 506 | 535 | 553 | 550 | |
| WOLEAI | 7 22'N | 143 55'E | 2 | 545 | 571 | 611 | 582 | 584 | 504 | 525 | 502 | 4[illegible]8 | 538 | 546 | 571 | |
| **MARSHALL ISLANDS** | | | | | | | | | | | | | | | | |
| JALUIT | 5 55'N | 169 39'E | 2 | 056 | 060 | 048 | 048 | 051 | 050 | 051 | 050 | 056 | 049 | 050 | 048 | PPS |
| PONAPE | 6 58'N | 158 13'E | 30 | 042 | 047 | 043 | 040 | 040 | 041 | 045 | 048 | 043 | 045 | 043 | 038 | PPS |
| **MAURITANIA** | | | | | | | | | | | | | | | | |
| ATAR | 20 31'N | 13 04'W | 227 | 700 | 724 | 706 | 736 | 698 | 713 | 686 | 682 | 610 | 644 | 649 | 680 | |
| FORT GOUROUD | 22 41'N | 12 42'W | 297 | 732 | 705 | 719 | 740 | 726 | 695 | 669 | 637 | 617 | 566 | 629 | 732 | |
| NEMA | 16 37'N | 7 16'W | 269 | 634 | 633 | 616 | 600 | 587 | 533 | 568 | 575 | 577 | 593 | 565 | 565 | |
| NOUAKCHOTT | 18 07'N | 15 56'W | 5 | 743 | 713 | 742 | 745 | 714 | 712 | 672 | 672 | 673 | 691 | 681 | 693 | |
| PORT ETIENNE | 20 56'N | 17 03'W | 8 | 706 | 714 | 709 | 726 | 718 | 722 | 674 | 681 | 682 | 673 | 669 | 669 | |
| **MEXICO** | | | | | | | | | | | | | | | | |
| ALTOZOMONI | 19 07'N | 98 38'W | 3975 | 618 | 847 | 817 | 525 | 317 | 400 | 497 | 619 | 544 | 666 | 697 | - | |
| CHIHUAHUA | 28 38'N | 106 05'W | 1430 | 342 | 563 | 390 | 343 | 402 | 387 | 339 | 468 | 513 | 465 | 510 | 346 | |
| CIUDAD UNIV. | 19 20'N | 99 11'W | 2268 | 546 | 706 | 786 | 595 | 555 | 461 | 461 | 518 | 503 | 502 | 557 | 594 | |
| TACUBAYA | 19 24'N | 99 06'W | 2300 | 594 | 623 | 633 | 578 | 531 | 514 | 455 | 483 | 449 | 501 | 570 | 592 | |
| VERACRUZ | 19 12'N | 96 08'W | 12 | 503 | 594 | - | - | 643 | 664 | 541 | 616 | 616 | 654 | 630 | 657 | |
| - | 27 30'N | 110 00'W | - | 672 | 687 | 688 | 683 | 688 | 682 | 649 | 650 | 685 | 762 | 678 | 631 | |
| - | 27 30'N | 107 00'W | - | 672 | 687 | 688 | 683 | 688 | 651 | 649 | 650 | 685 | 719 | 678 | 631 | |
| - | 25 00'N | 109 00'W | - | 562 | 583 | 582 | 586 | 584 | 584 | 527 | 550 | 553 | 611 | 560 | 517 | |
| - | 23 00'N | 110 00'W | - | 570 | 578 | 584 | 583 | 629 | 621 | 583 | 615 | 582 | 609 | 585 | 527 | |
| - | 20 00'N | 106 00'W | - | 582 | 594 | 594 | 568 | 570 | 555 | 569 | 572 | 550 | 575 | 568 | 541 | |

APPENDIX A (CON'T)

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | MEXICO (CON'T) | | | | | | | | | | |
| - | 20 00'N | 91 00'W | - | 535 | 594 | 594 | 524 | 527 | 491 | 494 | 528 | 515 | 562 | 553 | 508 | |
| - | 17 30'N | 93 00'W | - | 494 | 534 | 488 | 445 | 444 | 411 | 446 | 441 | 405 | 445 | 487 | 482 | |
| - | 17 00'N | 100 00'W | - | 624 | 610 | 594 | 567 | 576 | 554 | 567 | 574 | 543 | 570 | 597 | 616 | |
| - | 30 00'N | 110 00'W | - | 699 | 721 | 681 | 724 | 729 | 687 | 687 | 686 | 723 | 717 | 719 | 679 | |
| | | | | | | MONGOLIA | | | | | | | | | | |
| ULAN-BATOR | 47 51'N | 106 45 | - | 639 | 653 | 657 | 568 | 619 | 548 | 530 | 551 | 553 | 583 | 538 | 558 | |
| | | | | | | MOZAMBIQUE | | | | | | | | | | |
| BEIRA | 19 08'S | 34 08'E | 7 | 566 | 516 | 629 | 640 | 614 | 665 | 637 | 676 | 601 | 574 | 593 | 532 | |
| LOURENCO MARQUEZ | 25 58'S | 32 36'E | 59 | 572 | 593 | 610 | 639 | 672 | 690 | 669 | 657 | 555 | 484 | 535 | 506 | |
| LUMBO | 15 00'S | 40 07'E | 10 | 539 | 534 | 571 | 635 | 640 | 614 | 660 | 708 | 731 | 716 | 718 | 585 | |
| | | | | | | NETHERLANDS | | | | | | | | | | |
| DE BILT | 52 06'N | 5 11'E | 42 | 341 | 323 | 414 | 428 | 466 | 462 | 432 | 407 | 416 | 337 | 269 | 256 | |
| WAGENINGEN | 52 00'N | 5 36'E | 20 | 305 | 306 | 392 | 424 | 444 | 425 | 393 | 398 | 412 | 338 | 258 | 267 | |
| | | | | | | NEW GUINEA | | | | | | | | | | |
| BALIEM | 4 04'S | 138 57'E | 1615 | - | - | 607 | 637 | 626 | 659 | 625 | 629 | 547 | 659 | 629 | 570 | |
| HOLLANDIA | 2 34'S | 140 29'E | 99 | 455 | 474 | 509 | 352 | 490 | 531 | 492 | 495 | 480 | 489 | 485 | 473 | |
| MERAUKE | 8 28'S | 140 23'E | 3 | 523 | 516 | 489 | 485 | 480 | 360 | 451 | 502 | 547 | 542 | 558 | 458 | |
| RABUAL | 4 00'S | 152 00'E | 6 | 517 | 503 | 529 | 516 | 565 | 592 | 520 | 556 | 548 | 534 | 510 | 486 | |
| | | | | | | NEW ZEALAND | | | | | | | | | | |
| INVERCARGILL | 46 25'S | 168 19'E | 0 | 518 | 511 | 473 | 429 | 433 | 399 | 479 | 504 | 522 | 508 | 489 | 495 | |
| NANDI | 17 45'S | 177 27'E | 16 | 650 | 612 | 541 | 556 | 599 | 646 | 657 | 652 | 644 | 640 | 616 | 609 | |
| OHAKEA | 40 12'S | 175 23'E | 51 | 577 | 537 | 522 | 502 | 457 | 486 | 477 | 520 | 557 | 531 | 535 | 544 | |
| RAOUL ISLAND | 29 15'S | 177 55'W | 49 | 590 | 545 | 565 | 532 | 566 | 478 | 535 | 520 | 563 | 553 | 596 | 658 | |
| WELLINGTON | 41 17'S | 174 46'E | 126 | 549 | 502 | 506 | 483 | 420 | 455 | 435 | 486 | 542 | 513 | 502 | 494 | |
| WHENUAPAI | 36 47'S | 174 39'E | 31 | 532 | 501 | 509 | 515 | 461 | 478 | 478 | 483 | 523 | 483 | 511 | 501 | |
| | | | | | | NIGER | | | | | | | | | | |
| AGADEZ | 16 59'N | 7 59'E | 496 | 757 | 742 | 701 | 711 | 684 | 684 | 687 | 674 | 705 | 734 | 753 | 739 | |
| BILMA | 18 41'N | 12 55'E | 362 | 674 | 692 | 625 | 645 | 637 | 656 | 605 | 661 | 640 | 683 | 702 | 669 | |
| NAIMEY | 13 29'N | 2 10'E | 223 | 698 | 742 | 724 | 671 | 662 | 650 | 601 | 562 | 622 | 703 | 732 | 750 | |
| | | | | | | NIGERIA | | | | | | | | | | |
| BENIN CITY | 6 33'N | 5 37'E | 109 | 394 | 441 | 452 | 441 | 429 | 414 | 339 | 330 | 367 | 433 | 464 | 458 | |
| ENUGU | 6 28'N | 7 33'E | 137 | 501 | 508 | 462 | 494 | 496 | 567 | 400 | 378 | 419 | 453 | 516 | 538 | |
| IBADAN | 7 26'N | 3 54'E | 228 | 508 | 512 | 486 | 481 | 481 | 445 | 373 | 342 | 385 | 456 | 521 | 519 | |
| IKEJA | 6 35'N | 3 20'E | 38 | 503 | 571 | 565 | 559 | 501 | 454 | 432 | 402 | 430 | 484 | 607 | 528 | CFP |
| ILORIN | 8 29'N | 4 35'E | 287 | 586 | 601 | 556 | 545 | 530 | 635 | 460 | 429 | 419 | 504 | 593 | 598 | CFP |
| JOS | 9 52'N | 8 54'E | 1286 | 639 | 630 | 581 | 558 | 531 | 530 | 482 | 463 | 499 | 568 | 648 | 655 | |
| KADUNA | 10 36'N | 7 27'E | 646 | 627 | 628 | 596 | 579 | 560 | 546 | 488 | 449 | 500 | 563 | 635 | 644 | |
| KANO | 12 03'N | 8 23'E | 476 | 628 | 613 | 589 | 589 | 578 | 573 | 561 | 514 | 570 | 618 | 634 | 632 | |
| MAIDUGURI | 11 51'N | 13 05'E | 354 | 653 | 636 | 588 | 600 | 601 | 585 | 540 | 503 | 570 | 629 | 659 | 644 | |
| MAKURDI | 7 41'N | 8 37'E | 970 | 595 | 585 | 530 | 579 | 564 | 635 | 485 | 404 | 487 | 530 | 584 | 632 | CFP |

APPENDIX A (CON'T)

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | VALUES OF MONTHLY AVG. KH * 1000 [1] | | | | | | | | | | | | |
| **NIGERIA (CON'T)** | | | | | | | | | | | | | | | | |
| MAMFE (Camaroon) | 5 43'N | 9 17'E | 152 | 470 | 503 | 461 | 439 | 453 | 406 | 368 | 345 | 374 | 427 | 449 | 467 | |
| MINNA | 9 37'N | 6 32'E | 260 | 585 | 577 | 562 | 571 | 569 | 478 | 411 | 407 | 492 | 563 | 644 | 627 | PPP |
| PORT HARCOURT | 4 51'N | 7 01'E | 20 | 452 | 452 | 437 | 440 | 433 | 386 | 347 | 359 | 362 | 390 | 420 | 485 | |
| SOKOTO | 13 01'N | 5 15'E | 352 | 651 | 632 | 603 | 600 | 575 | 602 | 536 | 513 | 571 | 623 | 643 | 643 | |
| YOLA | 9 14'N | 12 28'E | 175 | 626 | 630 | 570 | 580 | 576 | 553 | 516 | 497 | 533 | 592 | 636 | 642 | |
| **NORWAY** | | | | | | | | | | | | | | | | |
| BERGEN | 60 24'N | 5 19'E | 44 | 301 | 301 | 507 | 387 | 487 | 427 | 361 | 369 | 298 | 232 | 233 | 202 | |
| BLINDERN | 59 56'N | 10 44'E | - | 022 | 031 | 040 | 047 | 043 | 046 | 045 | 044 | 035 | 029 | 022 | 017 | PPS |
| BRONNOYSUND | 65 29'N | 12 13'E | 13 | 017 | 034 | 043 | 040 | 031 | 033 | 026 | 035 | 033 | 021 | 020 | 006 | PPS |
| GJERMUNDNES | 62 37'N | 7 10'E | 31 | 019 | 040 | 038 | 034 | 036 | 035 | 028 | 032 | 034 | 027 | 024 | 010 | PPS |
| GREEN HARBOR | 78 00'N | 14 05'E | - | * | * | 442 | 515 | * | * | * | * | 317 | 351 | * | * | |
| HAUGASTOL | 60 31'N | 7 52'E | 988 | 026 | 033 | 048 | 054 | 048 | 047 | 040 | 036 | 036 | 031 | 029 | 019 | PPS |
| HORNSUND | 77 00'N | 15 33'E | 11 | * | * | 007 | 160 | * | * | * | * | 616 | 278 | * | * | |
| KJEVIK | 58 12'N | 8 05'E | 15 | 026 | 032 | 041 | 052 | 049 | 057 | 049 | 047 | 043 | 032 | 022 | 022 | PPS |
| LILLEHAMMER | 61 06'N | 10 29'E | 228 | 019 | 024 | 051 | 050 | 045 | 041 | 038 | 038 | 036 | 032 | 026 | 018 | PPS |
| MURCHISON BAY | 80 03'N | 18 15'E | 7 | * | * | 576 | 648 | * | * | * | * | 372 | * | * | * | |
| SOLA | 58 53'N | 5 38'E | 13 | 020 | 033 | 038 | 044 | 045 | 045 | 035 | 035 | 037 | 026 | 021 | 013 | PPS |
| TROMSO | 69 39'N | 18 57'E | 118 | * | 422 | 423 | 492 | 413 | * | * | 368 | 351 | 309 | 391 | * | |
| TRONDHEIM | 63 25'N | 10 27'E | 133 | 016 | 039 | 040 | 035 | 039 | 036 | 030 | 036 | 033 | 026 | 018 | 015 | PPS |
| ULLENSVANG | 60 20'N | 6 40'E | 988 | 023 | 027 | 047 | 048 | 044 | 043 | 040 | 030 | 037 | 022 | 021 | 017 | PPS |
| UTSIRA | 59 18'N | 4 53'E | 56 | 017 | 029 | 037 | 046 | 044 | 044 | 033 | 035 | 035 | 024 | 020 | 014 | PPS |
| **PAKISTAN** | | | | | | | | | | | | | | | | |
| KARACHI | 24 54'N | 67 08'E | - | 630 | 653 | 670 | 614 | 574 | 542 | 409 | 449 | 472 | 605 | 634 | 642 | |
| MULTAN | 30 12'N | 71 26'E | - | 607 | 609 | 557 | 590 | 566 | 579 | 573 | 546 | 570 | 599 | 530 | 547 | |
| PESHAWAR | 34 00'N | 71 31'E | - | 556 | 641 | 552 | 569 | 546 | 594 | 559 | 555 | 595 | 638 | 565 | 530 | |
| QUETA | 30 12'N | 66 57'E | - | 663 | 638 | 613 | 680 | 712 | 750 | 729 | 747 | 735 | 754 | 643 | 585 | |
| **PALAU ISLAND** | | | | | | | | | | | | | | | | |
| PALAU ISLAND | 7 20'N | 134 29'E | - | 507 | 499 | 520 | 515 | 481 | 492 | 443 | 467 | 476 | 479 | 471 | 545 | |
| **PANAMA** | | | | | | | | | | | | | | | | |
| ALBROOK A.B. | 8 39'N | 79 34'W | 6 | 505 | 572 | 596 | 554 | 459 | 390 | 428 | 422 | 508 | 457 | 478 | 554 | |
| **PERU** | | | | | | | | | | | | | | | | |
| HUANCAYO | 12 02'S | 75 19'W | 3313 | 705 | 552 | 645 | 669 | 695 | 736 | 760 | 752 | 707 | 696 | 669 | 629 | |
| **PHILIPPINES** | | | | | | | | | | | | | | | | |
| QUEZON CITY | 14 40'N | 121 05'E | - | 439 | 389 | 510 | 575 | 505 | 477 | 389 | 404 | 407 | 451 | 484 | 511 | |
| **POLAND** | | | | | | | | | | | | | | | | |
| BIALOWIEZA | 52 42'N | 23 51'E | 200 | 346 | 352 | - | 501 | 513 | - | 475 | - | - | 422 | 207 | 222 | |
| BRWINOW | 52 08'N | 20 43'E | 96 | 308 | 350 | 440 | 526 | 507 | 490 | 424 | 431 | 458 | 429 | 256 | 296 | |
| DANZIG | 54 23'N | 18 37'E | - | 332 | 528 | 422 | 473 | 511 | 525 | 484 | 483 | 466 | 378 | 287 | 270 | |
| GDYNIA | 54 30'N | 18 36'E | - | 296 | 379 | 433 | 448 | 494 | 516 | 465 | 451 | 429 | 366 | 300 | 232 | |
| KASPROWY-WIERCH | 49 14'N | 19 59'E | 2007 | 517 | 405 | 596 | 506 | 466 | 358 | 380 | 364 | 419 | 541 | 515 | 422 | |



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APPENDIX A (CON'T)

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | VALUES OF MONTHLY AVG. KH * 1000 [1] | | | | | | | | | | | | |
| | | | | | | POLAND (CON'T) | | | | | | | | | | |
| KOLOBRZEG | 54 11'N | 15 35'E | 19 | 431 | 408 | 446 | 489 | 564 | 519 | 490 | 506 | 495 | 394 | 268 | 361 | |
| SUWALKI | 54 06'N | 22 57'E | 165 | 467 | 432 | 576 | 551 | 595 | 560 | 539 | 546 | 511 | 447 | 282 | 366 | |
| SZCZAWNO-ZDROJ | 50 48'N | 16 16'E | 441 | 424 | 378 | 420 | 414 | 475 | 475 | 413 | 469 | 429 | 412 | 305 | 405 | |
| SZRENICA | 50 48'N | 15 31'E | 1364 | - | - | - | 328 | 359 | 323 | 353 | 310 | 337 | 344 | 373 | - | |
| WARSAW | 52 19'N | 20 59'E | 113 | 246 | 326 | 395 | 418 | 468 | 363 | 406 | 406 | 385 | 322 | 228 | 187 | |
| WROCLAW | 51 07'N | 17 05'E | 116 | 327 | 361 | 358 | 377 | 360 | 487 | 484 | 458 | 441 | 390 | 257 | 265 | |
| ZAKOPANE | 49 17'N | 19 58'E | 486 | 415 | 508 | 468 | 426 | 365 | - | 315 | 491 | 484 | 498 | 402 | 387 | |
| | | | | | | PORTUGAL | | | | | | | | | | |
| BRAGANCA | 41 49'N | 6 46'W | 725 | 427 | 558 | 499 | 617 | 620 | 672 | 744 | 691 | 632 | 600 | 573 | 422 | |
| CALDAS DA SAUDE | 41 22'N | 8 29'W | 74 | 424 | 453 | 464 | 567 | 584 | 622 | 649 | 578 | 524 | 564 | 488 | 439 | |
| COIMBRA | 40 12'N | 8 25'W | 141 | 503 | 582 | 481 | 614 | 592 | 595 | 627 | 618 | 591 | 618 | 565 | 509 | |
| EVORA | 38 34'N | 7 54'W | 309 | 492 | 570 | 518 | 646 | 644 | 701 | 743 | 695 | 640 | 596 | 544 | 479 | |
| FARO | 37 01'N | 7 55'W | 14 | 550 | 626 | 599 | 700 | 721 | 763 | 769 | 746 | 715 | 652 | 569 | 555 | |
| LISBOA | 38 07'N | 9 01'W | 77 | 507 | 585 | 545 | 652 | 665 | 698 | 743 | 710 | 649 | 613 | 559 | 490 | |
| M. ESTORIL | 38 07'N | 9 06'W | 31 | 559 | 563 | 590 | 676 | 673 | 710 | 751 | 695 | 650 | 629 | 603 | 510 | |
| PENHAS DOURADAS | 40 25'N | 7 33'W | 1383 | 470 | 611 | 512 | 624 | 646 | 701 | 784 | 722 | 672 | 634 | 564 | 492 | |
| PORTO | 41 08'N | 8 36'W | 96 | 435 | 523 | 509 | 655 | 659 | 664 | 685 | 644 | 614 | 589 | 533 | 431 | |
| VENDAS NOVAS | 38 07'N | 8 05'W | 127 | 500 | 538 | 483 | 603 | 525 | 668 | 706 | 671 | 619 | 603 | 457 | 357 | |
| | | | | | | PORT. GUINEA | | | | | | | | | | |
| BISSAU | 11 52'N | [illegible] 30'W | 29 | 615 | 631 | 707 | 716 | 676 | 579 | 525 | 420 | 554 | 596 | 594 | 605 | |
| KANKAN | 10 23'N | 9 18'E | 377 | 625 | 614 | 596 | 568 | 561 | 558 | 500 | 483 | 523 | 586 | 595 | 601 | |
| SIGUIRI | 11 26'N | 9 10'W | 362 | 622 | 633 | 610 | 589 | 569 | 564 | 519 | 482 | 535 | 591 | 590 | 598 | |
| | | | | | | PORT. TIMOR | | | | | | | | | | |
| DILI | 8 06'S | 125 06'E | 3 | 530 | 529 | 557 | 576 | 608 | 605 | 593 | 622 | 616 | 617 | 587 | 534 | |
| | | | | | | PUERTO RICO | | | | | | | | | | |
| SAN JUAN | 18 28'N | 66 06'W | 26 | 655 | 661 | 697 | 675 | 600 | 659 | 695 | 632 | 630 | 636 | 623 | 679 | |
| | | | | | | RHODESIA AND NYASALAND | | | | | | | | | | |
| BULAWAYO | 20 09'S | 28 37'E | 1330 | 552 | 539 | 625 | 668 | 706 | 696 | 718 | 723 | 676 | 622 | 556 | 502 | |
| ZOMBA | 15 23'S | 35 18'E | - | 039 | 036 | 038 | 053 | 054 | 047 | 046 | 064 | 061 | 065 | 050 | 036 | PPS;86 |
| | | | | | | SAMOA | | | | | | | | | | |
| APIA | 13 48'S | 172 00'W | 5 | 037 | 039 | 045 | 045 | 050 | 046 | 053 | 056 | 050 | 048 | 043 | 037 | |
| | | | | | | SAO TOME | | | | | | | | | | |
| ILHA DE | 0 23'N | 6 43'E | 8 | 378 | 404 | 392 | 438 | 485 | 479 | 431 | 420 | 414 | 396 | 412 | 385 | |
| | | | | | | SENEGAL | | | | | | | | | | |
| DAKAR | 14 43'N | 17 26'W | 17 | 563 | 594 | 631 | 629 | 610 | 594 | 503 | 424 | 476 | 517 | 550 | 536 | |
| | | | | | | SIERRA LEONE | | | | | | | | | | |



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VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | [illegible] LEONE (CON'T) | | | | | | | | | |
| LUNGI | 8 37'N | 13 12'W | 38 | 499 | 508 | 546 | 590 | 473 | 498 | 336 | 386 | 426 | 568 | 513 | 535 | |
| | | | | | | | SPAIN | | | | | | | | | |
| ALMERIA | 37 00'N | 2 30'W | - | 537 | 568 | 590 | 602 | 586 | 595 | 614 | 611 | 589 | 570 | 539 | 514 | |
| BADAJOZ | 39 00'N | 7 00'W | - | 442 | 516 | 458 | 435 | 448 | 600 | 630 | 619 | 570 | 522 | 492 | 438 | |
| LAS ROZAS | 40 30'N | 3 30'W | - | 449 | 540 | 513 | 582 | 567 | 580 | 626 | 616 | 558 | 518 | 470 | 443 | |
| SAN PABLO | 37 30'N | 6 00'W | - | 392 | 531 | 530 | 572 | 565 | 573 | 592 | 571 | 552 | 503 | 446 | 425 | |
| | | | | | | | SPANISH W. AFRICA | | | | | | | | | |
| CABO JUBY | 27 56'N | 12 55'W | 6 | 565 | 583 | 574 | 570 | 550 | 506 | 491 | 529 | 540 | 564 | 544 | 539 | |
| | | | | | | | SUDAN | | | | | | | | | |
| EL-FASHER | 13 37'N | 25 20'E | 730 | 620 | 639 | 636 | 574 | 582 | 573 | 570 | 595 | 609 | 625 | 632 | 605 | |
| JUBA | 4 52'N | 31 37'E | 457 | 557 | 553 | 522 | 537 | 593 | 583 | 628 | 565 | 589 | 604 | 582 | 580 | |
| KHARTOWN | 15 36'N | 32 33'E | 380 | 649 | 650 | 650 | 627 | 613 | 576 | 574 | 570 | 589 | 611 | 639 | 647 | |
| PORT SUDAN | 19 35'N | 37 13'E | 3 | 629 | 632 | 660 | 666 | 654 | 602 | 605 | 596 | 633 | 601 | 609 | 552 | |
| TOZI | 12 30'N | 34 00'E | 440 | 570 | 572 | 580 | 531 | 550 | 524 | 500 | 516 | 547 | 558 | 550 | 566 | |
| WAD MEDANI | 14 24'N | 33 29'E | 405 | 632 | 639 | 632 | 599 | 614 | 573 | 528 | 560 | 595 | 670 | 646 | 653 | |
| | | | | | | | SWAN ISLAND | | | | | | | | | |
| SWAN ISLAND | 17 24'N | 83 56'W | 18 | 657 | 632 | 692 | 680 | 652 | 571 | 609 | 585 | 625 | 543 | 587 | 582 | |
| | | | | | | | SWEDEN | | | | | | | | | |
| ERKEN | 59 50'N | 18 38'E | - | 363 | 486 | 512 | 473 | 483 | 483 | 474 | 422 | 436 | 316 | 210 | 233 | |
| FROSON | 63 12'N | 14 29'E | 364 | 383 | 595 | 589 | 541 | 543 | 515 | 463 | 487 | 414 | 314 | 249 | 270 | |
| HARADS | 66 05'N | 20 57'E | - | 267 | 400 | 400 | 364 | 350 | 406 | 501 | 409 | 360 | 248 | 171 | 829 | |
| KARLSTAD | 59 22'N | 13 28'E | 47 | 362 | 456 | 509 | 448 | 527 | 567 | 485 | 476 | 460 | 326 | 208 | 246 | |
| KIRUNA | 67 48'N | 20 24'E | - | * | 550 | 584 | 615 | 499 | * | 430 | 421 | 395 | 355 | 378 | * | |
| SANDVIKEN | 60 37'N | 16 48'E | - | 255 | 419 | 445 | 488 | 533 | 472 | 494 | 450 | 438 | 329 | 256 | 254 | |
| STOCKHOLM | 59 21'N | 17 57'E | 43 | 326 | 406 | 494 | 457 | 501 | 500 | 499 | 482 | 435 | 343 | 246 | 278 | |
| SVALOV | 55 55'N | 13 07'E | 72 | 308 | 299 | 438 | 440 | 475 | 517 | 440 | 430 | 493 | 390 | 215 | 147 | |
| TEG | 63 49'N | 20 04'E | - | 367 | 468 | 480 | 488 | 506 | 582 | 580 | 504 | 441 | 331 | 137 | 117 | |
| TORSLANDA | 57 42'N | 11 58'E | 6 | 263 | 324 | 431 | 474 | 490 | 549 | 449 | 454 | 493 | 349 | 177 | 137 | |
| ULTUNA | 59 49'N | 17 49'E | - | 325 | 476 | 566 | 474 | 467 | 464 | 429 | 449 | 309 | 284 | 275 | 286 | |
| VISBY | 57 39'N | 18 20'E | 47 | 243 | 398 | 492 | 530 | 561 | 582 | 498 | 480 | 474 | 326 | 183 | 161 | |
| | | | | | | | SWITZERLAND | | | | | | | | | |
| BASLE | 47 35'N | 7 35'E | 317 | 390 | 486 | 385 | 437 | 515 | 457 | - | - | 500 | 316 | 206 | 316 | |
| DAVOS | 46 48'N | 9 49'E | 1590 | 532 | 576 | 605 | 606 | 546 | 521 | 533 | 511 | 520 | 518 | 498 | 512 | |
| GENEVE | 46 15'N | 6 10'E | - | 019 | 032 | 047 | 052 | 052 | 057 | 064 | 061 | 054 | 040 | 022 | 014 | PPS |
| HOCHSERFAUS | 47 13'N | 8 17'E | 1817 | 533 | 701 | 642 | 611 | 604 | 608 | 584 | 536 | 582 | 583 | 485 | 539 | HOC |
| JUNGFRAUJOCH | 46 32'N | 7 58'E | 3472 | 612 | 670 | 718 | 699 | 573 | 571 | 664 | 630 | 508 | 557 | 589 | 599 | |
| LOCARNO-MONTL | 46 10'N | 8 48'E | 379 | 506 | 542 | 532 | 498 | 479 | 534 | 562 | 529 | 507 | 459 | 455 | 471 | |
| WEISSFLUHJOCH | 46 50'N | 9 48'E | 2670 | 688 | 826 | 679 | 757 | 579 | 422 | 469 | 439 | 639 | 583 | 610 | 628 | |
| ZURICH | 47 23'N | 8 33'E | - | 309 | 358 | 443 | 472 | 444 | 520 | 513 | 491 | 463 | 331 | 295 | 284 | |
| | | | | | | | THILAND | | | | | | | | | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **THILAND (CON'T)** | | | | | | | | | | | | | | | | |
| BANGKOK | 13 44'N | 100 30'E | 20 | 600 | 619 | 526 | 537 | 532 | 504 | 431 | 447 | 429 | 469 | 620 | 628 | |
| CHIANGMAI | 18 47'N | 98 59'E | - | 603 | 596 | 509 | 550 | 547 | 478 | 395 | 503 | 522 | 578 | 631 | 663 | |
| NAKHON PHANOM | 17 30'N | 104 40'E | 142 | 656 | 511 | 503 | 507 | 518 | 381 | 373 | 469 | 391 | 592 | 622 | 641 | |
| SONGKHLA | 7 11'N | 100 37'E | 15 | 658 | 676 | 583 | 568 | 550 | 572 | 528 | 529 | 506 | 460 | 521 | 564 | |
| **TRINIDAD** | | | | | | | | | | | | | | | | |
| PORT-OF-SPAIN | 10 38'N | 61 24'W | - | 587 | 647 | 674 | 562 | 518 | 503 | 507 | 587 | 613 | 570 | 555 | 587 | |
| **TUNISIA** | | | | | | | | | | | | | | | | |
| TUNIS-EL AOUINA | 36 50'N | 10 14'E | 3 | 606 | 589 | 562 | 628 | 679 | 653 | 704 | 696 | - | 542 | 559 | 543 | |
| **UGANDA** | | | | | | | | | | | | | | | | |
| MOROTO | 2 31'N | 34 40'E | 1372 | 716 | 672 | 660 | 642 | 674 | 676 | 559 | 644 | 664 | 793 | 687 | 691 | |
| **UNION OF SOUTH AFRICA** | | | | | | | | | | | | | | | | |
| ALEXANDER BAY | 28 34'S | 16 32'E | 21 | 727 | 712 | 693 | 707 | 687 | 684 | 662 | 697 | 712 | 713 | 715 | 706 | |
| BLOEMFONTEIN | 29 07'S | 26 13'E | 1422 | 635 | 617 | 609 | 663 | 658 | 695 | 710 | 734 | 716 | 670 | 685 | 645 | |
| CAPETOWN | 33 54'S | 18 27'E | 19 | 712 | 681 | 675 | 607 | 527 | 594 | 586 | 589 | 640 | 646 | 687 | 696 | |
| CAPETOWN (WINGFIELD) | 33 54'S | 18 32'E | 17 | 715 | 682 | 682 | 610 | 632 | 602 | 567 | 580 | 633 | 652 | 660 | 684 | |
| DURBAN | 29 50'S | 31 02'E | 5 | 475 | 507 | 544 | 557 | 574 | 624 | 595 | 575 | 532 | 474 | 470 | 486 | |
| KEETMANSHOOP | 26 34'S | 18 07'E | 1066 | 723 | 707 | 675 | 724 | 737 | 753 | 769 | 762 | 759 | 741 | 746 | 727 | |
| KIMBERLY | 28 48'S | 24 46'E | 1197 | 592 | 608 | 595 | 645 | 640 | 671 | 676 | 724 | 711 | 693 | 684 | 659 | |
| MARION ISLAND | 46 51'S | 37 45'E | 23 | 477 | 505 | 492 | 453 | 460 | 453 | 499 | 541 | 535 | 551 | 530 | 497 | |
| MAUN | 19 59'S | 23 25'E | 945 | 536 | 524 | 575 | 589 | 645 | 660 | 692 | 708 | 682 | 613 | 588 | 547 | |
| PIETERSBURG | 23 52'S | 29 27'E | 1230 | 613 | 594 | 620 | 648 | 703 | 717 | 658 | 678 | 625 | 632 | 635 | 581 | |
| PORT ELIZABETH | 33 59'S | 25 36'E | 61 | 594 | 630 | 592 | 563 | 583 | 632 | 622 | 619 | 603 | 587 | 630 | 589 | |
| PRETORIA | 25 45'S | 28 14'E | 1369 | 575 | 557 | 588 | 607 | 644 | 690 | 686 | 711 | 650 | 605 | 587 | 552 | |
| ROODEPLAAT | 26 35'S | 28 21'E | 1189 | 514 | 606 | 606 | 641 | 676 | 696 | 663 | 705 | 634 | 615 | 613 | 558 | |
| SWAKOPMUND | 22 41'S | 14 31'E | - | 603 | 585 | 619 | 609 | 601 | 643 | 552 | 631 | 607 | 641 | 656 | 620 | |
| UPINGTON | 28 26'S | 21 16'E | 814 | 648 | 631 | 621 | 641 | 672 | 731 | 701 | 705 | 678 | 652 | 649 | 637 | |
| WINDHOEK | 22 34'S | 17 06'E | 1217 | 638 | 609 | 615 | 680 | 744 | 758 | 787 | 778 | 740 | 698 | 683 | 669 | |
| **U. S. S. R.** | | | | | | | | | | | | | | | | |
| ARALSKOYE MORE | 46 41'N | 61 40'E | 62 | 609 | 625 | 606 | 589 | 696 | 693 | 614 | 634 | 660 | 551 | 447 | 451 | |
| ARARAT PLAIN | 40 11'N | 44 24'E | - | 534 | 485 | 481 | 560 | 654 | 693 | 704 | 706 | 677 | 694 | 512 | 434 | |
| ARKHANGLSK | 64 30'N | 40 42'E | 4 | 347 | 350 | 512 | 574 | 414 | 473 | 500 | 462 | 311 | 272 | 216 | 422 | |
| CAPE CHELYUSKIN | 77 43'N | 104 17'E | 12 | * | * | 595 | 672 | * | * | * | * | 356 | 462 | * | * | |
| CHETYRCHSTOLBOVOY I | 70 37'N | 162 24'E | 30 | * | 612 | 668 | 702 | 630 | * | * | 397 | 377 | 326 | 833 | * | |
| CHITA (TCHITA) | 52 03'N | 113 29'E | 671 | 547 | 629 | 631 | 600 | 559 | 519 | 461 | 464 | 498 | 521 | 510 | 457 | |
| DIXON ISLAND | 73 30'N | 80 24'E | 17 | * | 756 | 594 | 726 | * | * | * | 416 | 347 | 440 | * | * | |
| HAYES ISLAND | 80 37'N | 58 03'E | 20 | * | * | 565 | 509 | * | * | * | * | 276 | 879 | * | * | |
| JAKUTSK | 62 01'N | 129 43'E | 98 | 532 | 589 | 694 | 705 | 575 | 571 | 476 | 531 | 492 | 482 | 483 | 484 | |
| KAUNAS | 54 56'N | 23 59'E | 71 | 322 | 350 | 515 | 471 | 501 | 503 | 496 | 463 | 433 | 352 | 205 | 261 | |
| KHARBOROVSK | 48 31'N | 135 07'E | 86 | 605 | 651 | 590 | 482 | 497 | 479 | 458 | 468 | 509 | 478 | 535 | 569 | |
| KIEV | 50 24'N | 30 32'E | 167 | 340 | 392 | 420 | 380 | 528 | 490 | 515 | 509 | 457 | 438 | 251 | 273 | |
| KICHINEV | 49 00'N | 28 51'E | 90 | 425 | 455 | 471 | 468 | 555 | 542 | 611 | 570 | 540 | 528 | 298 | 384 | |
| KOTELNYI ISLAND | 76 00'N | 137 54'E | 10 | * | * | 585 | 690 | * | * | * | * | 327 | 360 | * | * | |
| KUIBYCHEV | 53 14'N | 50 10'E | 137 | 385 | 478 | 520 | 573 | 535 | 516 | 536 | 516 | 417 | 330 | 359 | 292 | |
| LENINGRAD | 59 57'N | 30 42'E | 71 | 293 | 271 | 529 | 467 | 472 | 510 | 527 | 464 | 392 | 265 | 213 | 257 | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | U.S.S.R. (CON'T) | | | | | | | | |
| NOVOSIBIRSK | 54 54'N | 82 57'E | 130 | 516 | 554 | 594 | 503 | 513 | 505 | 493 | 495 | 494 | 332 | 324 | 390 | |
| ODESSA | 46 26'N | 30 46'E | 43 | 350 | 399 | 460 | 462 | 577 | 537 | 598 | 579 | 535 | 517 | 288 | 328 | |
| OIMYAKON | 63 16'N | 143 09'E | 740 | 634 | 686 | 752 | 740 | 608 | 510 | 496 | 567 | 496 | 515 | 603 | 647 | |
| OKHOTSK | 59 22'N | 143 12'E | 6 | 584 | 696 | 741 | 610 | 520 | 449 | 358 | 480 | 452 | 522 | 516 | 591 | |
| OLENEK | 68 30'N | 112 26'E | 127 | * | 587 | 664 | 697 | 578 | * | * | 419 | 364 | 428 | 578 | * | |
| OMSK | 55 01'N | 73 23'E | 120 | 508 | 524 | 581 | 564 | 521 | 548 | 485 | 506 | 486 | 334 | 369 | 439 | |
| PREOBRAZHENIA ISLAND | 74 40'N | 112 50'E | 24 | * | 919 | 586 | 617 | * | * | * | 373 | 308 | 302 | * | * | |
| SEMIPALATINSK | 50 25'N | 80 18'E | 190 | 651 | 674 | 696 | 507 | 578 | 579 | 574 | 567 | 636 | 486 | 408 | 524 | |
| SVERDLOVSK | 56 44'N | 61 04'E | 290 | 445 | 471 | 615 | 570 | 501 | 491 | 496 | 483 | 415 | 301 | 338 | 369 | |
| TASHKENT | 41 20'N | 69 18'E | 478 | 394 | 422 | 435 | 485 | 566 | 618 | 653 | 649 | 638 | 528 | 467 | 402 | |
| TBILISI | 41 43'N | 44 48'E | 403 | 389 | 456 | 406 | 499 | 514 | 522 | 584 | 580 | 518 | 488 | 355 | 390 | |
| TIKHAYA BAY | 80 20'N | 52 48'E | 16 | * | * | - | - | * | * | * | * | 373 | - | * | * | |
| TURUKHANSK | 65 47'N | 87 57'E | 38 | 575 | 561 | 593 | 685 | 569 | 497 | 510 | 479 | 293 | 378 | 399 | * | |
| UEDINENIA ISLAND | 77 30'N | 82 14'E | 17 | * | * | 581 | 676 | * | * | * | * | 280 | 277 | * | * | |
| VERKHOYANSK | 67 33'N | 133 23'E | 137 | * | 596 | 653 | 706 | 578 | * | 460 | 501 | 428 | 504 | 476 | * | |
| VLADIVOSTOK | 43 16'N | 132 03'E | 80 | 605 | 641 | 584 | 495 | 518 | 413 | 434 | 388 | 551 | 540 | 587 | 555 | |
| WELLEN | 66 10'N | 169 53'E | 6 | 488 | 477 | 600 | 649 | 601 | 529 | 442 | 354 | 262 | 353 | 239 | 973 | |
| WRANGEL ISLAND | 70 58'N | 178 32'E | 3 | * | 581 | 658 | 692 | 561 | * | * | 359 | 311 | 388 | * | * | |
| YUZNO-SAKHALINSK | 46 57'N | 142 43'E | 22 | 556 | 641 | 595 | 534 | 498 | 422 | 402 | 414 | 463 | 475 | 525 | 642 | |
| | | | | | | | | UNITED ARAB REPUBLIC | | | | | | | | |
| GIZA | 30 02'N | 31 13'E | 21 | 580 | 623 | 672 | 670 | 656 | 671 | 667 | 664 | 659 | 626 | 570 | 565 | |
| | | | | | | | | UNITED KINGDOM | | | | | | | | |
| ABERPORTH | 52 08'N | 4 34'W | 115 | 353 | 363 | 423 | 457 | 521 | 589 | 431 | 454 | 471 | 360 | 300 | 309 | |
| CAMBRIDGE | 52 13'N | 0 06'E | 23 | 333 | 331 | 376 | 394 | 443 | 434 | 434 | 396 | 407 | 384 | 292 | 278 | |
| ESKDALEMUIR | 55 19'N | 3 12'W | 246 | 406 | 297 | 355 | 410 | 433 | 371 | 379 | 368 | 385 | 352 | 275 | 264 | |
| GARSTON; WATFORD | 51 42'N | 0 23'W | 85 | 235 | 279 | 322 | 372 | 394 | 388 | 375 | 367 | 367 | 300 | 228 | 215 | |
| KEW OBSER. | 51 28'N | 0 19'W | 5 | 251 | 282 | 330 | 394 | 413 | 416 | 395 | 390 | 382 | 322 | 263 | 236 | |
| LERWICK OBSERV. | 60 08'N | 1 11'W | 82 | 354 | 383 | 382 | 404 | 415 | 432 | 345 | 328 | 382 | 318 | 301 | 286 | |
| ROTHANSTED | 51 48'N | 0 21'W | 128 | 312 | 344 | 374 | 408 | 429 | 425 | 386 | 379 | 376 | 324 | 272 | 243 | |
| | | | | | | | | UNITED STATES | | | | | | | | |
| AK ADAK | 51 53'N | 176 38'W | 5 | 339 | 375 | 381 | 386 | 355 | 325 | 319 | 317 | 339 | 360 | 357 | 326 | |
| ANNETTE | 55 02'N | 131 34'W | 34 | 341 | 380 | 415 | 448 | 451 | 405 | 414 | 400 | 385 | 324 | 312 | 291 | |
| BARROW | 71 18'N | 156 47'W | 4 | * | 446 | 565 | 545 | 374 | * | * | 348 | 310 | 285 | 356 | * | |
| BETHEL | 60 47'N | 161 48'W | 46 | 380 | 466 | 514 | 511 | 459 | 422 | 376 | 335 | 378 | 370 | 330 | 286 | |
| BETTLES | 66 55'N | 151 31'W | 205 | 306 | 472 | 555 | 583 | 553 | * | 459 | 418 | 432 | 376 | 286 | * | |
| BIG DELTA | 64 00'N | 145 44'W | 388 | 363 | 484 | 562 | 559 | 536 | 495 | 474 | 463 | 451 | 394 | 353 | 156 | |
| FAIRBANKS | 64 49'N | 147 52'W | 138 | 315 | 471 | 552 | 544 | 517 | 486 | 454 | 425 | 427 | 373 | 328 | 056 | |
| GULKANA | 62 09'N | 145 27'W | 481 | 368 | 472 | 555 | 568 | 514 | 489 | 472 | 462 | 445 | 421 | 336 | 239 | |
| HOMER | 59 38'N | 151 30'W | 22 | 399 | 451 | 508 | 521 | 496 | 486 | 465 | 427 | 415 | 412 | 376 | 299 | |
| JUNEAU | 58 22'N | 134 35'W | 7 | 321 | 350 | 391 | 426 | 402 | 392 | 371 | 349 | 325 | 284 | 280 | 228 | |
| KING SALMON | 58 71'N | 156 39'W | 15 | 451 | 494 | 527 | 500 | 464 | 428 | 402 | 374 | 404 | 437 | 416 | 392 | |
| KODIAK | 57 45'N | 152 20'W | 34 | 382 | 423 | 491 | 490 | 427 | 424 | 408 | 411 | 399 | 421 | 368 | 330 | |
| KOTZEBUE | 66 52'N | 162 38'W | 5 | 236 | 447 | 535 | 560 | 535 | * | 449 | 406 | 416 | 385 | 225 | 000 | |
| MC GRATH | 62 58'N | 155 37'W | 103 | 350 | 457 | 524 | 524 | 476 | 441 | 405 | 379 | 398 | 359 | 325 | 212 | |
| NOME | 64 30'N | 165 26'W | 7 | 273 | 459 | 509 | 538 | 507 | 487 | 416 | 376 | 402 | 381 | 268 | 046 | |
| SUMMIT | 63 20'N | 149 08'W | 733 | 370 | 459 | 537 | 551 | 523 | 454 | 414 | 290 | 406 | 399 | 365 | 206 | |
| YAKUTAT | 59 31'N | 139 40'W | 9 | 324 | 356 | 415 | 438 | 397 | 373 | 351 | 338 | 332 | 323 | 287 | 233 | |
| AL BIRMINGHAM | 33 34'N | 86 45'W | 192 | 425 | 464 | 490 | 531 | 532 | 529 | 508 | 521 | 507 | 520 | 470 | 427 | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UNITED STATES (CON'T) | | | | | | | | | | | | | | | | |
| MOBILE | 30 41'N | 88 15'W | 67 | 457 | 495 | 513 | 538 | 536 | 519 | 483 | 493 | 492 | 531 | 485 | 446 | |
| MONTGOMERY | 32 18'N | 86 24'W | 62 | 435 | 472 | 499 | 545 | 544 | 545 | 517 | 526 | 505 | 530 | 485 | 445 | |
| AR FORT SMITH | 35 20'N | 94 22'W | 141 | 474 | 499 | 508 | 518 | 549 | 574 | 579 | 571 | 532 | 533 | 491 | 469 | |
| LITTLE ROCK | 34 44'N | 92 14'W | 81 | 457 | 494 | 504 | 515 | 553 | 580 | 570 | 565 | 535 | 539 | 480 | 453 | |
| AZ PHOENIX | 33 26'N | 112 01'W | 339 | 613 | 657 | 685 | 747 | 767 | 756 | 698 | 693 | 701 | 676 | 628 | 600 | |
| TUCSON | 32 07'N | 110 56'W | 779 | 633 | 665 | 692 | 744 | 765 | 755 | 658 | 657 | 680 | 671 | 637 | 612 | |
| WINSLOW | 35 01'N | 110 44'W | 1488 | 622 | 658 | 687 | 731 | 744 | 746 | 657 | 650 | 681 | 668 | 639 | 608 | |
| YUMA | 32 40'N | 114 36'W | 63 | 642 | 678 | 718 | 762 | 782 | 777 | 689 | 703 | 709 | 687 | 650 | 627 | |
| CA ARCATA | 40 59'N | 124 06'W | 69 | 418 | 460 | 479 | 531 | 534 | 536 | 506 | 492 | 507 | 468 | 411 | 409 | |
| BAKERSFIELD | 35 25'N | 119 03'W | 150 | 490 | 551 | 619 | 673 | 720 | 756 | 752 | 736 | 706 | 649 | 545 | 468 | |
| CHINA LAKE | 35 41'N | 117 41'W | 681 | 587 | 619 | 675 | 718 | 732 | 755 | 732 | 796 | 704 | 658 | 602 | 586 | |
| DAGGETT | 34 52'N | 116 47'W | 588 | 602 | 632 | 682 | 728 | 744 | 761 | 730 | 723 | 708 | 667 | 617 | 593 | |
| EL TORO | 33 40'N | 117 44'W | 116 | 572 | 594 | 610 | 613 | 594 | 605 | 663 | 652 | 606 | 584 | 564 | 564 | |
| FRESNO | 36 46'N | 119 43'W | 100 | 440 | 524 | 619 | 678 | 714 | 750 | 752 | 741 | 714 | 653 | 535 | 417 | |
| LONG BEACH | 33 49'N | 118 09'W | 17 | 563 | 586 | 611 | 616 | 592 | 590 | 645 | 635 | 594 | 573 | 554 | 552 | |
| LOS ANGELES | 33 56'N | 118 24'W | 32 | 564 | 587 | 615 | 621 | 590 | 584 | 647 | 630 | 588 | 570 | 556 | 555 | |
| MOUNT SHASTA | 41 19'N | 122 19'W | 1093 | 450 | 502 | 532 | 589 | 634 | 666 | 722 | 691 | 665 | 582 | 463 | 446 | |
| NEEDLES | 3 46'N | 114 37'W | 270 | 322 | 423 | 554 | 711 | 848 | 922 | 833 | 719 | 619 | 476 | 362 | 304 | |
| OAKLAND | 37 44'N | 122 12'W | 2 | 492 | 540 | 585 | 627 | 637 | 644 | 650 | 630 | 619 | 565 | 510 | 489 | |
| POINT MUGU | 34 07'N | 119 07'W | 4 | 568 | 592 | 623 | 622 | 579 | 566 | 504 | 586 | 563 | 563 | 560 | 564 | |
| RED BLUFF | 40 09'N | 122 15'W | 108 | 436 | 506 | 565 | 635 | 687 | 711 | 748 | 717 | 690 | 602 | 476 | 428 | |
| SACRAMENTO | 38 31'N | 121 30'W | 8 | 427 | 509 | 593 | 657 | 702 | 735 | 753 | 729 | 699 | 622 | 498 | 420 | |
| SAN DIEGO | 32 44'N | 117 10'W | 9 | 572 | 596 | 610 | 613 | 574 | 570 | 614 | 621 | 594 | 582 | 569 | 567 | |
| SAN FRANCISCO | 37 37'N | 122 23'W | 5 | 490 | 534 | 583 | 626 | 641 | 651 | 669 | 649 | 633 | 570 | 508 | 483 | |
| SANTA MARIA | 34 54'N | 120 27'W | 72 | 537 | 564 | 609 | 615 | 614 | 646 | 656 | 639 | 611 | 596 | 554 | 544 | |
| SUNNYVALE | 37 25'N | 122 04'W | 12 | 507 | 546 | 593 | 632 | 655 | 672 | 683 | 664 | 637 | 578 | 518 | 493 | |
| CO COLORADO SPRINGS | 38 49'N | 104 43'W | 1881 | 645 | 643 | 633 | 635 | 614 | 649 | 619 | 624 | 647 | 647 | 607 | 618 | |
| DENVER | 39 45'N | 104 52'W | 1625 | 632 | 632 | 634 | 622 | 617 | 643 | 636 | 633 | 642 | 632 | 587 | 602 | |
| EAGLE | 39 39'N | 106 55'W | 1985 | 565 | 602 | 621 | 639 | 652 | 686 | 668 | 645 | 656 | 634 | 575 | 566 | |
| GRAND JUNCTION | 39 07'N | 108 32'W | 1475 | 580 | 616 | 637 | 655 | 687 | 711 | 690 | 674 | 677 | 645 | 597 | 586 | |
| PUEBLO | 38 17'N | 104 31'W | 1439 | 635 | 630 | 633 | 641 | 623 | 667 | 647 | 647 | 651 | 641 | 603 | 605 | |
| CT HARTFORD | 41 56'N | 72 41'W | 55 | 394 | 426 | 421 | 443 | 455 | 461 | 462 | 445 | 441 | 436 | 357 | 351 | |
| CU GUANTANAMO BAY | 19 54'N | 75 09'W | 16 | 597 | 617 | 633 | 641 | 594 | 568 | 606 | 597 | 579 | 560 | 579 | 582 | |
| DC WASHINGTON | 38 57'N | 77 27'W | 88 | 417 | 447 | 460 | 480 | 496 | 520 | 509 | 499 | 494 | 479 | 420 | 383 | |
| DE WILMINGTON | 39 40'N | 75 36'W | 24 | 428 | 462 | 476 | 490 | 494 | 515 | 510 | 500 | 490 | 477 | 427 | 401 | |
| FL APALACHICOLA | 29 44'N | 85 02 W | 6 | 458 | 497 | 532 | 585 | 599 | 556 | 512 | 506 | 518 | 553 | 516 | 466 | |
| DAYTONA BEACH | 29 11'N | 81 03'W | 12 | 507 | 530 | 555 | 585 | 564 | 509 | 504 | 503 | 496 | 500 | 507 | 489 | |
| JACKSONVILLE | 30 30'N | 81 42'W | 9 | 494 | 523 | 554 | 580 | 561 | 524 | 508 | 508 | 489 | 499 | 504 | 477 | |
| MIAMI | 25 48'N | 80 16'W | 2 | 513 | 540 | 555 | 570 | 530 | 481 | 502 | 486 | 477 | 496 | 508 | 521 | |
| ORLANDO | 28 33'N | 81 20'W | 36 | 520 | 537 | 563 | 588 | 571 | 511 | 510 | 500 | 500 | 516 | 529 | 510 | |
| TALAHASSEE | 30 23'N | 84 22'W | 21 | 480 | 509 | 538 | 569 | 555 | 523 | 493 | 503 | 506 | 537 | 509 | 473 | |



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VALUES OF MONTHLY AVG. KH * 1000 [1]

UNITED STATES (CON'T)

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| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TALLAHASSEE | 30 23'N | 84 22'W | 21 | 480 | 509 | 538 | 569 | 555 | 523 | 493 | 503 | 506 | 537 | 509 | 473 | |
| TAMPA | 27 58'N | 82 32'W | 3 | 518 | 538 | 564 | 590 | 573 | 517 | 496 | 494 | 496 | 528 | 527 | 507 | |
| WEST PALM BEACH | 26 41'N | 80 06'W | 6 | 495 | 514 | 543 | 558 | 530 | 479 | 505 | 496 | 467 | 471 | 491 | 501 | |
| GA ATLANTA | 33 39'N | 84 26'W | 315 | 433 | 465 | 494 | 536 | 531 | 528 | 508 | 517 | 496 | 516 | 485 | 437 | |
| AUGUSTA | 33 22'N | 81 58'W | 45 | 450 | 484 | 505 | 548 | 535 | 525 | 506 | 504 | 490 | 522 | 500 | 462 | |
| MACON | 32 42'N | 83 39'W | 110 | 450 | 479 | 510 | 549 | 540 | 530 | 501 | 518 | 497 | 528 | 503 | 457 | |
| SAVANNAH | 32 08'N | 81 12'W | 16 | 458 | 484 | 519 | 555 | 531 | 510 | 501 | 488 | 469 | 510 | 496 | 464 | |
| HI BARBERS POINT | 21 19'N | 158 04'W | 10 | 529 | 550 | 547 | 555 | 573 | 582 | 584 | 587 | 579 | 559 | 540 | 533 | |
| HILO | 19 43'N | 155 04'W | 11 | 475 | 465 | 442 | 433 | 453 | 481 | 473 | 475 | 490 | 484 | 446 | 450 | |
| HONOLULU | 21 20'N | 157 55'W | 5 | 517 | 533 | 539 | 544 | 566 | 576 | 580 | 586 | 578 | 554 | 526 | 518 | |
| LIHUE | 21 59'N | 159 21'W | 45 | 490 | 501 | 493 | 498 | 529 | 535 | 538 | 542 | 558 | 525 | 485 | 489 | |
| IA BURLINGTON | 40 47'N | 91 07'W | 214 | 455 | 495 | 492 | 513 | 543 | 580 | 584 | 569 | 534 | 528 | 457 | 415 | |
| DES MOINES | 41 32'N | 93 39'W | 294 | 470 | 508 | 504 | 523 | 542 | 581 | 588 | 571 | 545 | 541 | 466 | 435 | |
| MASON CITY | 43 09'N | 93 20'W | 373 | 482 | 519 | 514 | 517 | 552 | 578 | 585 | 577 | 546 | 532 | 452 | 430 | |
| SIOUX CITY | 42 24'N | 96 23'W | 336 | 479 | 510 | 508 | 534 | 553 | 581 | 595 | 579 | 547 | 537 | 470 | 438 | |
| ID BOISE | 43 34'N | 116 13'W | 874 | 432 | 528 | 578 | 625 | 664 | 674 | 734 | 694 | 679 | 605 | 482 | 434 | |
| LEWISTON | 46 23'N | 117 01'W | 438 | 349 | 422 | 478 | 505 | 542 | 551 | 658 | 621 | 584 | 493 | 357 | 334 | |
| POCATELLO | 42 55'N | 11 23'W | 1365 | 465 | [illegible] | 601 | 619 | 664 | 678 | 729 | 705 | 685 | 630 | 514 | 457 | |
| IL CHICAGO | 41 47'N | 87 45'W | 190 | 416 | 451 | 475 | 491 | 519 | 549 | 545 | 538 | 516 | 493 | 404 | 363 | |
| MOLINE | 41 27'N | 90 31'W | 181 | 432 | 478 | 477 | 490 | 509 | 539 | 543 | 535 | 516 | 503 | 420 | 385 | |
| SPRINGFIELD | 39 50'N | 89 40'W | 187 | 441 | 483 | 475 | 502 | 539 | 574 | 576 | 559 | 541 | 520 | 450 | 405 | |
| IN EVANSVILLE | 38 03'N | 87 32'W | 118 | 404 | 440 | 464 | 490 | 513 | 543 | 538 | 533 | 512 | 510 | 428 | 381 | |
| FORT WAYNE | 41 00'N | 85 12'W | 252 | 361 | 405 | 416 | 455 | 484 | 504 | 501 | 497 | 481 | 462 | 358 | 322 | |
| INDIANAPOLIS | 39 44'N | 86 17'W | 246 | 372 | 418 | 430 | 463 | 488 | 511 | 506 | 509 | 493 | 475 | 384 | 343 | |
| SOUTH BEND | 41 42'N | 86 19'W | 236 | 339 | 391 | 425 | 467 | 500 | 525 | 519 | 521 | 492 | 462 | 354 | 307 | |
| KS DODGE CITY | 37 46'N | 99 58'W | 787 | 575 | 596 | 593 | 615 | 602 | 646 | 643 | 631 | 613 | 606 | 555 | 553 | |
| GOODLAND | 39 22'N | 101 42'W | 1124 | 584 | 585 | 586 | 604 | 595 | 645 | 649 | 632 | 608 | 612 | 561 | 562 | |
| TOPEKA | 39 04'N | 95 38'W | 270 | 498 | 517 | 515 | 541 | 553 | 582 | 596 | 590 | 560 | 549 | 500 | 466 | |
| WITCHITA | 37 39'N | 97 25'W | 408 | 543 | 560 | 563 | 581 | 586 | 621 | 627 | 623 | 587 | 581 | 539 | 519 | |
| KY LEXINGTON | 38 02'N | 84 36'W | 301 | 383 | 417 | 443 | 484 | 503 | 520 | 518 | 518 | 497 | 489 | 412 | 371 | |
| LOUISVILLE | 38 11'N | 85 44'W | 149 | 386 | 424 | 446 | 480 | 495 | 521 | 514 | 517 | 497 | 490 | 411 | 375 | |
| LA BATON ROUGE | 30 32'N | 91 09'W | 23 | 432 | 473 | 502 | 525 | 536 | 535 | 492 | 503 | 497 | 531 | 466 | 431 | |
| LAKE CHARLES | 30 07'N | 93 13'W | 3 | 396 | 449 | 476 | 490 | 530 | 548 | 504 | 497 | 502 | 560 | 459 | 407 | |
| NEW ORLEANS | 29 59'N | 90 15'W | 3 | 451 | 494 | 512 | 555 | 564 | 557 | 511 | 515 | 511 | 540 | 486 | 448 | |
| SHREVEPORT | 32 28'N | 93 49'W | 79 | 444 | 486 | 500 | 509 | 540 | 571 | 566 | 566 | 536 | 550 | 494 | 454 | |
| MA BOSTON | 42 22'N | 71 02'W | 5 | 400 | 429 | 441 | 448 | 471 | 497 | 491 | 466 | 484 | 459 | 367 | 376 | |
| MD BALTIMORE | 39 11'N | 76 40'W | 47 | 431 | 463 | 477 | 490 | 495 | 514 | 510 | 494 | 492 | 479 | 430 | 401 | |
| PATUXENT RIVER | 38 17'N | 76 25'W | 14 | 432 | 464 | 478 | 504 | 508 | 519 | 508 | 501 | 496 | 481 | 446 | 415 | |
| ME BANGOR | 44 48'N | 68 49'W | 62 | 429 | 475 | 496 | 498 | 506 | 508 | 523 | 513 | 499 | 461 | 380 | 401 | |
| CARIBOU | 46 52'N | 68 01'W | 190 | 443 | 510 | 537 | 500 | 465 | 481 | 497 | 484 | 452 | 400 | 324 | 373 | |
| PORTLAND | 43 39'N | 70 19'W | 19 | 402 | 429 | 430 | 446 | 457 | 468 | 466 | 461 | 453 | 439 | 353 | 361 | |
| MI ALPENA | 45 04'N | 83 34'W | 219 | 347 | 407 | 469 | 488 | 504 | 514 | 530 | 505 | 461 | 411 | 312 | 291 | |
| DETROIT | 42 25'N | 83 01'W | 191 | 352 | 412 | 434 | 474 | 499 | 510 | 515 | 494 | 482 | 453 | 349 | 321 | |
| FLINT | 42 58'N | 83 44'W | 233 | 331 | 392 | 419 | 456 | 483 | 496 | 504 | 489 | 463 | 434 | 321 | 296 | |
| GRAND RAPIDS | 42 53'N | 85 31'W | 245 | 318 | 399 | 444 | 480 | 511 | 535 | 537 | 527 | 489 | 449 | 332 | 297 | |
| HOUGHTON | 47 10'N | 88 30'W | 329 | 262 | 345 | 445 | 484 | 490 | 503 | 519 | 492 | 416 | 393 | 262 | 234 | |
| SAULT STE. MARIE | 46 28'N | 84 22'W | 221 | 335 | 419 | 483 | 487 | 497 | 495 | 517 | 490 | 427 | 387 | 288 | 295 | |
| TRAVERSE CITY | 44 44'N | 85 35'W | 192 | 292 | 371 | 454 | 486 | 506 | 523 | 537 | 512 | 463 | 413 | 303 | 271 | |
| MN DULUTH | 46 50'N | 92 11'W | 432 | 409 | 473 | 489 | 485 | 484 | 484 | 523 | 498 | 449 | 421 | 336 | 349 | |
| INTERNATIONAL FAL | 48 34'N | 93 23'W | 361 | [illegible] | 498 | 514 | 519 | 510 | 508 | 544 | 528 | 472 | 430 | 332 | 365 | |
| MINNEAPOLIS-ST P | 44 53'N | 93 13'W | 255 | 441 | 501 | 502 | 499 | 509 | 527 | 554 | 537 | 499 | 473 | 389 | 377 | |
| ROCHESTER | 43 55'N | 92 30'W | 402 | 432 | 478 | 483 | 484 | 495 | 520 | 536 | 526 | 491 | 467 | 384 | 374 | |
| MO COLUMBIA | 38 49'N | 92 13'W | 270 | 443 | 477 | 481 | 501 | 542 | 572 | 592 | 579 | 534 | 524 | 452 | 413 | |
| KANSAS CITY | 39 18'N | 94 43'W | 315 | 478 | 495 | 495 | 520 | 541 | 569 | 589 | 575 | 537 | 526 | 482 | 453 | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

UNITED STATES (CON'T) (CON'T)

| | STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SPRINGFIELD | 37 14'N | 93 23'W | 387 | 466 | 484 | 492 | 521 | 541 | 569 | 578 | 574 | 535 | 527 | 474 | 446 | |
| | ST. LOUIS | 38 45'N | 90 23'W | 172 | 453 | 482 | 491 | 514 | 540 | 573 | 574 | 560 | 537 | 523 | 461 | 418 | |
| MS | JACKSON | 32 19'N | 90 05'W | 101 | 436 | 478 | 510 | 539 | 556 | 560 | 536 | 537 | 520 | 535 | 478 | 439 | |
| | MERIDIAN | 32 20'N | 88 45'W | 94 | 431 | 472 | 494 | 524 | 533 | 543 | 512 | 524 | 501 | 529 | 475 | 433 | |
| MT | BILLINGS | 45 48'N | 108 32'W | 1088 | 484 | 517 | 551 | 533 | 562 | 595 | 671 | 648 | 593 | 557 | 473 | 474 | |
| | CUT BANK | 48 36'N | 112 22'W | 1170 | 471 | 518 | 555 | 534 | 559 | 561 | 647 | 619 | 569 | 534 | 463 | 451 | |
| | DILLON | 45 5'N | 112 33'W | 1588 | 505 | 560 | 584 | 569 | 583 | 586 | 673 | 645 | 607 | 567 | 492 | 486 | |
| | GLASGOW | 48 13'N | 106 37'W | 700 | 444 | 498 | 538 | 534 | 542 | 561 | 620 | 606 | 561 | 531 | 452 | 439 | |
| | GREAT FALLS | 47 29'N | 111 22'W | 1116 | 460 | 519 | 562 | 529 | 546 | 576 | 658 | 626 | 570 | 547 | 454 | 420 | |
| | HELENA | 46 36'N | 112 00'W | 1188 | 436 | 494 | 539 | 524 | 548 | 558 | 658 | 621 | 577 | 535 | 456 | 430 | |
| | LEWISTOWN | 47 03'N | 109 27'W | 1264 | 448 | 491 | 536 | 511 | 533 | 564 | 646 | 614 | 564 | 529 | 449 | 441 | |
| | MILES CITY | 46 26'N | 105 52'W | 803 | 471 | 517 | 556 | 543 | 558 | 587 | 646 | 636 | 588 | 552 | 478 | 467 | |
| | MISSOULA | 46 55'N | 114 05'W | 972 | 329 | 405 | 465 | 489 | 526 | 529 | 657 | 607 | 557 | 473 | 364 | 322 | |
| NC | ASHEVILLE | 35 26'N | 82 32'W | 661 | 462 | 486 | 507 | 535 | 518 | 510 | 498 | 495 | 483 | 511 | 491 | 454 | |
| | CAPE HATTERAS | 35 16'N | 75 33'W | 2 | 436 | 475 | 513 | 569 | 563 | 560 | 538 | 519 | 521 | 504 | 502 | 452 | |
| | CHARLOTTE | 35 13'N | 80 56'W | 234 | 457 | 484 | 510 | 544 | 532 | 528 | 513 | 515 | 501 | 520 | 497 | 461 | |
| | CHERRY POINT | 34 54'N | 76 53'W | 11 | 476 | 507 | 534 | 574 | 552 | 533 | 513 | 496 | 504 | 515 | 516 | 487 | |
| | GREENSBORO | 36 05'N | 79 57'W | 270 | 468 | 494 | 514 | 543 | 537 | 536 | 522 | 517 | 506 | 514 | 495 | 466 | |
| | RALEIGH | 35 52'N | 78 47'W | 134 | 451 | 477 | 498 | 530 | 519 | 512 | 497 | 491 | 491 | 496 | 476 | 446 | |
| ND | BISMARCK | 46 46'N | 100 45'W | 502 | 490 | 544 | 552 | 515 | 545 | 564 | 616 | 605 | 554 | 526 | 447 | 444 | |
| | FARGO | 46 54'N | 96 48'W | 274 | 438 | 498 | 520 | 521 | 541 | 546 | 598 | 589 | 535 | 509 | 406 | 406 | |
| | MINOT | 48 16'N | 101 17'W | 522 | 439 | 487 | 510 | 524 | 548 | 541 | 593 | 586 | 535 | 515 | 415 | 409 | |
| NE | GRAND ISLAND | 40 58'N | 98 19'W | 566 | 523 | 532 | 535 | 566 | 571 | 613 | 621 | 604 | 570 | 568 | 512 | 496 | |
| | NORTH OMAHA | 41 22'N | 96 01'W | 404 | 510 | 524 | 521 | 523 | 543 | 580 | 590 | 580 | 521 | 529 | 453 | 454 | |
| | NORTH PLATTE | 41 08'N | 100 41'W | 849 | 551 | 559 | 566 | 577 | 576 | 620 | 638 | 620 | 592 | 591 | 530 | 531 | |
| | SCOTTSBLUFF | 41 52'N | 103 36'W | 1206 | 555 | 566 | 562 | 562 | 561 | 611 | 640 | 626 | 611 | 585 | 519 | 523 | |
| NH | CONCORD | 43 12'N | 71 30'W | 105 | 401 | 426 | 429 | 449 | 461 | 466 | 470 | 459 | 443 | 431 | 349 | 352 | |
| NJ | LAKEHURST | 40 02'N | 74 20'W | 37 | 425 | 450 | 462 | 483 | 484 | 485 | 477 | 475 | 471 | 467 | 417 | 396 | |
| | NEWARK | 40 42'N | 74 10'W | 9 | 431 | 457 | 467 | 483 | 489 | 491 | 493 | 487 | 479 | 472 | 410 | 391 | |
| NM | ALBUQUERQUE | 35 03'N | 106 37'W | 1619 | 643 | 666 | 682 | 714 | 728 | 737 | 697 | 696 | 697 | 683 | 648 | 632 | |
| | CLAYTON | 36 27'N | 103 09'W | 1515 | 638 | 637 | 650 | 659 | 638 | 664 | 639 | 640 | 646 | 651 | 613 | 618 | |
| | FARMINGTON | 36 45'N | 108 14'W | 1677 | 633 | 662 | 670 | 691 | 705 | 731 | 694 | 689 | 696 | 675 | 630 | 608 | |
| | ROSWELL | 33 24'N | 104 32'W | 1103 | 627 | 655 | 682 | 703 | 705 | 720 | 685 | 678 | 666 | 655 | 617 | 611 | |
| | TRUTH OR CONSEQUE | 33 14'N | 107 16'W | 1481 | 666 | 690 | 710 | 741 | 733 | 731 | 664 | 669 | 674 | 675 | 661 | 640 | |
| | TUCUMCARI | 35 11'N | 103 36'W | 1231 | 640 | 645 | 662 | 673 | 664 | 683 | 658 | 658 | 647 | 639 | 616 | 623 | |
| | ZUNI | 35 06'N | 108 48'W | 1965 | 625 | 644 | 652 | 695 | 710 | 716 | 634 | 632 | 670 | 662 | 623 | 609 | |
| NV | ELKO | 40 50'N | 115 47'W | 1547 | 541 | 598 | 618 | 634 | 667 | 693 | 735 | 721 | 713 | 659 | 561 | 534 | |
| | ELY | 39 17'N | 114 52'W | 1906 | 605 | 631 | 661 | 663 | 667 | 688 | 685 | 689 | 716 | 677 | 605 | 583 | |
| | LAS VEGAS | 36 05'N | 115 10'W | 664 | 641 | 681 | 714 | 748 | 760 | 763 | 725 | 718 | 728 | 694 | 640 | 623 | |
| | LOVELOCK | 40 04'N | 118 33'W | 1190 | 613 | 659 | 690 | 719 | 739 | 752 | 779 | 770 | 757 | 711 | 624 | 597 | |
| | RENO | 39 30'N | 119 47'W | 1341 | 596 | 639 | 681 | 714 | 729 | 739 | 754 | 744 | 741 | 692 | 601 | 575 | |
| | TONOPAH | 38 04'N | 117 08'W | 1653 | 646 | 682 | 717 | 736 | 742 | 764 | 756 | 749 | 745 | 713 | 647 | 633 | |
| | WINNEMUCCA | 40 54'N | 117 48'W | 1323 | 544 | 595 | 622 | 658 | 684 | 703 | 750 | 731 | 720 | 660 | 560 | 537 | |
| | YUCCA FLATS | 36 57'N | 116 03'W | 1197 | 644 | 662 | 700 | 729 | 741 | 750 | 743 | 729 | 729 | 695 | 631 | 624 | |
| NY | ALBANY | 42 45'N | 73 48'W | 89 | 390 | 421 | 430 | 453 | 457 | 473 | 484 | 471 | 452 | 426 | 339 | 338 | |
| | BINGHAMTON | 42 13'N | 75 59'W | 499 | 322 | 346 | 372 | 420 | 435 | 460 | 465 | 447 | 434 | 401 | 300 | 275 | |
| | BUFFALO | 42 56'N | 78 44'W | 215 | 301 | 336 | 389 | 447 | 465 | 493 | 498 | 476 | 446 | 411 | 301 | 272 | |
| | MASSENA | 44 56'N | 74 52'W | 63 | 372 | 408 | 445 | 465 | 473 | 486 | 492 | 473 | 447 | 406 | 314 | 315 | |
| | NEW YORK (CN. PRK) | 40 47'N | 73 58'W | 57 | 393 | 416 | 438 | 455 | 474 | 468 | 473 | 462 | 457 | 446 | 367 | 349 | |
| | NEW YORK (LGA) | 40 46'N | 73 54'W | 16 | 429 | 458 | 471 | 486 | 490 | 493 | 500 | 493 | 482 | 473 | 408 | 394 | |
| | ROCHESTER | 43 07'N | 77 40'W | 169 | 317 | 346 | 397 | 456 | 468 | 497 | 500 | 479 | 450 | 411 | 303 | 271 | |
| | SYRACUSE | 43 07'N | 76 07'W | 124 | 335 | 354 | 391 | 451 | 460 | 486 | 493 | 474 | 453 | 409 | 300 | 276 | |
| OH | AKRON-CANTON | 40 55'N | 81 26'W | 377 | 338 | 376 | 408 | 454 | 483 | 503 | 500 | 497 | 480 | 453 | 349 | 307 | |
| | CINCINNATI | 39 04'N | 84 40'W | 271 | 366 | 406 | 421 | 461 | 483 | 503 | 496 | 504 | 484 | 474 | 382 | 345 | |

VALUES OF MONTHLY AVG. KH * 1000 [1]

UNITED STATES (CON'T) (CON'T)

| | STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CLEVELAND | 41 24'N | 81 51'W | 245 | 313 | 353 | 393 | 453 | 488 | 504 | 512 | 494 | 471 | 438 | 329 | 282 | |
| | COUMBUS | 40 00'N | 82 53'W | 254 | 349 | 381 | 408 | 449 | 476 | 496 | 491 | 508 | 478 | 462 | 360 | 322 | |
| | DAYTON | 39 54'N | 84 13'W | 306 | 370 | 408 | 426 | 465 | 491 | 513 | 507 | 510 | 491 | 472 | 377 | 338 | |
| | TOLEDO | 41 36'N | 83 48'W | 211 | 353 | 402 | 426 | 465 | 498 | 514 | 518 | 505 | 485 | 462 | 353 | 319 | |
| | YOUNGSTOWN | 41 16'N | 80 40'W | 361 | 309 | 343 | 379 | 429 | 460 | 481 | 486 | 470 | 452 | 428 | 320 | 278 | |
| OK | OKLAHOMA CITY | 35 24'N | 97 36'W | 397 | 512 | 528 | 543 | 554 | 551 | 589 | 596 | 593 | 551 | 548 | 521 | 500 | |
| | TULSA | 36 12'N | 95 54'W | 206 | 481 | 499 | 512 | 517 | 524 | 555 | 569 | 569 | 527 | 525 | 490 | 469 | |
| OR | ASTORIA | 46 09'N | 123 53'W | 7 | 319 | 374 | 404 | 440 | 473 | 445 | 492 | 481 | 480 | 407 | 332 | 299 | |
| | BURNS | 43 35'N | 119 03'W | 1271 | 436 | 498 | 527 | 564 | 599 | 623 | 691 | 658 | 633 | 555 | 455 | 427 | |
| | MEDFORD | 42 22'N | 122 52'W | 396 | 342 | 446 | 491 | 554 | 591 | 623 | 694 | 665 | 611 | 507 | 369 | 313 | |
| | NORTH BEND | 43 25'N | 124 15'W | 5 | 387 | 440 | 467 | 516 | 542 | 545 | 592 | 563 | 537 | 473 | 399 | 374 | |
| | PENDLETON | 45 41'N | 118 51'W | 456 | 345 | 414 | 482 | 524 | 566 | 587 | 674 | 638 | 605 | 511 | 368 | 327 | |
| | PORTLAND | 45 36'N | 122 36'W | 12 | 306 | 373 | 413 | 456 | 488 | 485 | 574 | 535 | 489 | 406 | 324 | 285 | |
| | REDMOND | 44 16'N | 121 09'W | 940 | 452 | 498 | 535 | 579 | 608 | 625 | 687 | 656 | 625 | 542 | 451 | 437 | |
| | SALEM | 44 55'N | 123 01'W | 61 | 316 | 387 | 431 | 475 | 509 | 506 | 603 | 565 | 529 | 424 | 333 | 296 | |
| PA | ALLENTOWN | 40 39'N | 75 26'W | 117 | 411 | 439 | 454 | 470 | 474 | 486 | 494 | 481 | 466 | 460 | 390 | 369 | |
| | ERIE | 42 05'N | 80 11'W | 225 | 287 | 346 | 397 | 459 | 478 | 505 | 514 | 456 | 460 | 425 | 301 | 255 | |
| | HARRISBURG | 40 13'N | 76 51'W | 106 | 410 | 438 | 453 | 469 | 478 | 494 | 494 | 481 | 474 | 459 | 390 | 376 | |
| | PHILADELPHIA | 39 53'N | 75 15'W | 9 | 420 | 447 | 460 | 475 | 480 | 496 | 492 | 488 | 477 | 467 | 413 | 390 | |
| | PITTSBURG | 40 30'N | 80 13'W | 373 | 329 | 358 | 396 | 438 | 463 | 482 | 473 | 469 | 454 | 443 | 344 | 295 | |
| | WILKES-SCRANTON | 41 20'N | 75 44'W | 289 | 366 | 404 | 422 | 449 | 461 | 481 | 489 | 472 | 455 | 452 | 344 | 325 | |
| PN | KORROR ISLAND | 7 20'N | 134 29'E | 33 | 480 | 502 | 500 | 513 | 487 | 463 | 456 | 458 | 469 | 477 | 487 | 471 | |
| | KWAJALEIN ISLAND | 8 44'N | 167 44'E | 8 | 549 | 570 | 553 | 527 | 502 | 507 | 505 | 519 | 496 | 486 | 496 | 518 | |
| | WAKE ISLAND | 19 17'N | 166 39'E | 4 | 567 | 583 | 593 | 590 | 600 | 595 | 562 | 558 | 550 | 552 | 575 | 573 | |
| PR | SAN JUAN | 18 26'N | 66 00'W | 19 | 548 | 563 | 581 | 570 | 531 | 531 | 549 | 549 | 528 | 528 | 540 | 531 | |
| RI | PROVIDENCE | 41 44'N | 71 26'W | 19 | 414 | 438 | 442 | 462 | 481 | 485 | 475 | 469 | 461 | 461 | 383 | 378 | |
| SC | CHARLESTON | 32 54'N | 80 02'W | 12 | 439 | 470 | 502 | 548 | 533 | 509 | 505 | 479 | 483 | 507 | 503 | 455 | |
| | COLUMBIA | 33 57'N | 81 07'W | 69 | 464 | 493 | 515 | 557 | 543 | 536 | 516 | 515 | 503 | 524 | 510 | 473 | |
| | GREENVILLE | 34 54'N | 82 13'W | 296 | 459 | 485 | 512 | 543 | 527 | 528 | 513 | 516 | 496 | 520 | 501 | 454 | |
| SD | HURON | 44 23'N | 98 13'W | 393 | 452 | 481 | 501 | 528 | 547 | 575 | 613 | 601 | 560 | 537 | 458 | 420 | |
| | PIERRE | 44 23'N | 100 17'W | 526 | 491 | 513 | 543 | 556 | 575 | 600 | 640 | 632 | 591 | 571 | 493 | 458 | |
| | RAPID CITY | 44 03'N | 103 04'W | 966 | 494 | 528 | 550 | 546 | 551 | 583 | 625 | 622 | 597 | 573 | 505 | 485 | |
| | SIOUX FALLS | 43 34'N | 96 44'W | 435 | 473 | 504 | 511 | 528 | 552 | 574 | 604 | 583 | 551 | 535 | 465 | 438 | |
| TN | CHATTANOOGA | 35 02'N | 85 12'W | 210 | 398 | 426 | 454 | 496 | 497 | 504 | 486 | 495 | 472 | 489 | 441 | 395 | |
| | KNOXVILLE | 35 49'N | 83 59'W | 299 | 402 | 436 | 464 | 515 | 518 | 522 | 505 | 507 | 493 | 502 | 444 | 399 | |
| | MEMPHIS | 35 03'N | 89 59'W | 87 | 431 | 468 | 493 | 525 | 541 | 562 | 553 | 554 | 520 | 532 | 467 | 428 | |
| | NASHVILLE | 36 07'N | 86 41'W | 180 | 380 | 419 | 443 | 498 | 524 | 539 | 530 | 530 | 499 | 502 | 420 | 369 | |
| TX | ABILENE | 32 26'N | 99 41'W | 534 | 537 | 553 | 588 | 582 | 584 | 610 | 601 | 590 | 551 | 554 | 535 | 537 | |
| | AMARILLO | 35 14'N | 101 42'W | 1098 | 611 | 620 | 631 | 648 | 635 | 658 | 639 | 639 | 623 | 622 | 593 | 598 | |
| | AUSTIN | 30 18'N | 97 42'W | 189 | 472 | 503 | 519 | 501 | 525 | 576 | 593 | 579 | 544 | 542 | 496 | 479 | |
| | BROWNSVILLE | 25 54'N | 97 26'W | 6 | 444 | 467 | 505 | 533 | 554 | 596 | 630 | 604 | 555 | 548 | 480 | 442 | |
| | CORPUS CHRISTI | 27 46'N | 97 30'W | 13 | 458 | 488 | 505 | 507 | 536 | 586 | 620 | 595 | 560 | 554 | 494 | 455 | |
| | DALLAS | 32 51'N | 96 51'W | 149 | 484 | 505 | 533 | 514 | 541 | 589 | 596 | 589 | 549 | 542 | 503 | 492 | |
| | KINGSVILLE | 27 31'N | 97 49'W | 17 | 462 | 492 | 505 | 513 | 535 | 570 | 599 | 574 | 538 | 542 | 487 | 454 | |
| | LAREDO | 27 32'N | 99 28'W | 158 | 485 | 506 | 534 | 533 | 560 | 581 | 604 | 600 | 565 | 549 | 490 | 476 | |
| | LUBBOCK | 33 39'N | 101 49'W | 988 | 622 | 639 | 667 | 689 | 687 | 702 | 676 | 668 | 635 | 632 | 613 | 605 | |
| | LUFKIN | 31 14'N | 94 45'W | 96 | 445 | 487 | 505 | 509 | 535 | 570 | 565 | 560 | 522 | 557 | 496 | 459 | |
| | MIDLAND-ODESSA | 31 56'N | 102 12'W | 871 | 619 | 639 | 681 | 690 | 696 | 709 | 672 | 666 | 633 | 636 | 617 | 611 | |
| | PORT ARTHUR | 29 57'N | 94 01'W | 7 | 432 | 475 | 489 | 502 | 536 | 559 | 521 | 521 | 516 | 534 | 475 | 433 | |
| | SAN ANGELO | 31 22'N | 100 30'W | 582 | 541 | 552 | 591 | 581 | 582 | 606 | 597 | 591 | 549 | 553 | 539 | 537 | |
| | SAN ANTONIO | 29 32'N | 98 28'W | 242 | 478 | 508 | 522 | 502 | 543 | 576 | 599 | 583 | 551 | 543 | 498 | 481 | |
| | SHERMAN | 33 43'N | 96 40'W | 233 | 480 | 499 | 517 | 512 | 531 | 583 | 582 | 584 | 551 | 547 | 506 | 483 | |
| | WACO | 31 37'N | 97 12'W | 155 | 472 | 504 | 527 | 507 | 508 | 585 | 599 | 589 | 548 | 541 | 498 | 486 | |
| | WICHITA FALLS | 33 58'N | 98 29'W | 314 | 526 | 543 | 560 | 561 | 578 | 612 | 608 | 596 | 560 | 559 | 531 | 523 | |

APPENDIX A (CON'T)

VALUES OF MONTHLY AVG. KH * 1000 [1]

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **UNITED STATES (CON'T) (CON'T)** | | | | | | | | | | | | | | | | |
| UT BRYCE CANYON | 37 42'N | 112 09'W | 2313 | 634 | 655 | 676 | 696 | 706 | 728 | 678 | 662 | 698 | 682 | 630 | 618 | |
| CEDAR CITY | 37 42'N | 113 06'W | 1712 | 613 | 625 | 656 | 682 | 710 | 742 | 701 | 688 | 715 | 679 | 615 | 593 | |
| SALT LAKE CITY | 40 46'N | 111 58'W | 1288 | 501 | 570 | 613 | 632 | 684 | 700 | 726 | 701 | 694 | 644 | 542 | 491 | |
| VA NORFOLK | 36 54 N | 76 12'W | 9 | 457 | 483 | 508 | 544 | 543 | 549 | 519 | 514 | 503 | 496 | 491 | 456 | |
| RICHMOND | 47 30'N | 77 20'W | 50 | 691 | 633 | 581 | 557 | 521 | 513 | 501 | 518 | 558 | 612 | 669 | 709 | |
| ROANOKE | 37 19'N | 79 58'W | 358 | 452 | 472 | 493 | 514 | 507 | 516 | 503 | 496 | 492 | 499 | 468 | 439 | |
| VT BURLINGTON | 44 28'N | 73 09 W | 104 | 358 | 393 | 424 | 447 | 461 | 473 | 484 | 468 | 444 | 403 | 298 | 295 | |
| WA OLYMPIA | 46 58'N | 122 54 W | 61 | 285 | 355 | 401 | 444 | 481 | 464 | 540 | 500 | 475 | 371 | 302 | 267 | |
| SEATTLE-TACOMA | 47 27'N | 122 18'W | 122 | 285 | 357 | 407 | 460 | 566 | 493 | 635 | 523 | 475 | 388 | 307 | 263 | |
| SPOKANE | 47 38'N | 117 32'W | 721 | 348 | 439 | 501 | 532 | 567 | 570 | 666 | 630 | 595 | 500 | 365 | 322 | |
| WHIDBEY ISLAND | 48 21 N | 122 40'W | 17 | 325 | 396 | 449 | 483 | 522 | 499 | 561 | 519 | 492 | 398 | 339 | 309 | |
| YAKIMA | 46 34'N | 120 32'W | 325 | 379 | 464 | 528 | 563 | 592 | 594 | 665 | 635 | 605 | 514 | 388 | 347 | |
| WI EAU CLAIRE | 44 52'N | 91 29'W | 273 | 428 | 492 | 496 | 494 | 492 | 512 | 531 | 516 | 476 | 455 | 364 | 362 | |
| GREEN BAY | 44 29'N | 88 08'W | 214 | 420 | 469 | 498 | 496 | 503 | 522 | 531 | 515 | 482 | 447 | 370 | 364 | |
| LA CROSSE | 43 52'N | 91 15'W | 205 | 434 | 485 | 491 | 489 | 500 | 521 | 534 | 527 | 487 | 463 | 383 | 372 | |
| MADISON | 43 08'N | 89 20'W | 262 | 449 | 499 | 500 | 476 | 508 | 532 | 543 | 538 | 505 | 479 | 380 | 376 | |
| MILWAUKEE | 42 57'N | 87 54'W | 211 | 414 | 454 | 477 | 491 | 515 | 541 | 550 | 541 | 508 | 476 | 392 | 363 | |
| WV CHARLESTON | 38 22'N | 81 36'W | 290 | 355 | 381 | 409 | 444 | 472 | 486 | 471 | 466 | 466 | 459 | 389 | 342 | |
| HUNTINGTON | 38 22'N | 82 33'W | 255 | 375 | 408 | 432 | 474 | 493 | 505 | 495 | 486 | 478 | 474 | 404 | 362 | |
| WY CASPER | 42 55'N | 106 28'W | 1612 | 589 | 624 | 631 | 628 | 642 | 684 | 711 | 700 | 678 | 638 | 572 | 570 | |
| CHEYENNE | 41 09'N | 104 49'W | 1872 | 610 | 623 | 608 | 593 | 578 | 618 | 625 | 613 | 631 | 623 | 574 | 590 | |
| ROCK SPRINGS | 41 39'N | 109 04'W | 2056 | 599 | 645 | 655 | 654 | 680 | 704 | 714 | 700 | 698 | 663 | 588 | 585 | |
| SHERIDAN | 44 46'N | 106 58'W | 1209 | 488 | 516 | 546 | 532 | 551 | 590 | 655 | 638 | 597 | 552 | 476 | 467 | |
| **URUGUAY** | | | | | | | | | | | | | | | | |
| MONTEVIDEO | 34 52'S | 56 10'W | 25 | 652 | 558 | 636 | 606 | 582 | 535 | 528 | 548 | 576 | 590 | 632 | 639 | |
| SAN JORGE | 32 05'S | 56 00'W | 122 | 663 | 705 | 619 | 592 | 559 | 486 | 551 | 587 | 555 | 591 | 631 | 623 | |
| **VENEZUELA** | | | | | | | | | | | | | | | | |
| BARCELONA | 10 07'N | 64 41'W | 7 | 596 | 603 | 588 | 546 | 527 | 500 | 544 | 561 | 595 | 567 | 577 | 592 | |
| BARQUISIMETO | 10 04'N | 69 19'W | 591 | 545 | 598 | 540 | 530 | 519 | 559 | 584 | 568 | 588 | 599 | 505 | 587 | |
| CALABOZO | 8 48'N | 67 27'W | 100 | 579 | 613 | 602 | 558 | 512 | 545 | 509 | 522 | 431 | 553 | 566 | 554 | |
| CARACAS | 10 30'N | 66 53'W | 862 | 594 | 647 | 612 | 573 | 479 | 503 | 536 | 561 | 564 | 523 | 529 | 576 | |
| CIUDAD BOLIVAR | 8 09'N | 63 33'W | 50 | 562 | 572 | 554 | 543 | 541 | 485 | 547 | 584 | 607 | 574 | 563 | 588 | |
| CORO | 11 25'N | 69 41'W | 20 | 678 | 690 | 705 | 641 | 602 | 630 | 673 | 663 | 678 | 621 | 639 | 656 | |
| GUIRIA | 10 35'N | 62 18'W | 8 | 494 | 496 | 502 | 516 | 531 | 491 | 521 | 538 | 542 | 481 | 479 | 507 | |
| L ORCHILA | 11 48'N | 66 11'W | 3 | 613 | 660 | 662 | 652 | 538 | 590 | 503 | 642 | 663 | 644 | 607 | 663 | |
| MAIQUETIA | 10 36'N | 66 59'W | 43 | 594 | 661 | 564 | 496 | 475 | 617 | 661 | 636 | 675 | 598 | 596 | 609 | |
| MARACAIBO | 10 39'N | 71 36'W | 40 | 580 | 562 | 510 | 535 | 468 | 511 | 553 | 575 | 687 | 538 | 576 | 631 | |
| MARACAY | 10 15'N | 67 39'W | 442 | 715 | 725 | 689 | 645 | 514 | 589 | 619 | 637 | 674 | 570 | 622 | 652 | |
| MATURIN | 9 45'N | 63 11'W | 70 | 518 | 536 | 508 | 475 | 461 | 415 | 441 | 495 | 474 | 487 | 474 | 487 | |
| MERIDA | 8 30'N | 71 15'W | 1495 | 681 | 665 | 649 | 636 | 592 | 548 | 598 | 637 | 633 | 594 | 635 | 716 | |
| MORON | 10 31'N | 68 11'W | 4 | 722 | 696 | 692 | 630 | 591 | 619 | 733 | 699 | 700 | 661 | 685 | 698 | |
| PUERTO AYACUCHO | 5 41'N | 67 38'W | 134 | 551 | 532 | 481 | 508 | 397 | 421 | 406 | 497 | 483 | 499 | 312 | 514 | |
| SAN ANTONIO | 7 51'N | 72 27'W | 404 | 566 | 567 | 466 | 416 | 493 | 476 | 507 | 522 | 517 | 522 | 533 | 556 | |
| SANTA ELENA | 4 36'N | 61 67'W | 907 | 546 | 522 | 551 | 554 | 467 | 491 | 512 | 553 | 592 | 534 | 541 | 507 | |
| SAN FERNANDO | 7 54'N | 67 25'W | 73 | 538 | 552 | 531 | 459 | 394 | 391 | 424 | 429 | 452 | 476 | 514 | 536 | |
| TUMEREMO | 7 18'N | 61 27'W | 180 | 465 | 451 | 452 | 470 | 472 | 452 | 485 | 476 | 567 | 523 | 515 | 486 | |
| **VIETNAM** | | | | | | | | | | | | | | | | |
| CHAPA | 22 21'N | 103 49'E | 1570 | 395 | 442 | 574 | 376 | 404 | 363 | 403 | 378 | 439 | 389 | 478 | 607 | |



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APPENDIX A (CON'T)

| STATION | LAT | LONG | ELEV | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | NOTES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | VALUES OF MONTHLY AVG. KH * 1000 [1] | | | | | | | | | | |
| | | | | | | VIETNAM (CON'T) | | | | | | | | | | |
| PHU-LEIN | 20 48'N | 106 38'E | 125 | 305 | - | 234 | 384 | 474 | 493 | 492 | - | - | - | 505 | 450 | |
| | | | | | | WAKE ISLAND | | | | | | | | | | |
| WAKE ISLAND | 19 17'N | 166 39'E | 12 | 679 | 708 | 688 | 694 | 694 | 694 | 685 | 686 | 685 | 687 | 716 | 644 | |
| | | | | | | YUGOSLAVIA | | | | | | | | | | |
| BANJA LUKA | 44 47'N | 17 13'E | 153 | 366 | 420 | 404 | 488 | 576 | 513 | 559 | 536 | 575 | 470 | 167 | 278 | |
| BEOGRAD | 44 47'N | 20 32'E | 243 | 394 | 439 | 459 | 452 | 504 | 528 | 550 | 498 | 523 | 478 | 339 | 344 | |
| HERCAGNOVI | 42 28'N | 18 31'E | 34 | 299 | 172 | 343 | 402 | 502 | 511 | 575 | 565 | 508 | 439 | 290 | 242 | |
| LJUBLJANA | 46 04'N | 14 31'W | 300 | 224 | 268 | 320 | 401 | 471 | 419 | 483 | 455 | 414 | 302 | 139 | 169 | |
| NEGOTIN | 44 14'N | 22 32'E | 39 | 400 | 476 | 381 | 477 | 556 | 570 | 601 | 586 | 518 | 421 | 206 | 326 | |
| PARG | 45 36'N | 14 38'E | 863 | 378 | 330 | 313 | 341 | 416 | 357 | 450 | 431 | 408 | 358 | 188 | 234 | |
| SKOPJE | 41 59'N | 21 28'E | 240 | 311 | 472 | 394 | 465 | 553 | 556 | 601 | 582 | 528 | 431 | 303 | 270 | |
| SLJEME | 45 54'N | 15 37'W | 999 | 347 | 366 | 384 | 427 | 492 | 407 | 489 | 461 | 454 | 382 | 231 | 276 | |
| SPLIT | 43 31'N | 16 26'E | 122 | 403 | 417 | 405 | 464 | 488 | 458 | 552 | 539 | 511 | 441 | 313 | 310 | |
| ULOINJ | 41 55'N | 19 13'E | 53 | 401 | 476 | 457 | 521 | 633 | 661 | 688 | 664 | 574 | 494 | 323 | 306 | |
| ZAGREB-GRIC | 45 29'N | 15 59'E | 157 | 314 | 376 | 396 | 466 | 539 | 460 | 436 | 525 | 499 | 390 | 224 | 253 | |
| ZLATIBOR | 43 44'N | 19 43'E | 1030 | 476 | 601 | 535 | 495 | 556 | 547 | 593 | 566 | 549 | 459 | 364 | 410 | |



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# APPENDIX B
# FAILURE RATES FOR RELIABILITY ESTIMATION

## B.1 FAILURE-RATE TRENDS

A system or equipment of mature design, when operated and maintained under specified conditions or operational environment, should exhibit a relatively constant failure rate throughout a specified period of use. Exhibit B-1 depicts the three failure-rate trends normally encountered in the life cycle of an item -- a decreasing failure rate during manufacture of initial installation; a constant failure-rate trend during the useful period; and an increasing failure-rate trend signifying wearout of certain constituent elements of the system.

The "useful" period is defined as the period of operation between the installation "debugging" period and the scheduled replacement of items causing the wearout trend. A constant failure rate can be achieved in PV systems when quality acceptance criteria are applied in the purchase of components (e. g., PV modules, batteries, regulators, etc.) for the system; when the installed PV system is fully debugged of any design-margin and interface tolerance problems; and when wearout failure modes in these constituent components are identified and are circumvented by planned (scheduled) replacement of impending failures as a preventive maintenance policy.

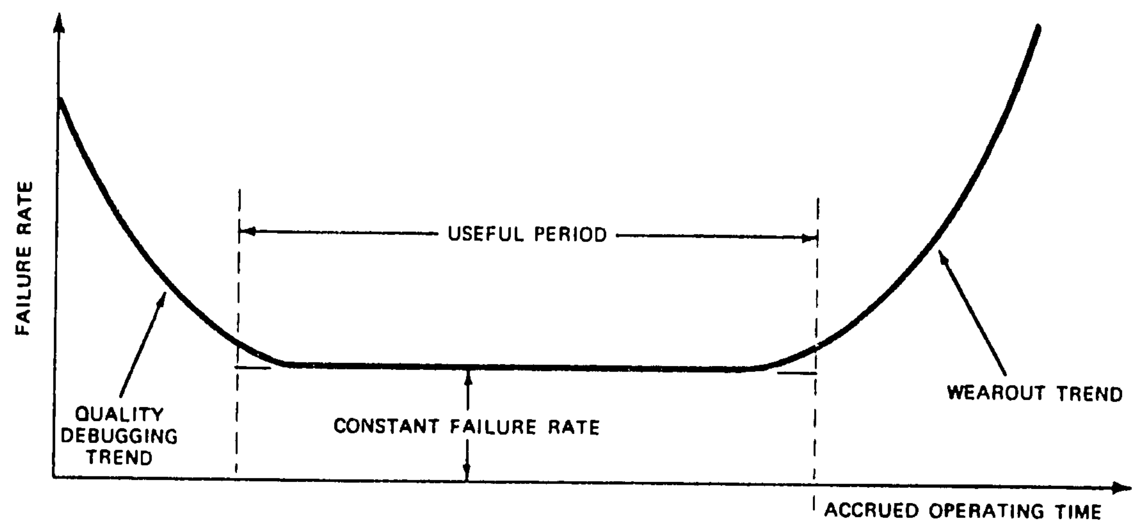


Exhibit B-1
FAILURE RATE OF AN ITEM AS A FUNCTION OF OPERATING TIME

## B.2 SOURCES OF FAILURE-RATE DATA

No formal failure experience data collection/analysis system has yet been established specifically for PV system applications. However, failure experience data from other system applications have been collected, analyzed, and periodically updated by several government activities. The data are published in useful handbook format for the guidance of design engineers in estimating and optimizing the reliability and maintainability of their system designs. Until PV-related failure data becomes available, the following existing failure-data sources are useful:

(a) Basic Electrical/Electronic Failure-Rate vs Stress Data -- Military Standardization Handbook (MIL-HDBK-217B), "reliability prediction of Electronic Equipment", published by the Government Printing Office. Provides basic failure rates under different levels of "use" stress factors (temperature, voltage, current, quality, application, etc.) for generic electrical and electronic part types (semiconductors, tubes, resistors, capacitors, relays, switches, connectors, wires, cables, etc.).

(b) Nonelectronic Parts Failure-Rate Data -- Nonelectronic Parts Reliability Data Book (NPRD-1), published by the DOD Reliability Analysis Center operated by IIT Research Institute (IITRI/RAC), Griffiss AFB, New York 13441.

(c) Government-Industry Data Exchange Program GIDEP -- provides summaries of failure-rate data reported by the GIDEP membership and published by GIDEP Operations Center, NWS Seal Beach, Corona, California 91720

(d) Photovoltaic Module Failure Experience -- monitored and periodically reported by MIT Lincoln Laboratory, Lexinggton, Massachusetts, under DOE sponsorship.

## B.3 ESTIMATED FAILURE RATES FOR CERTAIN ITEMS IN THE TYPICAL PV SYSTEM

Exhibit B-2 is a table presenting the range and average failure-rate experience for generic part and equipment types which may be used in stand-alone PV systems. These values are derived from the sources described in paragraph B-2 above. They are useful for feasibility estimation in preliminary design, pending receipt of test data pertaining to the specific items actually to be employed in the PVPS final design. Failure rates are expressed in failures per $10^6$ calendar hours or $10^6$ operating cycles, as appropriate.

Exhibit B-2

PRELIMINARY FAILURE-RATE ESTIMATES OF SELECTED ITEMS

| Generic Item (Part or Component) | Range of Failure Rates (failures per $10^6$ hrs) | | | Reference |
|---|---|---|---|---|
| | Minimum | Average | Maximum | |
| Photovoltaic Cells: | | | | |
| Failures (Open Circuit) -- | | | | |
| Estimated From Diode Model | 0.01 | 0.03 | 0.30 | (a) |
| Experience (Nebraska MIT/LL) | -- | 0.02 | -- | (d) |
| Degradation (Dirt Accumulation Between Cleaning) -- | | | | |
| Nebraska Site Experience | 10.0 | 16.0 | 26.0 | (d) |
| Cambridge Site Experience | 36.0 | 38.0 | 40.0 | (d) |
| NYC Site Experience | 44.0 | 53.0 | 65.0 | (d) |
| Diode (Silicon), General Purpose | 0.002 | 0.02 | 0.10 | (a) |
| Circuit Breakers (CB) | 1.0 | 3.0 | 10.0 | (b) |
| Relay | 0.5 | 2.0 | 8.0 | (b) |
| Connections: | | | | |
| Weld | -- | 0.002 | -- | (a) |
| Wire Wrap | -- | >0.0001 | -- | (a) |
| Crimp | -- | 0.007 | -- | (a) |
| Connectors | -- | 0.5 | -- | (a) |
| Switches (All Types) | 1.0 | 3.0 | 10.0 | (b) |
| Battery Cells (2 Volts/Cell): | | | | |
| Random Cell Failure (Open/Short) | 0.30 | 0.80 | 2.40 | (b) |
| Gaussian Wearout (Mean Cycles to Failure) | 150 cy. | 500 cy. | 1500 cy. | Depends on Vendor Data |
| DC/DC Regulator (Typical 15 KW) | 70.0 | 200.0 | 500.0 | (a) |
| Engine/Generator Equipment: | | | | |
| Engine (Diesel) | 130.0 | 350.0 | 850.0 | (c) |
| Generator (DC) | 50.0 | 100.0 | 200.0 | (c) |
| Switching Device (Typical) | 100.0 | 200.0 | 445.0 | (a) |



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APPENDIX C

LISTING OF SPONSORS OF CODES AND STANDARDS

## C.1 LIST OF CODES AND STANDARDS AGENCIES AND THEIR ADDRESSES

American National Standards Institute, Inc.
1430 Broadway
New York, New York 10018

American Society for Testing and Materials
1916 Race Street
Philadelphia, Pennsylvania 19103

Building Officials and Code Administrators
International, Inc.
17926 South Halsted Street
Homewood, Illinois 60430

ETL Testing Laboratories, Inc.
Industrial Park
Cortland, New York 13405

Factory Mutual Research
1151 Boston-Providence Turnpike
Norwood, Massachusetts 02062

Institute of Electical and Electronics Engineers, Inc.
345 East 47th Street
New York, New York 10017

International Conference of Building Officials
5360 South Workman Mill Road
Whittier, California 90901

National Fire Protection Association
470 Atlantic Avenue
Boston, Massachuesetts 02210

Occupational Safety and Health Administration
Department of Labor
200 Constitution Ave, N.W.
Washington, D.C. 20004

Solar Energy Research Institute
1536 Cole Boulevard
Golden, Colorado 80401

Southern Building Code Congress International
3617 Eighth Avenue South
Birmingham, Alabama 35222

Underwriters Laboratories, Inc.
333 Pfingsten Road
Chicago, Illinois 60062

## C.2 LISTING OF CODES AND STANDARDS BY AGENCIES

### American National Standards Institute, Inc.

| Std.-No. | Title |
|---|---|
| ANSI A. 58.1-1972 | Building Code Requirements for Minimum Loads in Building and Other Structures |
| ANSI Z97.1-1975 | Safety Performance Specifications and Methods of Test for Safety Glazing Material Used in Buildings |

### American Society of Testing and Materials

| Std.-No. | Title |
|---|---|
| B 117-73 | Standard Method of Salt Spray (Fog) Testing |
| B 287-74 | Standard Method of Acetic Acid - Salt Spray (Fog) Testing |
| B 368-78 | Standard Method for Copper-Accelerated Acetic Acid-Salt Spray (Fog) Testing (Cass Test) |

American Society of Testing and Materials (Continued)

| Std. No. | Title |
|---|---|
| C 297-61 | Standard Method of Tension Test of Flat Sandwich Constructions in Flatwise Plane |
| C 355-64 | Standard Methods of Test for Water Vapor Transmission of Thick Materials |
| C 393-62 | Standard Method of Flexure Test of Flat Sandwich Constuctions |
| D 568-61 | Flammability of Plastics 0.127 cm (0.050 m) and Under in Thickness |
| D 635-63 | Flammability of Rigid Plastics over 0.127 cm (0.050 in.) in Thickness |
| D 638-77a | Standard Test Method for Tensile Properties of Plastics |
| D 750-68 | Recommended Practice for Operating Light-and Weather-Exposure Apparatus (Carbon-Arc Type) for Articficial Weather Testing of Rubber Compounds |
| D 775-73 | Standard Method of Drop Test for Shipping Containers |
| D 790-71 | Standard Test Method for Flexural Properties of Plastics and Electrical Insulating Materials |
| D 822-73 | Standard Recommended Practice for Operating Light-and Water-Exposure Apparatus (Carbon-Arc Type) for Testing Paint, Varnish, Lacquer, and Related Products |
| D 897-78 | Standard Test Method for Tensile Properties of Adhesive Bonds |
| D 1006-73 | Standard Recommended Practice for Conducting Exterior Exposure Tests of Paints on wood |
| D 1014-66 | Standard Method of Conducting Exterior Exposure Tests of Paint on Steel |
| D 1044-76 | Resistance of Transparent Plastics to Surface Abrasion Standard Test Method |
| D 1149-78 | Standard Test Method for Rubber Deterioration-Surface Ozone Cracking in a Chamber (Flat Specimen) |
| D 1433-58 | Flammability of Flexible Thin Plastic Sheeting |
| D 1435-75 | Standard Recommended Practice for Outdoor Weathering of Plastics |
| D 1828-70 | Recommended Practice for Atmospheric Exposure of Adhesive-Bonded Joints and Structures |
| D 1929-68 | Ignition Properties of Plastics |
| D 2247-73 | Standard Method for Testing Coated Metal Specimens of 100% Relative Humidity |
| D 2249-74 | Standard Method of Predicting the Effect of Weathering on Face Glazing and Bedding Compounds on Metal Sash D 2305-72 Methods of Testing Polymeric Film Used for Electrical Insulation |
| D 2565-76 | Standard Recommended Practice for Xenon Arc-Type (Water Coded Light-and Water-Exposure Apparatus for Exposure of Plastics) |
| D 2843-70 | Measuring the Density of Smoke from the Burning or Decomposition of Plastics |
| D 3161-76 | Standard Test Method for Wind Resistance of Asphalt Shingles |

American Society of Testing and Materials (Continued)

| Std. No. | Title |
|---|---|
| E 72-74a | Standard Methods of Conducting Strength Tests of Panels for Building Construction |
| E 84-70 | Standard Method of Test for Surface Burning Characteristics of Building Materials |
| E 96-66 | Standard Methods of Test for Water Vapor Transmission of Materials in Sheet Form |
| E 108-58 | Standard Methods of Fire Tests of Roof Coverings |
| E 119-73 | Standard Methods of Fire Tests of Building Construction and Materials |
| E 136-73 | Standard Method of Test for Noncombustibility of Elementary Materials |
| E 424-71 | Standard Methods of Test for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials |
| F 146-72 | Standard Methods of Test for Fluid Resistance of Gasket Materials |
| G 7-77a | Standard Practice for Atmospheric Environmental Exposure Testing of Nonmetallic Materials |
| G 21-70 | Standard Recommended Practice for Determining Resistance of Synthetic Polymeric Materials to Fungi |
| G 23-75 | Standard Recommended Practice for Operating Light-and Water-Exposure Apparatus (Carbon-Arc Type) for Exposure of Nonmetallic Materials |
| G 24-73 | Standard Recommended Practice for Conducting Natural Light Exposures Under Glass |
| G 26-77 | Standard Recommended Practice for Operating Light-Exposure Apparatus (Xenon-Arc Type) with and without Water for Exposure of Nonmetallic Materials |
| G 29-75 | Method of Test for Algal Resistance of Plastic Films |

Institute of Electrical and Electronics Engineers

| Std. No. | Title |
|---|---|
| 141 | Recommended Practice for Electric Power Distibution for Industrial Plants (IEEE Red Book) |
| 142 | Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book) |
| 242 | Recommended Practice for Electric Power Systems in Commercial Buildings (IEEE Gray Book) |
| 446 | Recommended Practice for Emergency and Standby Power Systems (IEEE Orange Book) |
| 485 | Sizing of Large Lead Storage Batteries for Generating Stations and Substations |

Federal Specification (General Services Administration)

| No | Title |
|---|---|
| DD-G-451C | Flat Glass for Glazing, Mirrors, and Other Uses |

Military Standard

| No. | Title |
|---|---|

MIL-STD-810C/10 March 1975/Environmental Test Methods:

Method 501.1 High Temperature
Method 502.1 Low Temperature
Method 508.1 Fungus
Method 509.1 Salt Fog
Method 507.1 Humidity
Method 506.1 Rain
Method 516.2 Shock

National Fire Protection Association

| No. | Title |
|---|---|
| NFPA 70-1981 | National Electical Code |
| NFPA 78-1975 | Lightning Protection Code |
| NFPA 251-1972 | Standard Methods of Fire Tests of Building Construction and Materials NFPA-255-1972Method of Test of Surface Burning Characteristics of Building Material |
| NFPA 256-1976 | Standard Methods of Fire Tests of Roof Coverings |
| NFPA 258-1976 | Standard Test Method for Measuring the Smoke Generated by Solid Materials |

National Bureau of Standards

| No. | Title |
|---|---|
| NBS-23 | Hail Resistance of Roofing Products |
| NBS-Special | Publication 473-003-003-017-15-2<br>Research and Innovation in the Building Regulatory Process<br>Sesstion 2B, Issues in Building Regulation<br>"Decision-Aiding Communications in the Regulatory Agency: The Partisan Uses of Technical Information," Francis T. Ventre |

National Building Codes

Title

Uniform Building Code
International Conferences of Building Officials
Southern Building Code
Southern Building Code Congress International
National Electric Code
National Fire Protection Association
BOCA
Building Officials and Code Administrators International



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Underwriters Laboratories

| No. | Title |
|---|---|
| UL 1 | Flexible Metal Conduit |
| UL 6 | Rigid Metal Conduit |
| UL 33 | Fusible Links |
| UL 50 | Cabinets and Boxes |
| UL 94 | Tests for Flammability of Plastic Materials |
| UL 96 | Lightning Protection Components |
| UL 231 | Power Outlets |
| UL 263 | Fire Tests of Building Construction & Materials |
| UL 310 | Quick Connect Terminals |
| UL 360 | Liquid-Tight Flexible Steel Conduit |
| UL 467 | Grounding and Bonding Equipment |
| UL 486 | Electric-Wire Connector and Soldering Lugs |
| UL 514 | Outlet Boxes and Fittings |
| UL 651 | Rigid Nonmetallic Conduit |
| UL 729 | Nonmetallic - Sheathed Cable |
| UL 723 | Tests for Surface Buring Characteristics of Building Materials |
| UL 790 | Tests for Fire Resistance of Roof Covering Materials |
| UL 854 | Service Entrance Cables |
| UL 857 | Busways and Associated Fittings |
| UL 997 | Wind Resistance of Prepared Roof Covering Materials |
| UL 1059 | Terminal Blocks |

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