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Performance Criteria for Photovoltaic Energy Systems

Volume I

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PREFACE

This document was prepared in response to legislative directives of the Photovoltaic Research, Development, and Demonstration Act of 1978 (P.L. 95-590). It presents results of work funded by the Photovoltaic Energy Systems Division of the Department of Energy (DOE) to identify, develop, and promulgate performance criteria and test methods for photovoltaic solar energy conversion systems. This work was managed by the Solar Energy Research Institute (SERI); however, the two-volume report is the result of joint efforts by individuals from national and private laboratories, and from industry, government, and public interest groups.

The performance criteria and test methods are intended to advance the goals of the National Photovoltaic Program by transferring research results and technological resources to private sector photovoltaic organizations. The report provides a common base for manufacturers and purchasers to use in evaluating and characterizing photovoltaic performance with respect to particular characteristics of interest. Portions of this work currently are being adopted by private sector organizations in consensus standard and code documents.

The work is reported in two volumes; this volume contains performance criteria and supporting commentary. Volume II contains test methods appropriate for evaluating specific criteria. Comments on the document are encouraged and should be addressed to Mr. Gary R. Nuss, Advanced Systems Research Branch, SERI, 1617 Cole Blvd., Golden, CO 80401.

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SUMMARY

This document is a response to the Photovoltaic Research, Development, and Demonstration Act of 1978 (P.L. 95-590) which requires the development of performance criteria for photovoltaic energy systems. More than 100 experts in photovoltaics and associated technologies have contributed to the writing and review of the performance criteria listed in this document. The performance criteria address characteristics of present-day photovoltaic systems that are important to manufacturers, government agencies, purchasers, and others interested in various aspects of photovoltaic system performance and safety.

The performance criteria apply to the system as a whole and to its possible subsystems: array, power conditioning, monitor and control, storage, cabling, and power distribution. They are further categorized according to the following performance attributes: electrical, thermal, mechanical/structural, safety, durability/reliability, installation/operation/maintenance, and building/site. Each criterion contains a statement of expected performance (nonprescriptive), a method of evaluation, and a commentary with further information or justification. Over 60 references for background information are given.

A glossary with definitions relevant to photovoltaic systems is presented in Appendix A. Test methods to measure performance characteristics of the subsystem elements are presented in Volume II. These test methods and other parts of the document may be expanded or revised as future experience and needs dictate. A subject index to the performance criteria is also included in Volume I.
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SECTION 1.0
INTRODUCTION

INTENT OF THE DOCUMENT

This document presents the state of the art in defining performance criteria for photovoltaic (PV) systems and their components—such as the PV array, power conditioning, monitor and control, and storage subsystems. A performance criterion, for the purposes of this document, describes a performance need or expectation that represents a characteristic (distinguishing trait, quality, or property) of the PV system, subsystem, or component that is directly or indirectly related to performance or safety. Each performance criterion contained herein consists of a criterion statement, an evaluation statement that describes how compliance with the criterion statement can be evaluated, and a commentary statement to provide necessary supportive or background information.

Performance criteria deal with the following seven attributes: electrical, thermal, mechanical/structural, safety, durability/reliability, installation, operation and maintenance, and building and site characteristics. They are directed not only to generic but also to specific applications such as remote stand-alone, residential, and intermediate load centers and central stations.

Performance criteria are not to be confused with performance specifications. Performance specifications are prescriptive; they specify the quantitative details of performance or design for a subject part. Performance criteria, such as are found in this document, are not prescriptive; they are performance-oriented to allow for innovation and for a variety of approaches to obtain desired objectives for a PV system or subsystem.

To the prospective user, the document is intended to be a resource that not only identifies performance considerations but also provides guidelines, recommendations, and important information applicable in the design, specification, procurement, installation, maintenance, and use of PV systems and subsystems. The user of this document may be anyone at any of the buyer-seller interfaces for PV materials and products; for example, a manufacturer, supplier, architect, designer, or knowledgeable user.

A WORD OF CAUTION

Although this collection of performance criteria is intended to provide a base for fair and uniform product characterizations and comparisons, a word of caution is included here for those who wish to use this document for the specification or procurement of PV products. This document is meant to be comprehensive in nature and application. By no means will all performance criteria be applicable or necessary for any given system or subsystem. These performance criteria are not intended for blanket use in regulatory or code documents. Furthermore, care must be exercised in selecting and applying individual criteria. Inappropriate or unnecessary application of performance criteria can lead to needless expense and system complexity, thereby defeating the goal of cost competitiveness for PV.

It is also important to recognize that this document, with its performance criteria and evaluation statements, is in an evolutionary stage and is subject to modifications and refinement as PV technology and experience grow. A few of the evaluation methods
cited in the evaluation statements are consensus standards. The remainder of those identified are at various stages of development and maturity. Several evaluation statements lack an existing applicable test method. These deficiencies in the test methods for PV are to be expected in a young, developing technology and industry. Test development needs are being addressed within the Department of Energy's National Photovoltaics Program and by several standards-writing organizations. In the interim, the test methods cited here must be applied with appropriate care.

SCOPE

This document is evolutionary in the sense that it is the product of many members of the PV community who are continuing to prepare additions and refinements for inclusion in subsequent editions. As the technology and the commercialization of PV continue to advance and as experience with PV broadens, this document will change to reflect these advances.

Performance criteria in the document are oriented primarily to PV systems using single-crystal silicon cell technology for flat-plate and concentrator array subsystems. To the extent possible, the criteria were prepared so as not to exclude any of the developing cell technologies. As these new technologies advance commercially, appropriate performance criteria will be prepared and introduced in future editions.

ORGANIZATION AND FORMAT

Performance criteria are organized according to the portion of the system to which they apply. This allows a reader interested in a particular hardware element to locate all applicable criteria quickly. This document is divided into sections dealing with the overall PV system and each of its major subsystems. Two sections are divided into subsections dealing with major subsystem elements.

Each performance criterion consists of three statements: a criterion, an evaluation, and commentary statement. The scope of each statement is as follows.

Criterion: A qualitative statement that addresses the user need or expectation for a given element. It is a general statement of what the element will be able to do. The criterion does not specify any levels of performance. Unless otherwise indicated, the criterion is intended for general application.

Evaluation: A statement that sets forth the test methods and other information on which conformance with the criterion can be evaluated. It states the standards, inspection methods, analysis, review procedures, historical documentation, or test methods that may be used. In some cases, the review of documentation of in-use performance or engineering analysis may be used as evaluative tools in lieu of testing.

Commentary: A statement that provides background and presents the rationale for the selection of the criterion, evaluation, or both. It also may suggest or provide, with supporting rationale, a basis for specific levels of performance that might be used. A major reason for including a commentary with each performance criteria statement is to ensure a workable process for updating criteria by establishing a basis for selecting performance levels and methods of evaluation. This process
should aid the reader when questions arise about the basis for a particular criterion. When appropriate, the commentary statement will provide specific information regarding the use of the performance criterion for specific applications.

The performance criteria in a given section or subsection are categorized according to seven attributes. Definition statements for these performance attributes are listed below.

**Electrical Attributes** are used to describe the ability of systems and subsystems to produce or manage electrical energy. Performance criteria include electrical power generation efficiency, mismatch, power conversion efficiency, sensing, switching, ripple and transient control, and insulation to prevent electrical breakdown and excessive leakage.

**Thermal Attributes** are used to describe the ability of systems and subsystems to produce or manage thermal energy. Performance criteria include thermal energy generation and transport, thermal losses, heat transfer rates, and circulation control.

**Mechanical/Structural Attributes** are used to describe (1) the mechanical and material features of systems and subsystems that can affect their performance, or (2) the ability of systems and subsystems to withstand normal transport and service conditions that result in mechanical stress, or (3) the ability of systems and subsystems to maintain their structural integrity when operating. Performance criteria include considerations of transportation; handling; mutual shadowing; orientation of arrays; thermal expansion; fluid pressure; loading due to wind, snow, ice, hail, or earthquake; and maintenance procedures.

**Safety Attributes** are used to describe the mitigation of hazards in systems and subsystems that could result in property damage, personal injury, or death. Performance criteria include fragile, toxic, and flammable materials; high temperatures; and electrical shock, lightning, and high light intensity.

**Durability/Reliability Attributes** are used to describe the ability of systems and subsystems to perform design functions for a specified interval under designated use conditions. Performance criteria consider degradation caused by exposure to moisture, solvents, pollutants, ultraviolet radiation, thermal shock, and temperature cycling.

**Installation, Operation, and Maintenance Attributes** describe system and subsystem features for safe and proper installation, operation, and maintenance. Performance criteria consider installation instructions, operating instructions, routine scheduled maintenance, corrective maintenance, replacement, repairs, and access.

**Building/Site Attributes** relate to integrating a system with a building and site. Performance criteria take into consideration shadows from adjacent structures, accessibility on a structure, penetration and loading of structures, and drainage.

An identifying code is used for the performance criteria and for the test methods (Volume II) specified in evaluation statements. The code is designed to allow the reader to recognize the hardware element and the performance attribute addressed. The letter codes for hardware elements and performance attributes are listed below.
Hardware

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<td>Array subsystem</td>
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<td>Cell</td>
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<td>Array/array field</td>
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Each performance criterion is assigned a code in the following manner:

hardware element.performance attribute.numerical order

Examples:

SY.E.2 system, electrical attribute, second in the series
MO.S.1 module, safety attribute, first in the series
ST.D.1 storage, durability/reliability attribute, first in the series

The first new criterion code appearing on a page is printed in the upper right-hand corner of each page to aid the reader in locating a given performance criterion.

A test method is assigned a code in the following manner:

TE.hardware element. performance attribute. numerical order

Examples:

TE.AR.M.8 test method.array.mechanical/structural.eighth in the series
TE.PC.E.1 test method.power conditioning.electrical.first in the series

The code for the test methods (Volume II) appears in the upper right-hand corner of each page containing that test method to aid the reader in locating it.

A glossary is provided in Appendix A. Many terms in the glossary have well-established definitions; new terms are defined according to current knowledge and usage. A nomenclature list follows the appendices. A subject index of performance criteria is provided at the end of the document to facilitate the location of performance criteria of specific interest to the reader.
Test methods are presented in Volume II. Not all necessary evaluation (i.e., test) techniques exist; therefore, a major secondary purpose of this document is to identify test methods that need to be considered in future technical development. The existing test methods and those yet to be developed will become the basis for consensus standards and development; however, these test methods are not yet consensus standards.

CONTRIBUTORS

This document was prepared for the U.S. Department of Energy (DOE) under the management of the Solar Energy Research Institute (SERI). Project manager for its development is Gary Nuss. Major contributors to the content, design, and format are Ron Ross and Alan Hoffman, Jet Propulsion Laboratory (JPL); Steve Forman, MIT/Lincoln Laboratory (MIT/LL); Hal Post, Sandia National Laboratories; Harry Schafft, U.S. National Bureau of Standards (NBS); and Steve Hogan, Richard DeBlasio, and Paul Longrigg, SERI.

The organizational structure created for the preparation of this document includes three Task Groups, a Task Group Steering Committee, and a Coordinating Council. The Task Groups prepared the performance criteria and documented the relevant test methods. The Task Group Steering Committee designed the document format and reviewed and edited all material. The Coordinating Council provided guidance and planning aid, and helped establish priorities for Task Groups. Coordinating Council members were invaluable in the early phases of this task; they provided direction, counsel, and technical resources to begin this effort.

Developing and preparing this document was a team effort and required the capabilities of a diverse group of people associated with photovoltaic technologies and applications. Many technical and professional people contributed their time and talents to the preparation of this material, and these people are the source of the technical content of this document; it could not have been compiled without their efforts.

Those individuals and companies that participated can be proud of their effort and its culmination. They have provided a valuable tool for the nation's energy future, and their work is gratefully acknowledged. A complete list of participants in each organizational group is presented in Appendix B.
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SECTION 2.0
PHOTOVOLTAIC SYSTEMS

INTRODUCTION

A photovoltaic (PV) power system is designed to convert solar energy into electrical energy suitable for connection to an application load. To achieve this conversion, various subsystems are required. Figure 2-1 presents an interface diagram for a generalized PV power system that shows various required component subsystems and the different interfaces that exist between them. Performance criteria for other than the system as a whole are discussed in other sections. For completeness, Fig. 2-1 includes a thermal subsystem, which may be used for applications requiring combined PV/thermal modules. Energy conversion for system applications can be represented by all or part of the subsystems noted, which are appropriately designed for the intended application. Similarly, the system design should include a set of requirements for environmental conditions applicable to the installation area, specific constraints associated with the application, nominal design operating conditions to supply the load, and specific goals.

The performance criteria identified in this section relate to the total system and often are general; however, more specific criteria will be available as additional information from ongoing photovoltaic system and application studies becomes available. Knowledge derived from experience with installation and operation of experimental facilities should also be included in future revisions. Many system criteria presented here (in terms of the total system) are related to and serve as lead-ins to the more specific subsystem performance criteria. The criteria pertain to the performance of a system regardless of application, unless an application dependence is noted.

Performance criteria relating directly to loads are not included. However, system design must consider potential interface problems with the load as well as possible modification of the load to achieve cost-effectiveness or satisfactory operation.

Performance criteria for the thermal subsystem are restricted to those characteristics unique to a combined PV/thermal system. As defined here, a combined collector is a single collector that provides electrical and thermal energy conversion. The basic design and operation of the thermal part of a combined system may be significantly different from a solar thermal system. Performance criteria for those characteristics of the thermal subsystem unaffected by these design and operational differences are identified in interim performance criteria (IPC) documents for solar heating and cooling systems [1,2] and will not be discussed here. Criteria for the thermal subsystem, especially as it interfaces with the array subsystem, are presently being developed for the combined PV/thermal system. These criteria will be included as they become available.

For those users desiring more information on system design and application analysis, see Refs. 3 through 12, 16, 21, and 27. These publications may be purchased from the National Technical Information Service (NTIS); 5285 Port Royal Road; Springfield, VA 22161; (703) 557-4780.
Note: The double-arrowed lines surrounding the System Monitor and Control Box denote two-way communication with all other parts of the system. The auxiliary energy subsystem, utility and loads are not considered to be part of the PV system for the purposes of this document.
SYSTEM PERFORMANCE CRITERIA

Electrical Attributes

SY.E.1 System Power Performance

Criterion. The power produced by the PV system, with that available from auxiliary sources, shall be sufficient to meet the power needs specified for the application.

Evaluation. The output power capability of the system, with that available from auxiliary sources, shall be determined by analysis or by experimental measurement at the input side to the load and compared with the power requirements of the load to verify that the needs of the application are met.

Commentary. At the time of installation, system power performance should be verified by experimental measurements to include array current-voltage (I-V) characteristics for known irradiance levels and power output through the power conditioning unit (PCU) for known operating conditions. During the developmental years of photovoltaic systems, the user will need to know whether the system operates as the manufacturer says it will. The user also will want to know if photovoltaic modules are damaged in shipping, handling, or installation. A current-voltage curve trace for the photovoltaic array at installation will indicate whether any modules have failed electrically. For an array with a high degree of series-parallelizing in the module interconnection scheme, a failed module will show up as a "stair-step" on the I-V curve. The PV array I-V characteristic for most systems would be generated upstream of any power conditioning equipment because of the limited input voltage or voltage range of the PCU.

As the commercial PV industry matures and module prices decrease, the added time and expense of checking out a large array may not be warranted unless there is sufficient reason to believe modules have suffered damage. Experimental verification of complete system power performance before installation usually will not be practical. Therefore, analytical methods employing functionally defined subsystems should be used to calculate system power performance [13,14,15]. After installation, performance should be verified by operating the system during certain conditions and extrapolating the results to expected future conditions.

System power rating is one method of specifying a system power output as well as a way of comparing various systems. The system power rating would be based on the array power characteristics at the Nominal Operating Cell Temperature (NOCT) condition and an irradiance level of 1000 W/m². System power rating would then be determined by adjusting the array power for losses associated with the cabling and power conditioning subsystems at the array power level noted above. In the case of PV systems employing an electrical storage subsystem, the system power rating becomes more difficult to define. For this reason, the system power rating will include only the effects of PV power-producing or power-conversion equipment and not of electrical storage devices.

System power output depends on system configuration and site weather characteristics. The system power level can be determined at each calculation point of the simulation procedure described for system energy performance (see SY.E.2 commentary). A power duration curve shows the number of hours the system is operating at or below a specific power level. Similarly, a power duration curve can also show the annual system energy output at or below a given power level. Figure 2-2 presents an example of this type of curve for a simulated residential system in the Southwest. From the figure, 10 MWh of
annual energy output is generated at a power level of 3 kW or less. The power curve levels out at 9.8-kW peak power output, but only 0.2 MWh of energy is generated between a power output of 8.1 kW and 9.8 kW. The power conditioner assumed in this simulation has an efficiency of 0.95 when operated at an input power level equal to the array NOCT peak power output. Thus, the array NOCT power output of 8.1 kW (at an irradiance level of 1000 W/m²), modified by the PCU efficiency and assuming zero cabling losses, yields a reasonable system power rating of 7.7 kW. Similar plots for system power performance in the Northeast and Southeast also indicate that the modified array peak power point at NOCT represents a reasonable system power rating.

SY.E.2 System Energy Performance

Criterion. The energy produced by the PV system, with that drawn from auxiliary sources, shall be sufficient to meet the cumulative energy needs specified for the application.

Evaluation. The energy output of the PV system on a daily, monthly, seasonal, or annual basis shall be determined by analysis or by experimental measurement. This energy, with that drawn from auxiliary sources, will be compared with that required by the load to verify that the needs of the application are met.

Commentary. Experimental verification of complete PV system energy performance prior to installation usually is not practical. Therefore, analytical methods using subsystems represented by empirical or experimentally determined performance characteristics are used to calculate system energy performance. Hour-by-hour simulations for representative days in each season may be sufficient to determine average monthly and total
annual energy supplied by the PV system, resulting in a much lower simulation cost than for hourly simulations over the entire year.

System energy performance for a utility-connected PV system can be determined analytically by following this procedure:

- specify system configuration;
- specify load;
- use appropriate weather data (e.g., SOLMET data [17]);
- specify array I-V characteristics as functions of irradiance, ambient air temperature, and wind speed;
- specify PCU performance; and
- specify performance of any additional subsystems, as required (e.g., battery performance).

From these data, PV system energy performance can be calculated using SOLCEL-II or other appropriate computer simulation programs [13,14,15]. Depending on the accuracy required, less sophisticated and less expensive simulation techniques may be used [16].

For PV/thermal systems, the total system energy performance may be specified by electrical system performance and thermal system performance. It should be noted, however, that the thermal subsystem may only have the function of providing active cooling for the PV array. In this case, a thermal system energy performance factor is not applicable.

System energy rating has been proposed as one concept whereby different systems serving the same load at the same location can be compared based on a common uniform computational method. A consensus methodology for system energy rating is being formulated by the IEEE standards subcommittee for PV systems.

**SY.E.3 Economic Performance**

**Criterion.** The economics of a PV system shall be provided in terms appropriate to the owner, the application, and the location.

**Evaluation.** Photovoltaic system economics shall be calculated using methods and inputs appropriate for different kinds of owners and different application characteristics. For utilities, levelized energy cost should be calculated based on revenue requirements. For other owners, net present value of the photovoltaic system is recommended.

**Commentary.** The use of economic analyses permits comparisons among system designs and investment opportunities. Economic parameters characteristic of the system's owner should be used. Utilities generally employ a revenue requirements approach like the one presented in Ref. 18. Other owners generally prefer an after-tax analysis (see Refs. 16 and 20). Values for discount rate, income tax rate, loan parameters, tax credits, electricity escalation, and depreciation parameters specific to the consumer should be used in costing. Estimates are required for PV subsystem costs, installation costs, indirect costs, and annual operation and maintenance (O&M) costs. For grid-connected systems with nonutility owners, conventional electricity savings should be calculated including
the effects of load profile/system output match, sellback rates, storage dispatch, and utility rate structures.

Many of the methods now recommended assume constant average escalation rates, tax rates, inflation rates, discount rates, and electricity rate structures over the analysis period. The uncertainty associated with estimating these parameters may not justify the requirement of more complex, time-varying procedures.

**SY.E.4 Array Capability**

**Criterion.** The capabilities of the array subsystem shall satisfy the needs of the PV system.

**Evaluation.** The solar energy converted by the array and the energy requirements of the system shall be reviewed and then compared with the design and specifications of the array subsystem to determine compliance.

**Commentary.** The evaluation of the array capabilities should be based on meeting system design functions and performance requirements using operating conditions, design parametric studies for the climatic region, and load characteristics for which the array is intended. Array performance should be based on module electrical performance measurements and, if appropriate, thermal performance.

The array selected depends on the design requirements. It may be selected to meet a peak system output or an annual system output. It may be limited in size because the roof area or ground area adjacent to the application site is limited. If these restrictions are not imposed, the array capability is determined from the results of system optimization studies that include performance and cost and that use the goals established by the system purchaser.

Array orientation is an important input to system performance calculations, affecting system power and energy production. System design optimization calculations should be used to select the optimum array orientation. Arrays can be either fixed, discretely adjustable, or continuously adjustable. Fixed arrays may be limited by the building roof orientation in a retrofit installation. Optimum selection of the fixed tilt angle depends on the load profile throughout the year. For instance, a summer peak demand would result in a lower optimum tilt angle than would a winter peak demand. Previous studies have shown, however, that on a yearly basis, deviations of ±15° from latitude for the tilt angle and ±20° east or west of due south may not result in significant decreases in incident energy.

**SY.E.5 Power Conditioning Capability**

**Criterion.** The capabilities of the power conditioning subsystem shall satisfy the needs of the PV system.

**Evaluation.** The power conditioning requirements of the system shall be reviewed and then compared with the design and specifications of the power conditioning subsystem to determine compliance.
Commentary. The determination of the correct size for the power conditioner will be based on a number of cost/performance trade-offs that depend on the requirements of the application. For most systems, high power conditioner efficiency is of paramount importance to ensure maximum system energy output. Because PCU efficiency increases with loading, the smallest power conditioner able to perform the required function should be used so that it operates at a high percentage of full-load rating most of the time.

For systems without storage, which sell back excess energy to the utility grid, the power conditioner is usually selected to have a full-load rating equal to or slightly less than the peak power rating of the array. In systems that include storage, the power conditioner size depends primarily on the application load. For example, in the case of a remote, stand-alone system, the power conditioner can be selected to have a full-load rating considerably lower than the peak array capability. On the other hand, for a PV system used for peaking service, the PCU size may be considerably greater than that of the array peak power.

Power conditioner performance requirements are based on the needs of the application. A grid-connected system may require high quality waveform and low harmonic injection current. Alternatively, a stand-alone system may have considerably less stringent requirements. These requirements and certain economic considerations should be used to select an appropriate power conditioning unit or units.

SY.E.6 Storage Capability

Criterion. The electrical storage subsystem, if it is included, shall satisfy the needs of the PV system.

Evaluation. The electrical storage requirements of the system shall be reviewed and then compared with the design and specifications of the electrical storage subsystem to determine compliance.

Commentary. For most stand-alone PV systems, battery storage is included to provide power to the load for periods when the PV array power output is insufficient to meet the load demand. For applications in which auxiliary power is provided, the question of whether electrical storage is appropriate is determined according to which designs are most effective and suitable, and how they compare economically. When auxiliary power comes from a utility grid, a cost/performance trade-off analysis determines the amount of storage, amount of power to be obtained from the grid, and amount of power to be fed back into the grid (if permitted). With battery storage, the initial capital cost, the round-trip efficiency loss, and the battery maintenance and replacement costs are significant parameters. With utility interconnection, the significant parameters are the utility cost for incoming power and the credit given or value paid by the utility for outgoing power.

SY.E.7 Auxiliary Energy

Criterion. The capabilities of the auxiliary energy subsystem, if it is included, shall satisfy the needs of the PV system.

Evaluation. The auxiliary energy requirements of the system shall be reviewed and then compared with the design and specifications of the auxiliary energy subsystem to determine compliance.
Commentary. In general, optimum systems designed for nonremote applications include no more than one day's electrical storage and two to three days' thermal storage of the energy needed to satisfy the loads. Therefore, an auxiliary source of energy must be available to satisfy the loads during several days of bad weather. In most cases, the utility serves as such a source, but a small, self-contained electrical generator can also be used. The choice becomes one of performance, economics, and availability. For systems providing thermal energy, the combined solar and auxiliary energy source must meet the system thermal design requirements.

SY.E.8 Lightning Protection

Criterion. PV systems shall be able to sustain induced current surges generated by nearby lightning strikes without excessive damage or significant performance degradation.

Evaluation. Documentation of satisfactory long-term performance under in-use conditions is considered to be the best verification of the protection scheme. When adequate information is not available, appropriate engineering analysis and tests should be considered to check or verify that lightning discharge current has a low impedance path to ground in preference to all high impedance paths.

Commentary. The purpose here is to control the level of damage to minimize system degradation and to prevent premature system failure. The criterion also addresses optical flash and the energy coupled into the system by the array structure and system wiring. However, electromagnetic interference (EMI) is not addressed.

PV systems are often installed on mountaintops and in other locations where the risk of lightning can be severe. It is the responsibility of the designer to determine the level of risk from lightning and the economic considerations appropriate for protection [23,24,25]. Primary protection for all system elements is afforded by good grounding practices and protection devices to shunt unwanted transients to ground.

PV arrays often have large surfaces, are fully exposed to lightning, and are difficult to protect by standard methods without affecting system performance. Photovoltaic modules probably will not be designed to withstand direct lightning strikes. However, the field wiring of a large system should be protected so that a lightning strike to a field cable would cause only local damage. Since one method of reducing damage is to minimize the probability of a direct strike, lightning rods or other protective devices should be specified as part of the system where they are warranted.

Array field support structures and collectors should be grounded appropriately. System grounding should be evaluated as part of the system design to ensure adequate grounding. Additional information is needed on the response of arrays to lightning and on optimum means of array protection.

Photovoltaic system power conditioning equipment is especially susceptible to damage from induced surges. Protection of these components does not appear to present problems substantially different from those of conventional electric power systems and structures and, therefore, is covered by existing codes and standards. Surge protectors should be specified where required for protection against induced surges, with particular attention to isolating system controls from surge currents. Filters, cable shielding, and surge suppression devices should be used to minimize transient effects and keep those induced on long cable runs from damaging solar cells or other electronics.
These considerations make it necessary to evaluate lightning risks and include protection as an integral part of system design. This ensures that lightning protection devices do not adversely affect other aspects of system performance; e.g., shadowing by lightning rods adjacent to the array hampers the performance of the system.

In combined PV/thermal systems, designers should always consider the possibility of lightning-induced insulation breakdown resulting in electrical voltages and currents in the thermal subsystem.

The safety of operating personnel should also be considered in the design of lightning protection and is dealt with in SY.S.1.

**SY.E.9 Electromagnetic Interference**

**Criterion.** The level of electromagnetic interference (EMI) radiated or conducted from a PV system shall be within acceptable levels of spurious EMI as specified by Federal Communications Commission (FCC) regulations.

**Evaluation.** System design plans and specifications shall be reviewed using accepted engineering practices to ensure conformance with appropriate FCC regulations. Field test data, if available, should be reviewed to verify conformance, although consensus measurement methodologies have not been established.

**Commentary.** Concerns have been identified about the potential adverse effects of EMI which may be radiated or conducted from a photovoltaic system. Areas of concern include airport/airline communications, telephone transmission, and radio and television interference.

EMI studies [28] have concluded that a PV array field can act as a transmitting radio frequency (RF) antenna when the DC cabling is stimulated with RF energy. Similarly, the PCU can add ripple to the array DC cabling which may be of sufficient magnitude to cause EMI radiation from the array field. PV cells can receive RF energy and conduct this energy through the DC power bus to the PCU.

Few measured EMI data are currently available because of the limited number of PV systems in operation as well as the complexity and cost of measurement systems. Some measurements which have been reported [29,30] for a system utilizing a well filtered PCU operating under a light load indicate that EMI radiation was well within regulatory limits.

The most recent information regarding acceptable levels of radiated EMI may be found in the Federal Register, Federal Communications Docket on Incidental Radiation. This document provides the latest in proposed federal regulations and, as part of a consensus process, is open to public comment.

**Thermal Attributes**

**SY.T.1 Prevention of Excessive Temperature Within the System**

**Criterion.** PV/thermal systems shall be able to maintain the operating temperature of its components at or below the maximum specified component temperature.
Evaluation. Review of drawings, specifications, testing, engineering analysis, and system control strategy shall be used to evaluate conformance to this criterion.

Commentary. In a PV/thermal system, excessive temperatures may be caused by component failure resulting in loss of coolant with an eventual stagnation condition or by a condition where the thermal energy received is greater than the thermal energy removed. Excessive temperatures could damage the photovoltaic cell string interconnects (melt the interconnect solder).

Causes of excessive temperature related to component failure may be either mechanical or electrical in nature. Mechanical failures may result from pipe breaks, flow stoppage, or valve or pump failure. Electrical failures may result from wiring or cable breaks or failure in the instrumentation sensing elements related to temperature, pressure, or flow.

Candidate methods to prevent excessive temperature and identification of appropriate instrumentation and control components for the thermal subsystem are identified in interim performance criteria (IPC) documents for solar heating and cooling systems [1,2].

For concentrator PV/thermal systems, the cooling subsystem-system monitor and control interface philosophy and logic should consider provisions for defocusing the array subsystem.

Mechanical/Structural Attributes

SY.M.1 Shipping

Criterion. Packaging of PV system components for shipping shall permit these components to withstand normal hazards incurred during transport without physical damage or loss of functional performance.

Evaluation. Documentation of satisfactory performance using equivalent packaging procedures for shipping PV components shall be used. When adequate information is unavailable, engineering analysis and review of carrier requirements may be used to demonstrate that the shipping container/package can withstand any dropping, loading, vibration, and environmental stresses. Appropriate tests may be developed and used for evaluation compliance.

Commentary. Breakage and damage resulting from shipment is a major problem. Proper package design must consider the properties (ruggedness) of the equipment being shipped. Standards exist that apply to different modes of transportation as well as different uses; i.e., domestic or export, governmental or commercial. However, in all cases, the burden for safe packaging and shipment lies primarily with the manufacturer, not with the carrier.

In general, common carriers require only that the shipping container be made of materials that afford safe handling, reasonable and proper protection of contents, and protection against damage to other freight equipment. The degree to which shipping and packaging do not conform to the carriers' stated and published packaging requirements can result in the carrier levying special rates and charges.

Commercial equipment has several levels of packaging. The first or "commercial standard" is cardboard and strapping. The next level is reinforced cardboard with strapping.
connected through a pallet. The next level is termed "export boxing" and is designed to survive shipboard handling and above-deck storage. The package is typically made from marine-grade plywood into a single, palletized shipping box lined with polyethylene with glued seams. The top (also marine-grade plywood) is sealed with water-resistant glue and then nailed. In this last case, the product inside must be wrapped and protected. Desiccant is not used because in a sealed environment it quickly absorbs water. After reaching its limit, it creates rather than eliminates a moisture problem.

Photovoltaic modules are particularly vulnerable to physical damage and should be adequately protected within the shipping container by liners, partitions, wrappers, excelsior, or other packing material. Specific stresses that occur during shipment include dropping (shock), loading (containers stacked on top of it), vibration, and environmental elements. Standardized tests for packaging can be found in the literature (see, e.g., Federal Test Method STD No. 101 B).

**SY.M.2 Handling**

**Criterion.** Components of PV systems shall withstand, without physical damage or loss of functional performance, the stresses that accompany handling in accordance with the manufacturer's prescribed handling procedures and precautions.

**Evaluation.** Documentation of satisfactory performance is needed after in-use handling and installation of equivalent components. When adequate information is unavailable, engineering analysis and review of the mechanical design, specifications, and manufacturer's procedures relative to appropriate handling, storage, and installation of the application shall indicate conformance.

**Commentary.** Handling of equipment by nontechnical personnel before and during installation must be considered during the mechanical design phase. Except for components directly exposed to the outside environment, physical stresses induced during transport and handling are generally substantially greater than will be applied during system operation.

Equipment hardware items (components, elements of subsystems, and subsystems) must be built to meet stresses from installation as well as those from shipping and handling. Ruggedness needs to be designed into the equipment. Components installed in large systems may be exposed to less stress than those installed in small systems because of higher skill levels of installers for the former. On the other hand, equipment familiar to solar installers might be treated with less care than equipment with which they are less familiar.

**SY.M.3 Piping for Pressurized Fluids**

**Criterion.** Piping that transfers liquid coolants for modules, receivers, or arrays shall not leak when subjected to specified pressures.

**Evaluation.** Module operating pressures and test data should be reviewed. If no data exist, then the Static Pressure Leakage Test described in Test Method 7.12 of NBSIR 78-1305A [18] shall be used to show compliance with this criterion.
Commentary. Pressurized leak testing should be done with the heat-transfer fluid designed for the system. Glycol mixtures and oil generally have a lower surface tension than water and may leak through watertight connections. It is preferred that tests be performed at both high temperatures (design operating) and low temperatures (below ambient) to evaluate connections and piping runs for expansion and contraction. The use of hot fluids can result in swelling of packing or joints to conceal leaks. Sweating may occur when testing with low temperature fluids, giving the appearance of a leak.

Precautions should be taken not to use excessive pressure during testing. Leak tests should be performed before enclosing, backfilling, or insulating the piping components. Overpressure protection for components by the use of expansion tanks, air vents, pressure gauges, and relief valves, for example, may be necessary during the test.

Safety Attributes

SY.S.1 System Safety

Criterion. The design, construction, operation, and maintenance of the PV system shall be in accordance with applicable safety codes and standards and regulatory requirements.

Evaluation. Review the design, the construction schedule and procedures, and the operational procedures along with system design criteria to show conformance with applicable safety codes and standards and with regulatory requirements.

Commentary. Safety reviews of system design, construction, and operating procedures are ongoing activities. It is wise to start this practice early in the design phase so that constant review will ensure a safe system with minimal, if any, construction or operational safety problems. If the system is large enough and the construction schedule tight, it may be advisable to hire a safety consultant to independently review the safety aspects of the design, installation, and operation.

Designed-in safety involves following code requirements, using "code-approved" (by independent testing laboratories) equipment, and having "inspected" installations. The National Electrical Code is a prime example, although other National Fire Protection Association (NFPA) codes are important, particularly when considering insurance requirements and related concerns of equipment flammability and toxic gas production. Standards exist for testing building materials—UL 263 (ANSI 2.1), "Fire Tests of Building Construction and Materials," and UL 790, "Tests for Fire Resistance of Roof Covering Materials."

Personnel safety is largely dictated by the Occupational Safety and Health Administration (OSHA) regulations. These regulations apply to any construction site—residential through central station—although only commercial-industrial facilities fall under the operating personnel safety requirements; residences are exempt.

SY.S.2 System Grounding

Criterion. The maximum cell string voltage above ground shall be within the voltage isolation capabilities of the PV module and other subsystem components during installation, operation, and maintenance.
Evaluation. Wiring plans, drawings, specifications, and calculations must be reviewed to determine proper placement and sizing of grounding conductors to:

- limit the voltage to ground;
- prevent excessive voltages from lightning, line surges, unintentional contact with higher voltage lines, or induced voltages from adjacent circuits or static charges; and
- facilitate the clearing of ground faults by circuit protective equipment.

This review shall indicate conformance to this criterion. The sizing of a grounding conductor shall be sufficient to carry the expected fault current indefinitely or until the circuit interrupting devices (if present) act to clear the circuit. Voltage drop across ground bands should not exceed 1 V at the maximum anticipated fault current [34].

Commentary. System grounding stabilizes voltages and thereby prevents excessive stressing of insulation and facilitates the clearing of protective devices. Because of the many possible configurations of a photovoltaic system, one cannot simply require a grounded subsystem, such as the array, without complete knowledge of the grounding details associated with the other subsystems and their components, such as the diesel generator, the utility interface, or the battery storage.

Since having more than one system ground may have detrimental effects on overall system performance and personnel safety, conformance to this criterion must begin at the system level and encompass all subsystem components. The grounding method must be compatible with durability and reliability requirements.

SY.S.3 Equipment Grounding

Criterion. Electrical equipment structures shall be electrically connected to earth by a permanent and continuous path.

Evaluation. A review of wiring plans, drawings, specifications, and calculations (beginning at the system level and continuing to the equipment level) to determine proper placement and sizing of grounding conductors shall indicate conformance to this criterion. The sizing of a grounding conductor shall be sufficient to carry the expected fault current indefinitely or until the circuit interrupting devices (if present) act to clear the circuit.

Commentary. Grounding of electrical equipment structures, which includes all non-current-carrying metal frames, supports, and enclosures for circuit conductors and equipment, contributes to reliable ground fault protection by providing adequate conductors for the flow of ground fault current during line-to-ground faults. The equipment grounding conductor is separate from the system grounding (return) conductor. Equipment grounding systems, consisting of interconnected networks of equipment grounding conductors, perform two basic functions:

- they limit the shock voltage on non-current-carrying metal parts and enclosures for conductors, equipment, and devices to a safe level when ground faults occur; and
- they prevent damage to the installation by conducting ground fault currents of adequate magnitude to ensure fast operation of circuit protective equipment.
To ensure the continuous performance of these basic functions, each equipment grounding conductor and all connections in every ground fault current path must meet all of the following requirements:

- Conductors and connections must have sufficiently low impedance to (1) limit the shock voltage on non-current-carrying metal parts and enclosures to a safe level during ground fault and (2) conduct adequate ground fault current to ensure fast operation of circuit protective equipment.
- Conductors and connections must have adequate short-time current capacity to conduct fault currents likely to be imposed on them for the time required to open circuit protective equipment without being damaged by overheating.
- Conductors and connections must have adequate mechanical strength (or protection) to survive without becoming loose or breaking.
- Conductor and connector materials must not corrode.
- Conductor connections must be tight and remain tight to ensure the integrity of equipment grounding networks throughout the life of the electrical system.

Equipment grounding connectors and connections must be arranged so that current will flow through them only during ground faults. If grounded circuit conductors are incorrectly grounded or bonded to equipment grounding conductors, there may be an excessive flow of normal load current in the equipment grounding system that could lead to unwarranted interruptions in the operation of the PV system.

SY.S.4 Electrical Interrupts

**Criterion.** The system shall be provided with a means to interrupt current between the subsystems.

**Evaluation.** Review electrical connection drawings and equipment specifications to determine compliance with electrical code requirements.

**Commentary.** The electrical subsystems must be safe when personnel check and service them. The safety scheme must be able to isolate and/or interrupt the current between the subsystems in case of a fault. The National Electric Code (NEC) provides requirements for electrical systems but does not address PV systems. Since the insulation system of the PV array is considered part of the overall insulation system, it requires further evaluation and study.

SY.S.5 Fire Safety

**Criterion.** The materials used in electrical subsystems shall comply with applicable codes concerning flammability, flame spread, and release of excessive levels of smoke or toxic gases.

**Evaluation.** Review equipment specifications or test results to determine compliance with applicable codes concerning flammability, flame spread, and release of excessive smoke or toxic gases.
Commentary. Fire safety requirements and tests, such as those developed by Underwriters Laboratories (UL) and the American Society of Testing Materials (ASTM), may verify fire-safe performance. The company underwriting the insurance coverage may provide valuable assistance in ensuring that all safety requirements are met.

SY.S.6 Installation Plan

Criterion. The system installation shall minimize safety hazards to installation personnel.

Evaluation. The installation plan shall include clear and complete specified installation procedures that identify any unusual hazards. OSHA regulations should be observed in determining acceptable procedures.

Commentary. Because most installers are unfamiliar with PV systems, the system designer has a greater responsibility to provide adequate instructions. Since the system may present hazards when partially assembled, the designer must plan the installation activities to ensure that hazardous conditions do not exist at any time; e.g., by scheduling the installation of fault protection components as soon as possible. Specifically, the designer should remember that photovoltaic modules are energized when illuminated whether or not they are connected into the system; this may be easily forgotten by installers. Instructions should detail safe handling procedures for PV modules during installation, and modules should be designed with nonhazardous open-circuit voltage, or with integral protection, such as short-circuiting jumpers to be removed only when installation is complete.

Structural hazards may exist if not all structural elements are in place before array modules are mounted. If the array module is a structural element, the designer should consider whether the array design will meet structural criteria at all assembly stages.

Lightning and other fault protection elements of the system design should be installed as early as possible, so that the other elements are fully protected when installed.

Particular hazards exist with the installation of storage batteries, because of their high fault current capability and the possibility of chemical burns from the electrolyte that may leak from cells damaged in shipping. Existing codes and standards for large storage battery installations include provisions for protecting installers against these hazards. These provisions should be incorporated into system installation planning and instructions.

On-site work should be planned so that simultaneous activities do not interfere with each other and create safety hazards. Installers' skill level requirements should be specified as a part of the installation plan.

SY.S.7 Burn Hazards

Criterion. The casing of the system, individual subsystems, and all other exposed parts shall not become so hot that they present a burn hazard to personnel working near the unit.
**Evaluation.** A review of design drawings to verify that adequate surface cooling has been provided will indicate conformance with the criterion.

**Commentary.** If required, the subsystems should be provided with internal cooling fans and proper cooling air flow paths to maintain safe surface temperatures for maintenance personnel and other workers. Where cooling may be impractical, burn hazard areas should be indicated.

**Durability/Reliability Attributes**

**SY.D.1 System Reliability**

**Criterion.** The reliability of the PV system shall meet specifications.

**Evaluation.** Reliability and engineering analysis of the system, subsystems and components, and reliability demonstration tests as they are appropriate, shall be required. Field data, if available on operating systems, may be used to verify conformance.

**Commentary.** As used herein, reliability is the probability of the PV system to perform satisfactorily under stated operational and environmental conditions for a stated period of time. For PV systems that are expected to operate for long periods of time and are repairable, system reliability is usually expressed as mean time between failures (MTBF) or availability (operating time divided by operating time plus downtime).

Experience has shown that electrical and electromechanical systems and components follow the characteristic failure pattern ("bathtub curve") shown in Fig. 2-3. Region A is the early life (infant mortality) period where the failure rate is initially high and rapidly decreases with time. High initial failure rates result from improper design and defects introduced in manufacturing and installation. During Region B, the useful life, the failure rate is relatively low and constant. Region C is the wear-out period, where in spite of repairs and routine maintenance, failures occur at a rapidly increasing rate. The increasing failure rate results in the system becoming uneconomical to maintain.

![Figure 2-3. Characteristic Failure Curve for Electrical and Electro-Mechanical Systems](image)
The reliability specification should consider the entire curve, although quantitative requirements emphasize the useful life period. The most meaningful approach for determining the level of reliability is through cost trade-off analyses. Initial acquisition costs increase as reliability improvement features are incorporated into the design. Conversely, maintenance costs decrease with increasing reliability. The optimal reliability level is that point where the incremental cost of increasing reliability is equal to the incremental reduction in maintenance and support costs (life cycle) achieved by the increased reliability.

Design establishes the inherent reliability characteristics of a system. Fault tolerant design (e.g., redundancy) and functional system configurations should be emphasized to preclude system shutdown resulting from failure of a simple component. Attention to other design phase factors, including selection of components suitable for the application with proven reliability, adequate derating (safety margins), specifications control over procured materials and assemblies, design producibility, and design testing with rigid failure analysis and corrective action follow-up can contribute significantly to reliability. The designer also controls reliability through specification of production process controls; inspection criteria; screening, burn-in, and debugging procedures; installation, operation, and maintenance procedures; and acceptance/demonstration testing procedures. Obviously it is important that these operations are carried out according to the designer's specifications.

Because reliability is virtually impossible to measure during design, analytical techniques have been developed to provide some indication of progressive conformance with goals and requirements. Some of these are fault tree, failure mode, and effect analyses (to identify potential problem areas); prediction and other assessment techniques (to quantify reliability); and reliability design reviews and growth management.

Of primary importance in reliability testing and system operation is a firm set of definitions for system failure to minimize confusion in defining satisfactory system performance. The system specification must include a definition of system failure along with a definitive statement of the conditions of the test, field operations, or other means for demonstrating reliability compliance.

**Installation, Operation, and Maintenance Attributes**

**SY.II** Installation, Operation, and Maintenance Manual

**Criterion.** Guidance for the safe and successful installation, operation, and maintenance of a PV system and its associated subsystems shall be provided in one or more manuals.

**Evaluation.** A review of the manual(s) to ensure that information necessary to install, operate, and maintain the system or subsystem in a safe and reliable manner is provided shall indicate conformance to this criterion. The following issues should be addressed:

- Unpacking Procedure
- Site Preparation or Special Considerations
- Safe Installation Practices
- Specifications Sheet
- Theory of Operation
- Operating Procedures
- Safe Operating Practices

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Commentary. (See SY.S.6.) Optimum system performance and safe operation depend on the proper installation of the system, making installation information of prime importance. Installation instructions should detail safe handling and assembly procedures for system components. Since the system may present hazards when only partially assembled, installation instructions should caution against possible hazards.

In most cases, the daily operation of the photovoltaic system will be fully automatic and require no special attention. However, start-up and shut-down procedure instructions are required for user service and should be indicated on a simple label. Indicators of correct system operation (i.e., indicator lights and operation test points) should be mentioned. Additional specifications for anticipated system operating conditions at system access monitoring points are required to facilitate operational checks and troubleshooting.

Large equipment such as that used for intermediate load center or central power applications shall include a minimum of two copies of current installation, operation, and maintenance manuals. Manufacturers of commercial or consumer equipment suitable for residential use shall make current operation and maintenance manuals available to qualified repair personnel.

A block diagram that indicates how the entire system functions shall be supplied with a schematic diagram of each block highlighting the main power or electrical flow. If any part of the circuit is unusual, a simplified schematic should be provided to clarify the operation of that part. Inputs, outputs, and test points should be clearly specified.

Comprehensive maintenance instructions shall be provided to the system owner that include plans for maintaining the system. Warnings against hazards that can arise during the maintenance of the system should be highlighted along with a description of precautions to take to avoid these hazards. See AR.I.3 for additional commentary.

The manual shall list all parts of the system by subsystem according to shape, dimension, material, weight, function, and performance characteristics. The manual shall include sequence of operation and flow and wiring diagrams. It shall include a tabulation of those performance requirements that are dependent upon specific maintenance procedures. The maintenance procedures, including ordinary, preventive, and minor repairs, shall be cross-referenced for all subsystems and organized into a maintenance schedule. The manual shall describe operating procedures for all parts of the system. Similarly, it should include an outline of troubleshooting procedures if system failure or degraded performance occur. The outline should list system failure symptoms and probable causes, along with a concise description of the troubleshooting procedure. Equipment and the number of people required for the troubleshooting should be described. How and where electrical readings are to be taken should be clearly indicated by text, photographs, and drawings. Once the failed system/component is isolated, procedures for repair or replacement should be described.
The manual shall include all ordinary maintenance, preventive maintenance and minor repair work, and projections for equipment replacement. It should also include a format for keeping maintenance records—type of maintenance, time required to perform the maintenance, and other pertinent data.

Field inspections and maintenance operations require handling electrically active elements during daylight hours. A manual explaining special safety rules and regulations for cleaning, replacing, and inspecting equipment shall be written. It is important that field personnel understand these procedures.

The manufacturer shall state the equipment warranty period and specify which costs are covered, such as parts, labor, travel, and per diem for service personnel. Service availability shall be stated.

The above comments apply for all portions of the photovoltaic system and subsystems. Special considerations for each subsystem shall be detailed in their respective installation/operation/maintenance sections.

**SY.I.2 System Maintainability**

**Criterion.** A maintenance manual containing safe and easy methods of servicing systems and subsystems using a minimum of special equipment should be provided. Hazard warning labels should be included on those items or areas where potential problems exist.

**Evaluation.** A review of the maintenance manual and applicable documents and drawings should be made. Attention should be given to maintenance intervals and procedures as well as service procedures. It also is important to verify that appropriate sensors or access for sensors have been provided for inspecting and monitoring essential parameters.

**Commentary.** Maintenance and servicing of the PV system is required to provide for optimum and safe system operation. Some systems contain toxic or combustible materials (e.g., lead-acid batteries), or both, that could poison or burn maintenance personnel or cause fires or explosions when repairs involve soldering or welding. Electrical isolation of the system is mandatory to minimize electrical shock to maintenance personnel.

Parts, components, and equipment required for service, repair, or replacement shall be commercially available through the manufacturer or supplier. Parts replacement may vary from discrete components to plug-in circuit boards. In many instances, modular circuit boards are offered as replacements because of the proprietary nature of circuit design, and often cost less than removing the module and replacing individual components. The industry does not now have a specified time period during which replacement parts are offered and, thus, should adopt a time period that will provide for system operation over its design life.

Adequately located test sensors will permit system monitoring and expedite maintenance and repair. Typical test sensors include voltage, current, power, and temperature transducers and watt-hour meters. Specific measurements include array temperatures, DC input voltage and current, DC input power, AC output voltage, inverter output in watt-hours and VAR-hours, and transformer output in watt-hours and VAR-hours. In addition, reference cell temperature and short-circuit cell current could be measured from either an in-place reference cell or portable test instrument. A digital voltmeter and X-Y
plotter combination may also be used to measure and plot the I-V characteristic of the array. The amount and requirement for system monitoring sensors and the necessity for recording equipment vary with the system size and the maturity of system design. Larger systems and initial system installations require more monitoring capability.

For ease in service, problems must be diagnosed quickly, defective parts replaced easily, and operation verified accurately. A proper manual is essential. For residential equipment, a manual should be available to qualified service personnel. For larger installations, such as intermediate load center and central station applications, a manual should be available with the equipment. It should include simplified block diagrams, complete schematic designs, and significant signal flow field test procedures.

Where possible, the PV system should use subassemblies that can be replaced without extensive readjustment. Each subassembly should be documented, test points identified, and service checks defined. Substitution of parts or components should not be difficult. Repair time can be reduced if substitute boards or modules are stocked by the maintenance contractor with the number of functional boards or modules kept to a minimum, consistent with cost requirements. In cases of PV modules or batteries, it is particularly appropriate to ensure both safety and rapid interchange of the parts involved. Accessibility is also an important part of maintainability and is discussed in SY.I.3.

These comments apply to all portions of the photovoltaic system and subsystems. Special considerations for each subsystem are detailed in their respective installation/opera­tion/maintenance sections.

SY.I.3 Access for System Maintenance

**Criterion.** All items of equipment and system components that may require periodic examination for adjustment, servicing, and maintenance should be accessible for inspection, repair, removal, and replacement.

**Evaluation.** Drawings and specifications shall be reviewed and analyzed to determine if the system design will facilitate effective maintenance. The clear working space shall be checked against NEC requirements.

**Commentary.** Accessibility for system maintenance and servicing is required for each of the different PV subsystems. The degree of accessibility may vary from subsystem to subsystem.

For photovoltaic modules, concentrator receivers, optics, tracking controls, arrays, and their appurtenances, maintenance entails routine periodic inspection, servicing, washing, and removal or replacement. Maintenance should be performed without dismantling any adjoining major pieces of equipment or structural elements. Individual modules or panels should be replaceable or repairable with minimal disturbance of modules or panels in the array. Modules, concentrator optics, panels, and arrays should be designed to facilitate easy cleaning of optical surfaces. [See Sec. 3.0, MO.M.9 (Optical Surfaces Soiling) and MO.M.10 (Cleaning Tolerance)] Some equipment might be designed so that sequential installation is necessary, which could make it difficult to replace an individual panel without disturbing the entire array.

Access roads may be needed for the array field. The type of road needed will depend on the way in which maintenance will be performed.
For electronic components where "live" parts are exposed for servicing, inspection, removal, and replacement within the array field, the minimum clear working space shall not be less than in Table 2-1.

### Table 2-1. MINIMUM CLEAR WORKING SPACE

<table>
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<tr>
<th>DC Voltage to Ground&lt;sup&gt;b&lt;/sup&gt; (Volts)</th>
<th>Minimum Horizontal Spacing [meters (feet)]</th>
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<tr>
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<tr>
<td>150</td>
<td>600</td>
</tr>
</tbody>
</table>

<sup>a</sup>From NEC.
<sup>b</sup>For circuits isolated from ground, this represents the maximum voltage possible with any other part of the circuit connected to ground.

The information in Table 2-1 may not be applicable to central station use. In an array where the contacts of the plug and receptacle are not accessible, the working spacings in the table generally will not be required.

Test access should include connectors for auxiliary test equipment if the level of maintenance warrants them. In simple cases, a VOM or more complex equipment may be used to facilitate rapid service with minimal cost.

The safety of service personnel should also be considered. The use of warning labels and panel interlocks should mitigate or eliminate any dangerous conditions. See SY.S.1 (System Safety) for general system safety considerations.

### SY.I.4 Insurability

**Criterion.** The design, construction, and operation of the PV system shall be in accordance with applicable insurance requirements.

**Evaluation.** Review of the applicable insurance and the system design, construction plans and procedures, and operating procedures shall indicate conformance to this criterion.

**Commentary.** Various insurance companies place requirements on system design, construction, and operation [21]. These requirements come from the individual insurance companies' risk assessment and field data. The insurance involved is typically construction insurance, design or "trade-off" insurance, and owner's insurance.

Construction insurance typically specifies, based on the size and type of installation, the precautions and equipment that must be provided before and during installation. Such precautions are usually access control requirements (fencing to keep out intruders but allow fire equipment in), and work control requirements (safety helmets, the buddy system, etc.). OSHA requirements also affect work control requirements.
Design or "trade-off" insurance is an option where the cost of modifying equipment to make it more rugged is traded for the cost of insuring it against the possibility of a damaging situation occurring. For example, if a photovoltaic module were designed to survive 31-mm (1.25-in.) hail and the module were to be installed in a region where 50-mm (2-in.) hail was prevalent, the cost of redesigning the module for 50-mm hail would be measured against the present worth of insurance covering damages to the array should 50-mm hail occur in that region. The lower cost option would then be used in the system design.

Finally, owner's insurance covers the owner's responsibilities with respect to operation of the system. Installation design requirements may be specified particularly for a large installation. Examples of such requirements are fire coverage, protection, access control, maintenance facility fire requirements, and operational policies.

SY.1.5 Regulatory Requirements

Criterion. The PV system and all its components and subsystems shall meet all applicable local regulatory requirements for construction, installation, and operation.

Evaluation. Review of applicable regulations for system design, construction plans and procedures, and operating procedures shall indicate conformance to this criterion.

Commentary. The major regulatory constraints on PV systems are the building codes adopted by each jurisdiction in the United States [21].

A building code is a legal document which sets forth requirements to protect the public health, safety, and general welfare as they relate to the construction and occupancy of buildings and structures. The building code development process in the United States is quite complex. Building codes are normally enacted into law by local governments exercising the authority delegated to them for this purpose by the individual states. About 14,000 jurisdictions issue building permits in the United States. Thus, there is a considerable diversity of substantive provisions among the thousands of locally enacted codes, even though three-quarters of these codes are based on one of the four model codes.

Except in some larger cities, drafting of building codes in the United States is generally accomplished by the Model Code Association and allied groups. Three of the model code organizations are regionally located, and their membership is controlled by local government code officials:

- BOCA - Building Officials and Code Administrators International, Inc. (Basic Building Code)
- ICBO - International Conference of Building Officials (Uniform Building Code)

The responsibility for the fourth model code, the National Building Code, lies with the National Conference on Building Codes and Standards (NCBCS) for revision and update using the American National Standards Institute (ANSI) consensus procedures.

A recommended model code [22] for the use of solar heating, cooling, and hot water systems has been drafted and is currently under review. This document covers new solar-
related aspects of existing provisions pertaining primarily to structural, electrical, and fire codes.

**Building and Site Attributes**

**SY.B.1 Shading of the Array Field**

**Criterion.** The location and orientation of the array field shall be such that the output energy loss resulting from shading—by trees, external structures or appendages, or other arrays within the field—does not exceed the amount allowed for in the system design.

**Evaluation.** Calculations and array installation drawings shall be reviewed to determine areas of shading by objects such as mechanical equipment, chimneys, vents, trees, buildings, or other portions of the array field. The design provisions for counteracting the effects of array shadowing should be reviewed and analyzed to determine their ability to limit localized "hot-spot" heating and optimize the annual electrical energy output.

**Commentary.** Data are available for calculating solar azimuth and elevation angle as a function of site latitude, longitude, and time of day [19,26]. In some cases, the analysis of complex shadowing patterns may require a photographic investigation of the shading through the use of a scale model of the installation and a collimated light beam. Sophisticated computer codes are also available to analyze complex shadowing geometries.

Consideration shall be given to the site latitude, the height of nearby objects above the collector, the azimuth angle of the objects relative to the collector, and the cut-off angles at which solar energy can no longer be collected efficiently.

Where shadowing occurs, efforts should be made to minimize its effect on the array annual energy output. The effects of localized "hot-spot" heating due to shadowing should be considered in the design.

When arrays are mounted on structures that move to track the sun, complicated array-to-array shadowing patterns can occur that vary throughout the year. In general, detailed analyses are required to determine the shape that the shadows produce on the affected arrays, and the overall effect of the shadowing on annual system output.

**SY.B.2 Environmental Impact**

**Criterion.** The construction and operation of a PV power system shall not produce an unacceptable environmental effect on the immediate natural environment.

**Evaluation.** Plans and specifications shall be reviewed to ensure conformance with appropriate environmental regulations.

**Commentary.** Each PV power facility construction project requires its own set of permits, approvals, and certifications to satisfy environmental regulations [21]. Variations in these requirements occur according to differences in the types and locations of the projects. The National Environmental Policy Act (NEPA) may require that an environmental impact statement (EIS) be filed by the responsible federal agency for any project
requiring a federal license, permit, or certification and for all controversial projects. Under NEPA, only federal agencies are required to file an EIS. However, laws similar to NEPA have been enacted in many states at state, county, and city government levels.

The environmental assessment report, prepared by the applicant or a contractor, should address potential environmental effects that might result during the construction and operation of the facility. The report should include a discussion of the unavoidable effects, potential impacts, and mitigation of impacts on each of the following: geology and soils, surface and ground water, climate and air quality, noise, biology, land use, socioeconomics, traffic, aesthetics, cultural resources, and public acceptability.

SY.B.3 Siting

**Criterion.** The PV system shall be compatible with the site characteristics.

**Evaluation.** The PV system design, layout, and installation schedule and procedures shall be reviewed to determine conformance with the system’s design criteria and environmental impact statement, assessment, or report.

**Commentary.** Proper design integration, considering site preparation and system requirements, can save time and money and reduce frustration through a smooth installation schedule.

Many factors affect site preparation. The first is the site (geological) survey. This survey establishes the soil conditions which, in turn, dictate the foundation design. Expansive soil, if not discovered early, could cause problems with array settling and upheaval. If a site has mineral springs, a dewatering system of pumps and drains may be required to control erosion or array settling. In conjunction with site selection, an environmental survey is also made. Depending on the application size and other considerations, an environmental impact report may be required (see SY.B.2). This may be a statement (if a small application), an assessment (if an environmental problem exists), or a report (if a large application and/or many problems exist).

Once the site is selected, environmental concerns established, and the system configured, the effect of site preparations on the construction schedule must be considered. This is especially true as the application sizes get bigger and require more construction labor and better field coordination.

One important aspect of the construction planning phase is insurance (see SY.I.4). Construction insurance and owner's insurance specify certain site requirements before construction begins (e.g., fire protection tanks, hydrants, extinguishers, etc., and access control) and after the system begins operation (e.g., additional fire protection equipment and operator emergency procedural controls). The system location and safety concerns for passersby and observers will dictate the level of site isolation and protection required [e.g., 2.4-m (8-ft) chain-link fence, guards, electronic surveillance, etc]. An additional aspect of construction planning, especially for larger applications, involves the question of whether to use temporary buildings for construction or erect permanent buildings to use for construction purposes first and later converting them to their final use. Similarly, matters concerning services such as water and sewers must also be considered.
SY.B.4 Avoidance of Array Field Soiling

**Criterion.** Array fields shall have appropriate avoidance provisions to prevent excessive deposition and accumulation of dirt and debris on the arrays within the field.

**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be used.

**Commentary.** The placement of arrays at sites which are in close proximity to potentially large particle generation sources (e.g. dirt roads, smoke stacks) can result in significant electrical performance degradation. To minimize particulate deposition on the arrays, several measures can be considered during the design and layout of the array field, including site location relative to prevailing winds and particulate sources, placement of barrier fences, and the height above ground of the lowest point on the array (i.e., standoff). The principal advantage of barrier fences is the reduction in wind loading levels which in turn reduces the loading requirements on array support structure [30]. Barrier fences have the potential, if properly place, to deposit dirt entrained in the airstream away from the array rows, similar to use of a snowfence. Although no experience to date is available about photovoltaics, relevant information has been reported [31]. The standoff distance of the leading edge from the ground can be important to minimize the deposition of dirt by rain splashing on the area in front of an array. An additional consideration in site location is the upwind terrain and vegetation. A grassy field, for example, may cause less dirt accumulation than a bare field. However, large amounts of pollen can be released from vegetation during certain times of the year, resulting in significant soiling problems for the arrays. See AR.I.3 Commentary for representative module/array cleaning procedures.

**SYSTEM MONITOR AND CONTROL PERFORMANCE CRITERIA**

**Electrical Attributes**

**SM.E.1 System Monitor and Control Capability**

**Criterion.** The capabilities of the system monitor and control shall satisfy the needs of the PV system.

**Evaluation.** The monitor and control requirements of the system shall be reviewed and then compared with the design and specifications of the system monitor and control to determine compliance.

**Commentary.** A PV power system can satisfy the system loads in a number of different ways. Energy collected by the solar arrays can be sent to satisfy loads directly. Loads can also be satisfied by energy supplied by a battery, or from an auxiliary energy source (utility, diesel generator, etc.). If the system includes a battery, it can be charged by diverting some of the array energy from the loads, or it can be charged directly from the auxiliary energy source. If the system has no storage, then excess array energy can be sent to the utility for its use. When the system is designed, the optimum use of all subsystems must be considered relative to the goals set forth for overall system performance, and the system control must be designed to implement this strategy.
SM.E.2 Power Flow Control

**Criterion.** The system monitor and control shall determine and cause the flow of power through the system to implement the strategy required by the system design.

**Evaluation.** The required control strategy shall be compared with the drawings and specifications for the monitor and control circuitry to determine compliance.

**Commentary.** The energy produced at the array must be used optimally to maximize system efficiency and make the greatest use of the energy produced. Most solar energy systems include a number of options for energy and power flow because of the potential interactions between energy produced at the array, energy stored, energy required by the on-site loads, and auxiliary energy available at the utility. In general, computer simulations of annual system operation are used to compare the many possible strategies and to choose the one best for the application. The system hardware—in particular, the monitor and control circuitry—must implement the strategy selected.

SM.E.3 Load Management

**Criterion.** If load management is used, the system monitor and control shall coordinate the level of system output and the magnitude of the loads in accordance with the system strategy chosen.

**Evaluation.** The system operating strategy shall be compared with the schematic drawings and specifications for the system monitor and control circuitry to determine compliance.

**Commentary.** For some applications, the control of on-site loads by the PV system is permissible and provides a means to produce an optimum match between system output and on-site loading on a real-time basis, minimizing the need for auxiliary energy. Where such a strategy is used, the monitor and control circuitry must sense the output capability of the system and exert control over the load so that an optimum match is maintained. When the on-site load comprises a number of diverse loads, the monitor and control circuitry must be provided with a strategy of priorities so that loads are shed and picked up in the proper order as system output varies.

SM.E.4 System Monitor

**Criterion.** The system monitor and control shall determine the operating characteristics of the system and initiate necessary protective actions in case abnormal conditions occur.

**Evaluation.** Drawings and specifications for monitor and control circuitry shall be reviewed to determine that instrumentation has been provided for the measurement, indication, and recording of all system characteristics deemed necessary to monitor system operation and effect protective action under abnormal conditions.

**Commentary.** The PV system should be self-operating. During conditions of normal operation, the monitor and control subsystem should check appropriate parameters for inputs to the control circuits and display and record parameters, as necessary, to facilitate normal system operation, maintenance, and repair. The system monitor should also
sense abnormal conditions and, when necessary, initiate appropriate corrective or protective actions and indicate the need for servicing.

SM.E.5 System Disconnects

**Criterion.** The system monitor and control shall cause a visible (positive) disconnect between the system and its on-site loads and utility interconnection.

**Evaluation.** Schematic drawings and specifications shall be reviewed to verify that a positive disconnect is located at the system output and that the monitor and control circuitry can open the disconnect when necessary.

**Commentary.** Conditions may exist within the system, the on-site loads, or the utility grid where the PV system must be disconnected from the utility and loads. In some cases, this may be done for the protection of the system, the on-site loads, the utility, or its personnel. When repair or maintenance work must be done on the system, a visible (positive) disconnect must be used to prevent utility line voltage from being present in the system. Additional disconnects may be necessary to protect personnel from electrical hazards within the PV system (see SY.S.4). Code requirements will vary throughout the country, and some may require a visible (positive) disconnect between the PV system and the on-site load and utility tie. Quenching of arcs in D.C. switching should be adequate for safety purposes.

Thermal Attributes

SM.T.1 System Monitor

Refer to Performance Criteria SM.E.4 and SY.T.1. See below for additional commentary warranting particular attention.

**Commentary.** PV/thermal systems require greater monitoring of operating characteristics than PV only systems. The added thermal subsystem generally includes active mechanical components whose problem/failure may result in excessive temperatures or pressures. Contingency modes of operation, activation of a back-up system to relieve the problem, or notifying an operator that a problem is being experienced and needs resolution are examples of possible protective actions which may be used in abnormal conditions.
REFERENCES


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SECTION 3.0

ARRAY SUBSYSTEM

INTRODUCTION

This section provides performance criteria for elements of the array subsystem hierarchy illustrated in Fig. 3-1. This hierarchy is addressed in four subsections: cells, modules, concentrator optics/receivers, and arrays/array fields. Performance criteria for component elements, such as tracking and control, are subsumed in appropriate subsections. Other elements are not given separate performance criteria because they do not have unique performance attributes. For example, there are no performance criteria for panels because their performance requirements are not sufficiently different from those for modules or arrays.

Essentially all field and laboratory experience to date has been with PV systems using single-crystal silicon wafer technology. This section is based on the history of that technology and, in many cases, the attributes described were chosen to minimize or remove the effect of specific failure modes of single-crystal silicon on system performance. As other photovoltaic systems become commercially available, either they will be judged by these criteria or other criteria will have to be developed. Some criteria developed for single-crystal silicon wafer technology will have to be modified before they can be applied to other technologies, and additional performance criteria may be needed to properly evaluate the new systems. Users of this section will have to determine whether the present criteria apply to systems or devices using other technologies or advances within the single-crystal silicon technology.

The emphasis here has been to prepare criteria and test methods that would prove useful to the photovoltaic community in the near term. A few aspects of silicon technology have not been included because of the lack of present knowledge in a particular area: criteria and test methods for photovoltaic arrays with thermal heat output, some aspects of concentrating arrays, tracking, and control. These methods are now being developed in these and other areas and will be incorporated into later drafts of this document as they become available. The test methods referred to in this section with the code designation TE.A.R. are in Volume II.

SOLAR CELL PERFORMANCE CRITERIA

Electrical Attributes

CE.E.1 Flat-Plate Solar Cell Electrical Output

Criterion. A flat-plate solar cell, under given illumination, shall satisfy specifications for electrical output.

Evaluation. The electrical output of a flat-plate solar cell is characterized by certain parameters determined from the current-voltage (I-V) characteristic curve of the cell. Test TE.A.R.E.1 (Electrical Performance Test—Flat-Plate Cells, Modules, and Arrays) shall be used to determine either the entire curve or some portion of it.

Commentary. The I-V curve determines a great number of cell electrical parameters. These include the short circuit current (I_{sc}), the open circuit voltage (V_{oc}), the maximum
Figure 3-1. Photovoltaic Array Hierarchy
Enclosed for your information and use is the second edition of Performance Criteria for Photovoltaic Energy Systems (PC). The first publication of the PC document was in January 1981. Volume I presents current performance criteria for photovoltaic systems and their elements; Volume II presents existing test methods for verifying given performance criteria.

The document was developed to respond to directives contained in the Photovoltaic Research, Development, and Demonstration Act of 1978 (P.L. 95-590). It supports the National Photovoltaic Program of the Department of Energy by aiding the expeditious development of photovoltaic systems and their use as a viable energy option for the nation. Preparation of the PC was managed by the Solar Energy Research Institute (SERI) for the Department of Energy. SERI, as part of its Photovoltaic Performance Criteria and Test Methods task, enlisted the several elements of the photovoltaic community—manufacturers, users, test laboratories, government laboratories, universities, public interest groups—in both preparation and review of the document.

The PC document was developed to provide a valuable resource for the photovoltaic community. It identifies for photovoltaic systems pertinent performance needs and expectations that can assist in their equitable specification and procurement. The document also provides valuable information related to performance and safety that can be used in system design and application. This document can assist the development of better designed, better characterized, and more reliable systems that will promote greater user confidence.

Although this collection of performance criteria is intended to provide a base for fair and uniform product characterizations and comparisons, it is not a specification. Performance specifications are dictated by specific details of design, usage, or operation of a system or subsystem components. The performance criteria contained within the PC document address user needs or expectations and are statements of what system and subsystem characteristics are important and may need to be evaluated.
This document is meant to be comprehensive in nature and application. By no means will all performance criteria be applicable or necessary for any given system or subsystem. These performance criteria also are not intended for blanket use in regulatory or code documents. Furthermore, care must be exercised in selecting and applying individual criteria. Inappropriate or unnecessary application of performance criteria can lead to needless expense and system complexity; such practice will prevent attaining the goal of cost competitiveness for PV.

It is also important to recognize that this document, with its performance criteria and evaluation statements, is in an evolutionary stage and is subject to modification and refinement as PV technology and experience grow. Several of the test methods in the document are being addressed by appropriate standards writing organizations; in the future others will be. Out of the work of these organizations will come voluntary consensus standards for use by the photovoltaic community.

Your comments and suggestions regarding this document are welcomed.

Sincerely yours,

Gary R. Nuss
Advanced Systems Research

GRN:ml
Enclosure
power \( (P_m) \), the voltage and current at maximum power \((V_m, I_m)\), the cell electrical conversion efficiency \( (\eta_c) \), the curve fill factor \((FF)\) and, for some purposes, the output current at a specified voltage \( (I_v) \). The entire front area of the cell, including grids and contacts, is used in efficiency calculations.

This method may be used for determining either the encapsulated or unencapsulated cell efficiency. Encapsulated cell efficiency \((\eta_{EC})\) is often used to measure the cell's performance when combined with the anticipated encapsulant. It may be measured by contacting a single cell in a module that is illuminated according to Test TE.A.R.E.1.

Various considerations determine whether the entire curve or some portion of it is specified. For example, in a research environment it may be desirable to specify the entire curve and associated output parameters; while in the manufacturing environment it is common to sort cells on the assembly line by examining the current output at a single voltage level. The parameters measured also may be used in the sale or purchase of cells, the matching of cells for assembly into modules (see MO.E.4), solar cell research, and the detection of cell degradation.

Cell output parameters vary with temperature and the level and spectral content of the irradiance. For comparison purposes these are normalized to and reported at a temperature of 28°C, 1000 W/m\(^2\) irradiance, and air mass 1.5 spectrum.

**CE.E.2 Concentrator Solar Cell Electrical Output**

**Criterion.** A concentrator solar cell, under given illumination, shall satisfy specifications for electrical output.

**Evaluation.** The electrical output parameters of a concentrator solar cell are characterized by certain parameters that are determined from the current-voltage \((I-V)\) characteristic curve of the cell. Test TE.A.R.E.2 (Electrical Performance Test—Concentrator Solar Cells) shall be used to determine either the entire curve or some portion of it.

**Commentary.** The I-V curve determines a large number of cell electrical and performance parameters. These include the short circuit current \( (I_{sc}) \), the open circuit voltage \( (V_{oc}) \), the maximum power \( (P_m) \), the voltage and current at maximum power \( (V_m, I_m) \), the cell electrical conversion efficiency \( (\eta_c) \), the curve fill factor \((FF)\) and, for some purposes, the output current at a specified voltage \( (I_v) \). The active area of a concentrator cell for computation of efficiency is the area designed to be illuminated. This area includes interior grids and contacts. The active area may exclude the area of the cell that is covered by contacts at the outer edge of the cell provided the optical system avoids illuminating this area. Both the active area and total area of the cell should be included in the report. If deviations from these are applicable, the method of area and irradiance determination must be completely described.

Various considerations determine whether the entire curve or some portion of it is specified. For example, in a research environment it may be desirable to specify the entire curve and associated output parameters, while in the manufacturing environment it is common to sort cells on the assembly line by examining the current output at a single voltage level. The parameters measured also may be used in the sale or purchase of cells, the matching of cells for assembly into modules, solar cell research, and the detection of cell degradation.
Cell output parameters vary with temperature and the level and spectral content of the irradiance. For comparison purposes, the output parameters are adjusted to and reported at a temperature of 28°C and 1000 W/m² with the reference irradiance spectrum (see glossary). Tables or plots of efficiency and fill factor as a function of incident irradiance (air mass 1.5 spectrum) should be reported for 28°C and for a design operating temperature and irradiance.

**Mechanical/Structural Attributes**

**CE.M.1 Antireflection Coating Integrity**

**Criterion.** The antireflection (AR) coatings of solar cells to be used in either flat-plate or concentrator modules shall be capable of withstanding handling and exposure to water vapor without delamination during fabrication and assembly steps.

**Evaluation.** The acceptability of AR coatings on solar cells shall be evaluated using Test TE.AR.M.9 (Antireflection Coating Adhesion Test—Solar Cells). Changes in the color or delamination of the AR coating will be evaluated.

**Commentary.** AR coatings on solar cells must be able to withstand the cleaning and handling encountered during module manufacturing and be stable even in the presence of moisture throughout the life of the cell. Poorly adhering AR coatings often are destroyed even on encapsulated cells because of moisture. The loss of an AR coating on a silicon solar cell can cause as much as 30%-40% reduction in output power.

Certain cells are constructed of materials that are not intended for any exposure to air and, therefore, are packaged to prevent such exposure. These cells are considered an integral part of the completed module and are tested on the module level.

**CE.M.2 Structural Loading Capability**

**Criterion.** Flat-plate and concentrator solar cells shall be able to withstand steady-state and transient structural loading stresses applied during normal service for their design life.

**Evaluation.** Satisfactory long-term performance shall be documented under in-use conditions. When adequate information is unavailable, fracture mechanics analysis or structural loading tests (see Ref. 1) may be used to evaluate cell structural loading capability.

**Commentary.** Cells can encounter various steady-state and transient structural loading stresses during cell manufacture, module fabrication, shipping, handling, installation, and field use. During cell fabrication, wafers or cells with low fracture-strength distribution are likely to be fractured during subsequent cell processing and handling or in field service. To ensure the adequate strength of cells and provide a margin of safety against cracking under rapid and sustained loading, a proof test is commonly performed at a level somewhat higher than the expected condition. An assessment of several mechanical strength tests for silicon solar cells is given in Ref. 1.
CE.M.3 Contact Metallization Integrity

**Criterion.** Solar cell contact metallization for flat-plate or concentrator modules shall be capable of withstanding the stresses imposed by the attachment and subsequent handling of interconnects during manufacture and service.

**Evaluation.** Contact metallization integrity shall be evaluated by using Test TE.AR.M.8 (Contact Pull Strength [Wire Pull Test]—Solar Cells).

**Commentary.** Solar cells used in flat-plate or concentrator modules must be basically capable of being linked with an interconnector without loss of integrity of cell contacts. Various interconnector attachment techniques and designs are likely to be used by the module manufacturer, but in all cases the basic integrity of the cell contact metallization is required. Since Test TE.AR.M.8 is a destructive test, it is used as a qualification or in-process acceptance test on a sampling basis.

Certain cells are constructed of materials that are not intended to be exposed to air and are therefore packaged to prevent such exposure. The contact metallization integrity may best be determined by applying environmental stress to the completed module. In most cases, Test TE.AR.M.8, used for discrete silicon cells, will be suitable to evaluate the integrity of the provisions made for external contact (terminals).

**Durability/Reliability Attributes**

**CE.D.1 Temperature Cycling**

**Criterion.** Solar cells shall be capable of effectively withstanding the stresses induced by temperature cycling for their design life.

**Evaluation.** Satisfactory long-term performance shall be documented under in-use conditions in the field configuration; i.e., a component of a module or concentrator receiver. When adequate documentation is unavailable, the Solar Cell Temperature Cycling Test (in preparation) may be used to evaluate thermal cycling degradation.

The characteristics to be evaluated for determining temperature cycling withstanding capability include output power degradation and altered physical appearance.

**Commentary.** Array subsystem elements encounter temperature cycling stresses as a result of diurnal and climatic excursions. For various silicon cell types (fabricated with different metallization processes) sensitivity to temperature cycling stresses has varied widely. Some insight into the mechanisms responsible for existing results has been obtained [2].

**CE.D.2 Humidity**

**Criterion.** Solar cells used in either flat-plate or concentrator modules shall be capable of withstanding the effects of humidity.

**Evaluation.** To determine the acceptability of solar cell materials (i.e., contact metals and AR coatings) in the presence of humidity, Test TE.AR.D.3 (Humidity Test—Solar Cells) shall be used, except for those cells packaged to prevent exposure to air and
moisture. For the latter encapsulated cells, the entire encapsulated assembly shall be
tested at the module level with Test TE.A.R.D.4 (Humidity Test—Array Elements).

**Commentary.** Solar cells used in flat-plate or concentrator modules must be able to
withstand exposure to humidity. No matter what the encapsulation technique, short of
complete hermetic sealing, moisture will be present at the solar cell surfaces and con­
tacts. To ensure long-life operation of the module, the solar cell component must be
fabricated using moisture-resistant materials and processes. Therefore, the humidity
resistance requirement is placed on cells to be sealed in nonhermetic packages before
encapsulation.

Certain cells are constructed of materials that should not be exposed to air and, there­
fore, are packaged to prevent such exposure. These cells are considered an integral part
of the completed module and are tested on the module level.

**CE.D.3 Temperature Stress with Voltage Bias**

**Criterion.** Solar cells shall be able to withstand the stresses induced by the combined
effects of voltage bias and high temperature for their design life.

**Evaluation.** Satisfactory long-term performance shall be documented under in-use condi­
tions in the field configuration; i.e., as a component of a module or receiver. When ade­
quate documentation is unavailable, the Solar Cell Temperature Soak with Voltage Bias
Test (in preparation) may be used.

The characteristics to be evaluated for determining temperature stress with voltage bias
tolerance include output power degradation and altered physical appearance.

**Commentary.** From the semiconductor industry and early solar cell efforts, temperature
stress combined with voltage bias has been observed to accelerate a wide range of degra­
dation mechanisms within the devices. As part of an accelerated reliability testing pro­
gram, solar cells of different designs and from different manufacturers have been sub­
jected to various stresses including bias-temperature. The bias-temperature stress
testing showed a wide variability among cell types in their ability to withstand the effect
of the applied stress [15]. Degradation that could be accelerated by current flow, high
temperature, or both, includes junction penetration by metallization, electromigration,
segregation effects, or voiding in the metallization system which in turn could lead to
high series resistance or loss of tab adherence and other metal-related phenomena.

**MODULE PERFORMANCE CRITERIA**

**Electrical Attributes**

**MO.E.1 Module Electrical Output**

**Criterion.** A module, under given illumination, shall satisfy specifications for electrical
output.

**Evaluation.** The electrical output parameters of a module are those parameters deter­
mined from the current-voltage (I-V) characteristic curve of the module. Test
TE.A.R.E.1 (Electrical Performance Test—Flat-Plate Cells, Modules, and Arrays) shall be
used to determine either the entire curve or some portion of it for flat-plate modules. The test method for concentrator modules is in preparation.

**Commentary.** The I-V curve is used to determine a large number of module electrical parameters. These include the short circuit current (I_{sc}), the open circuit voltage (V_{oc}), the maximum power (P_{m}), the voltage and current at maximum power (V_m, I_m), the module electrical conversion efficiency (\eta_C), the curve fill factor (FF) and, for some purposes, the output current at a specified voltage (I_v). The area used in efficiency calculations is the entire front, normally illuminated area of the module, including the frame.

Various considerations determine whether the entire curve or some portion of it is specified. For example, in a research environment, it may be desirable to specify the entire curve and associated output parameters, while in the manufacturing process environment, it is common to sort modules on the assembly line by examining the short-circuit current and the current output at a single voltage level. The parameters measured may also be used in the sale or purchase of modules, the matching of modules for assembly into arrays, and the detection of module degradation.

Module output parameters vary with temperature and the level and spectral content of the irradiance. For comparing flat-plate modules, the output parameters are given at the electrical performance reporting conditions specified in Table B-1 of Test TE.AR.E.1. Reporting conditions are being developed for concentrator modules.

Cell temperatures for combined PV/thermal flat-plate modules are not only functions of outdoor environmental conditions but of fluid conditions as well. For intercomparison of PV/thermal and PV modules, electrical output parameters of the PV/thermal modules should be reported as a function of the cell temperatures obtained from results of Test TE.AR.T.3 (Operating Cell Temperature Determination—Flat-Plate Actively Cooled Modules).

**MO.E.2 Electrical Terminals**

**Criterion.** Electrical terminals for modules and receivers shall be designed and sized to facilitate field servicing and withstand the environmental and service stresses applied during normal service for their design life.

**Evaluation.** Satisfactory performance shall be documented under in-use conditions. When adequate information is unavailable, drawings, specifications, test data, and engineering analysis shall be reviewed and analyzed to verify compliance with the criterion.

**Commentary.** The primary requirements for electrical terminals consist of adequate current and voltage capacity, low ohmic contact resistance, and adequate environmental qualification consistent with low cost. Selection of a specific terminal depends on both site and application. Remote applications will have lower voltage and current requirements than large industrial applications. Environmental qualification consists of the ability to withstand temperature cycling, ultraviolet exposure, humidity, corrosive atmosphere, fungus, and pull loads. More definitive performance criteria for electrical terminals will be included in subsequent revisions of this report.
**MO.E.3 Module and Receiver Fault Tolerance**

**Criterion.** Modules and receivers shall endure commonly occurring circuit faults such as cracked or mismatched cells, single-point open-circuit failures, and nonuniform illumination (partial shadowing) without catastrophic effects, such as major power loss, encapsulant deterioration, or safety hazards.

**Evaluation.** Drawings, specifications, testing, and engineering analysis shall be used to evaluate the fault tolerance of the module circuit [3,4]. Experimental evaluation with artificially introduced fault conditions can also be carried out. Experimental simulation is particularly effective in evaluating module resistance to hot-spot heating.

**Commentary.** Field experience indicates that periodic circuit faults, such as partial shadowing, cracking of cells, and interconnect open circuits, occur even in highly reliable arrays. Under these fault conditions it is desirable to limit the degree of power loss and to ensure that possible hot-spot heating due to reverse biasing does not propagate the fault by such mechanisms as solder melting, encapsulant deterioration, or dielectric degradation.

Hot-spot heating is caused when operating current levels exceed the reduced short-circuit current capability of an individual cell or group of cells in an array circuit. The reduced short-circuit current fault condition can be caused by nonuniform illumination (local shadowing), individual cell degradation due to cracking or soiling, or loss of a portion of a series-parallel circuit due to individual interconnect open circuits. Under this condition, the over-currented cells dissipate power equal to the product of the current and the reversed voltage that develops across the cells. The over-currented cells can be heated to elevated temperatures high enough to melt solder.

These problems can be alleviated by designing redundancy and over-current carrying capability into the cell circuit. Redundant cell contact attachment points and interconnects are useful in reducing the probability of a single-point circuit failure causing an open-circuit or a reduced short-circuit current condition. By-pass diodes, extensive cell paralleling, and a low cell shunt resistance are effective in minimizing hot-spot heating by providing over-current carrying ability [3,4]. Good cell heat sinking and heat resistant encapsulant materials and processes are useful in controlling the effects of hot-spot heating such as gas generation and encapsulant deterioration.

**MO.E.4 Mismatch Losses in Modules and Arrays**

**Criterion.** Electrical mismatch losses caused by combining cells into modules and modules into arrays shall not exceed acceptable levels.

**Evaluation.** Engineering analysis or experimental measurement shall be used to evaluate the extent of mismatch losses [5]. Mismatch losses shall be evaluated by determining the difference between the power output of a cell or module network and the sum of the power output of the individual elements making up the network.

**Commentary.** Because of manufacturing process tolerances, cells and modules of the same design generally have a distribution of electrical performance current-voltage (I-V) characteristics. When a number of cells and modules are combined in series or parallel electrical circuits or both, mismatch losses occur that reduce the overall electrical efficiency of the module/array and may lead to reverse-biasing and hot-spot heating. These
mismatch losses can be controlled by limiting the variation in cell/module performance, by sorting and matching the performance of individual elements, or by using fault tolerant circuit design practices. Fault tolerant circuit design practices (performance criteria in preparation) are also desirable to control subsequent mismatch due to differential aging and other similar processes.

**Temperature Attributes**

**MO.T.1 Cell Temperature Control for Flat-Plate Modules**

**Criterion.** Modules shall be capable of maintaining the operating temperature of their cells at or below the maximum specified cell temperature.

**Evaluation.** Test TE.AR.T.1 (Nominal Operating Cell Temperature Determination—Flat-Plate) shall be used to measure the NOCT of a flat-plate module. Module drawings and specifications shall be reviewed to check that encapsulant materials used will perform for the expected design life. (See Durability/Reliability Attribute MO.D.2, Solar Weathering.)

**Commentary.** Electrical power output of solar cell modules decreases as temperatures increase (e.g., silicon at a rate of approximately 0.5% per °C). Also, higher temperatures will accelerate physical and chemical degradation of the module (e.g., corrosion). These power reductions can be minimized by controlling the cell operating temperature using techniques such as a substrate with high infrared emission, high thermal conductance, and low solar absorption; front cover/encapsulants with thin transparent materials and relatively high thermal conductivity; and avoiding an air gap between the front cover/encapsulant and the cells (i.e., avoiding a greenhouse effect) [12-14].

Fins give a slight advantage (less than 5°C) temperature reduction, but generally are not cost effective. The effectiveness of fins for roof mounting applications depends strongly on the backside air infiltration level. Transparent substrates offer a negligible advantage in open-frame mounting and can be a definite handicap for roof applications due to greenhouse effects. Water cooling offers significant improvement in module performance but is not expected to be cost-effective unless the application already involves heating or pumping water, or unless a gravity water system is feasible. At present, care in thermal design and cost considerations result in a NOCT of 43° to 48°C for open back flat-plate modules.

**MO.T.2 Cell Temperature Control for Concentrator Modules**

**Criterion.** Concentrator modules shall be capable of maintaining the operating temperature of their cells at or below the maximum specified cell temperature.

**Evaluation.** Module drawings and specifications shall be reviewed to see that the cooling mechanism works as expected, aided by Test TE.AR.T.3 (Operating Cell Temperature Determination—Flat-Plate Actively Cooled Modules), as appropriate.

**Commentary.** Because of high concentrations of sunlight, concentrator modules need a cooling system to keep cell interconnects from melting and power degradation from becoming excessive. Two kinds of cooling schemes are presently in use: actively cooled modules using a liquid to cool the cells, and passively cooled modules using cooling fins.
and ambient air. Whether an active or passive scheme is used will depend on application, power requirement, and type of concentrator. Actively cooled modules are attractive in total energy systems where thermal energy is needed. Passively cooled modules will run at higher temperatures than actively cooled modules, but those actively cooled will have parasitic power requirements. As a general rule, parabolic troughs and linear fresnel lens receivers with active cooling are more cost-effective than those with passive cooling; point-focus receivers with passive cooling are more cost-effective than active cooling.

The thermal interface in an actively cooled module provides a means for heat transfer from the cell to a heat absorbing fluid. A good thermal interface consists of materials that have a low thermal resistance. However, most materials that provide low thermal resistance also have low electrical resistances, implying poor electrical isolation (see MO.S.l). Therefore, to ensure proper electrical isolation and a good thermal interface, some accommodations in design are needed. Due to the high heat flux associated with concentrator modules, high thermal resistance causes the cells to operate at excessive temperatures and may damage the cells. If the interface does not provide uniform cooling of the cells, isolated hot spots may also degrade the electrical performance. An inadequately designed thermal interface is one possible reason for measured electrical or thermal performance to be less than expected.

MO.T.3 Thermal Performance for Flat-Plate PV/Thermal Modules

**Criterion.** A combined PV/thermal module shall satisfy its specifications for thermal output.

**Evaluation.** Either the ASHRAE 93-77 Test [16], or the ASHRAE 96-80 Test [17] (whichever is appropriate) shall be used at the module open circuit voltage to specify thermal performance. Thermal performance shall be referenced to average fluid temperature. In order to include the effect of electrical performance on thermal performance, the electrical efficiency shall be subtracted from the thermal efficiency.

**Commentary.** Combined PV/thermal modules have the ability to produce both electrical and thermal energy. For thermal performance the important parameters are derived from a thermal efficiency plot. Average fluid temperature is used for PV/thermal systems instead of the standard practice of using inlet temperature for two reasons: the average fluid temperature is not directly dependent on flowrate, and the average cell temperature is related to average fluid temperature.

It is important to remember that the thermal performance test is run at open circuit voltage so that the module produces no electrical power. To evaluate thermal performance under electrical load, the electrical efficiency should be computed at appropriate conditions (see TE.A.R.E.1 Electrical Performance Test—Flat-Plate Cells, Modules and Arrays) and subtracted from the thermal efficiency. Care must be taken that both efficiencies are referenced to the same area.

MO.T.4 Thermal Stagnation for Flat-Plate PV/Thermal Modules

**Criterion.** A flat-plate PV/thermal module shall be capable of withstanding the maximum anticipated internal temperatures and pressures without unacceptable degradation of performance over its design life.
Evaluation. Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be required. When adequate information is unavailable for module components, the "no-flow" aging procedure described in Test Method 7.2 of NBSIR 78-1305A [18] shall be used along with TE.AR.T.2, where appropriate, to evaluate thermal and electrical degradation.

Commentary. For a PV/T module, the stagnation temperature is reached when cooling fluid is no longer circulating and the irradiance and ambient temperature are at maximum. The maximum internal or stagnation temperature of a PV/T module is a function of the PV/T module geometry, module materials, and the ambient environment in which the module is operating.

For unglazed PV/T modules, stagnation temperatures are about the same as ordinary PV modules. However, some glazed PV/T modules can reach temperatures high enough to melt solder interconnects. Such high temperature PV/T modules should be designed with control systems that prevent a "no-flow" condition (see criteria statement MO.T.2). Design features to look for are materials compatibility, allowance for differential expansion, and materials durability.

Mechanical/Structural Attributes

MO.M.1 Flat-Plate Module Structural Adequacy

Criterion. Flat-plate PV modules shall support all loads expected during the design life of the module without structural failure or significant performance degradation.

Evaluation. The structural adequacy of flat-plate PV modules shall be demonstrated by analysis. Documentation of satisfactory long-term performance under in-use conditions shall be considered contributory evidence of structural adequacy. Additional evidence for modules may be obtained from the following Tests: TE.AR.M1 (Twisted Mounting Surface Test), TE.AR.M.2 (Structural Loading Test—Flat-Plate Modules [Cyclic Pressure Load Test]), and TE.AR.M.3 (Temperature Cycling Test—Flat-Plate Modules).

Commentary. The structural design of frames and structural substrates for modules depends primarily on the wind loading. Wind pressure loads on individual modules will be higher than the net average pressure acting on arrays. The structural design of glass superstrates for flat-plate modules, in many cases, will be dictated by minimum hail-withstanding requirements. For larger annealed glass superstrate modules, normal pressure loads (primarily wind) will control the structural design. Brittle materials, like glass, require design considerations because their strength is a function of surface condition (flaws and scratches), surface area of part, and time duration of loading. Some guidelines for designing glass superstrate PV modules are provided in Ref. 6.

MO.M.2 Concentrator Module Structural Adequacy

Criterion. In any sun-tracking operating mode, the concentrator module shall support design loads (dead weight, wind, earthquake, and constraint loads) without structural failure or performance degradation. In a nonoperating mode or position, the concentrator module shall support all loads expected during the design life of the system without structural failure or subsequent significant performance degradation when the system is returned to an operating condition.
**Evaluation.** The structural adequacy of concentrator modules shall be demonstrated by structural analysis. Documentation of satisfactory long-term performance under in-use conditions shall be considered contributory evidence of structural adequacy.

**Commentary.** Wind loading is recognized as a primary structural cost driver for concentrator modules. In some applications it may be cost-effective to take advantage of the reduced wind loading resulting from boundary layer effects near the ground (shielding from adjacent rows of arrays or wind shielding devices) provided that the increased cost of supporting analysis and documentation is defrayed by decreased structural costs. In connection with concentrator modules, it is appropriate to distinguish between operating and nonoperating loads. The operating loads occur while the array is in a sun-tracking mode. Operating wind loads, for example, may be less than nonoperating wind loads, because studies have shown that virtually all of the sun's irradiance occurs during periods when relatively low wind speeds exist. The operating loads (dead weight—thermal and wind) will significantly influence the structural design of the receiver and concentrator module because the optical quality and alignment of the concentrator module will be affected by these loads. Nonoperating loads occur at any time during the design life of the array. Concentrator modules must withstand these loads without structural failure, and permanent deformations of the concentrator module should not excessively reduce its ability to collect solar energy.

MO.M.3 Shipping (see SY.M.1)

MO.M.4 Handling (see SY.M.2)

MO.M.5 Attachment Provisions for Flat-Plate Modules

**Criterion.** Attachment of flat-plate modules to their intended supporting structure shall not result in deflections, stress points, or mechanical interferences of component parts that degrade the performance of the module over its design life.

**Evaluation.** Engineering analysis and drawings shall be reviewed to determine conformance with standardized codes and recommended practices for strengths of materials, flatness of surfaces, location, and clearances associated with mounting hardware (e.g., see ANSI-Y 14.5).

**Commentary.** Module mounting on support structures may use a variety of techniques ranging from aligned through-holes fasteners to adhesive bonding. To minimize problems in attaching modules to the supporting structure, the following factors affecting attachment should be reviewed: flatness of the mating interfaces of structure and modules, spacing allowances to adjacent modules, tolerances on sizes and locations of fasteners, and load-carrying capability of the fastening or attachment device. These factors should guarantee that no unacceptable deflections, stress points, or mechanical interference of component parts be experienced by the modules upon attachment to the intended supporting structure. An example of a standard design practice from ANSI-Y 14.5 that may be applicable is drilling holes for mounting materials. This standard practice calls for the hole to be drilled at least 1.5 diameters from the edge of the material. This practice is for single-piece materials (modules without frames) and is intended to minimize shear stress loads. For modules with metal frames around the edges (that provide more rigidity), holes can be closer to the edge.
**MO.M.6 Twist Capability of Flat-Plate Modules**

**Criterion.** Flat-plate PV modules shall be able to withstand small twists caused by mounting on a nonplanar surface.

**Evaluation.** Satisfactory performance shall be documented during normal field installation. When adequate information is unavailable, engineering analysis or the Twisted Mounting Surface Test, TE.AR.M.1, may be used.

**Commentary.** The intent of this criterion is to preclude damage to a module caused by the possible twisting of the module substrate when installed on a primary structure that is not entirely planar. An alternate approach would be to specify a stringent planar requirement for the primary structure. However, when module costs are reduced, structural costs for such a requirement would be unreasonably high. Current modules show no difficulty in tolerating small amounts of twist (≤1.25°) when the twist test is performed.

**MO.M.7 Interconnect Stress Relief**

**Criterion.** Electrical interconnects between cells in modules and in receivers shall be able to withstand environmentally induced stresses applied during normal service for their design life.

**Evaluation.** Satisfactory long-term performance shall be documented under in-use conditions. Module drawings and specifications shall be reviewed to check that materials will be thermally compatible and those used for interconnections will last the design life. When adequate information is unavailable, Tests TE.AR.M.2 (Structural Loading Test—Flat-Plate Module [Cyclic Pressure Load Test]), TE.AR.M.3 (Temperature Cycling Test—Flat-Plate Modules), or TE.AR.M.4 (Temperature Cycling Test—Concentrator Modules) shall be used to evaluate the effect of cyclic loading on interconnects.

**Commentary.** Receiver and flat-plate module interconnections can encounter various loading stresses depending on the construction of the array in which they are installed. The primary sources of movement due to structural deflection of the array are caused by positional changes during tracking; environmental loading due to wind, hail, and ice; and relative positional changes between the array structure and the supporting foundation. Induced fatigue is not immediate but will occur over a long period of time. Differences in thermal expansion coefficients of the solar cells, interconnects, encapsulants, and receiver supporting structure will also cause stress. Fatigue often occurs at the solder connection between the interconnect and the cell. Concentrator receiver interconnects differ from flat-plate interconnects in that the former are typically longer and wider and carry higher currents than the latter.

Techniques that are useful in reducing stress levels include reducing interconnect thickness; increasing expansion loop height; increasing the distance (and thereby the interconnector length) between attachments to the cells by measuring across the intercell gap; selecting a material with a higher endurance limit; modifying the lateral dimension of the interconnector loop so that maximum bending no longer concentrates at a single point on the loop; and preventing solder from filling (wicking) and stiffening expansion loop radii [7].
MO.M.8 Hail

**Criterion.** Modules and their exposed elements shall resist the impact of hailstones expected at the site without significant damage or major impairment of the functioning of the module or its optical elements.

**Evaluation.** Engineering analysis, based on an assessment of the environmental conditions at the specific site of interest, a comparison with test results from proven designs, or the Tests TE.AR.M.5 (Hail Test—Flat-Plate Modules) and TE.AR.M.6 (Hail Test—Concentrator Modules) may be used to evaluate the ability of modules and concentrator optics to withstand specified levels of hailstone impact.

**Commentary.** The intent is to preclude damage that would result in curtailment of module electrical performance or result in premature failure. Susceptible points on a flat-plate module include corners and edges, cell edges, and substrate supports; on a concentrator module, susceptible points are corners and edges of glass reflective surfaces and cover plates on receivers. The optical elements of concentrator systems may be fractured or dented by hailstones and functionally degraded.

Hailstone size depends to a great extent on site. Therefore, environmental conditions at a specific site should be assessed before the design. The methodology given in Ref. 8 can aid in that assessment. In lieu of site-determined hailstone size, Ref. 8 or 9 may be used as a guide in establishing the hailstone size for a particular application. For assessing risks to solar collectors, the U.S. Department of Housing and Urban Development (HUD) [9] has recommended using a hailstone diameter equal to 8 mm (0.3 in.) times the average number of hail days per year at the specific site.

Vulnerability to this environment may be reduced by appropriate material selection and structural design. Reference 10 may be useful in determining the damage potential of various hailstone sizes on glass sheet.

MO.M.9 Optical Surface Soiling

**Criterion.** Optical elements of modules, including receivers and optics, shall not retain dirt to an extent that would significantly impair the function of the photovoltaic equipment during its design life.

**Evaluation.** Satisfactory long-term performance shall be documented under in-use conditions. When adequate documentation is unavailable, engineering analysis or an outdoor soiling test may be used to evaluate optical surface soiling degradation. The characteristics to be evaluated for determining soiling withstand capability include output power degradation (specifically, changes in short-circuit current) and optical obscureness.

**Commentary.** The effect of retained dirt on optical surfaces of photovoltaic equipment is significant; e.g., flat-plate modules have experienced up to 60% power degradation after outdoor exposure. The optical loss results from absorption and scattering by particulates that collect on and may even become embedded in the surface. Particulates impinge on an optical surface through complex fluid mechanical interactions between the dust-laden atmosphere and the photovoltaic equipment. Initial particle adhesion is dominated by surface energetics. However, condensed water vapor at the particle-surface interface provides a vehicle for soluble components and dirt to form very strong chemical and physical bonds between the dirt and the surface. To keep the surface of the
module free from dirt, the illuminated optical surface(s) should be smooth and generally free of projections that could promote entrapment of dust and other debris. Particular attention should be given to the selection of materials that will minimize the accumulation of nonremovable contaminants, particulates, and stains on the optical surface. Also, materials should be used that will promote self-cleaning by natural processes like wind and rain. Field experiments with modules and top cover materials in different geographical locations indicate significant time and site dependence. Removal mechanics (such as rain and snow melt) are the key to long-term soiling differences [11]. While an acceptable laboratory test method is desirable, research work to date indicates soiling to be a very complex problem and development of a testing method in the near term is not envisioned. Side-by-side outdoor exposure testing for long periods of time at a variety of sites is currently the most effective way to evaluate soiling differences. See AR.I.3 Commentary for representative module cleaning procedures.

MO.M.10 Cleaning Tolerance

Criterion. Surfaces of modules, including receivers and concentrator optics, shall be able to withstand periodic cleaning during normal service for their design life.

Evaluation. Satisfactory performance under in-use conditions shall be documented. When adequate information is unavailable, drawings, specifications, engineering analyses, and the manufacturer's recommended practice shall be reviewed and analyzed.

Commentary. Cleaning of optical surfaces can cause marring and scratching of those surfaces to the extent that the electrical performance of the module is significantly affected. Optical surface materials should be selected that tolerate physical and chemical (e.g., solvents and detergents) cleaning techniques. Generally, manufacturers are expected to supply cleaning instructions for the optical surfaces of their products. With the cleaning instructions, the manufacturer should indicate any precautions necessary to take with either cleaning fluids or cleaning procedures. See AR.I.3 Commentary to representative module cleaning procedures.

MO.M.11 Off-Axis Survival of Concentrator Module and Receiver

Criterion. The concentrator module and receiver shall not be damaged due to concentrated sunlight traversing off the normally illuminated receiver during normal operating conditions (e.g., sun acquisition or de-steering operations) or abnormal operating conditions (e.g., tracking motor power failure).

Evaluation. Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be used to evaluate potential degradation. The characteristics to be evaluated are the use of materials that may be combustible and ignite, or soften or melt, thus impairing the mechanical integrity of the module.

Commentary. Concentrator modules and receivers can encounter complex steady-state and transient thermal loading during off-axis pointing. Depending on the specific concentrator optics chosen, the energy distribution can be highly nonuniform and may reach very high levels of concentration in localized areas. Depending on the nature of the off-axis condition (i.e., whether the array is moving or stopped) the module may be exposed to intense energy concentrations for extended periods of time.

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MO.M.12 Materials Compatibility

**Criterion.** Materials used in modules, receivers, and concentrator optics and the building elements with which they interact shall have sufficient chemical compatibility to prevent corrosive wear and deterioration that would significantly shorten their intended service life.

**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be used. When adequate information is unavailable, tests shall be performed.

**Commentary.** Dissimilar materials used in modules, concentrator receivers, and optics can be incompatible when exposed to the thermal extremes and humidity of the environment, or when they come in contact with corrosive chemicals such as heat transfer and other fluids. When several different materials come in contact in an outside environment, a corrosive electrochemical couple can destroy the components quite rapidly if the proper selection of materials is not made. When dissimilar materials are used in contact with heat transfer or other fluids, testing to evaluate compatibility is suggested.

The use of protective finishes, corrosion inhibitors, or dielectric fittings that electrically isolate dissimilar materials may be desirable. For plastics, plasticizer migration may be a concern. The presence of pinholes in protective coatings may drastically accelerate corrosive action. In considering the compatibility of dissimilar materials, all elements of a solar system should be evaluated—including the energy transport system, structural support and connections, fabricated parts, and roofing materials.

MO.M.13 Physical Deterioration of Gaskets, Sealants, and Polymeric Coupling Hoses (See CR.M.4)

MO.M.14 Compatibility of Materials with Heat Transfer Fluids (See CR.M.5)

MO.M.15 Deterioration of Fluids or Phase-Change Materials (See CR.M.7)

MO.M.16 Effects of Decomposition Products (See CR.M.8)

MO.M.17 Corrosion by Leachable Substances (See CR.M.6)

MO.M.18 Cell Temperature Control for Flat-Plate Modules (Recoded to MO.T.1)

MO.M.19 Piping for Pressurized Fluids (See SY.M.3)

**Safety Attributes**

MO.S.1 Electrical Voltage Isolation

**Criterion.** PV modules shall provide an electrical insulation system to isolate live circuit elements and protect against human injury or performance degradation due to electrical shock or short circuits to the module mounting structure.
Evaluation. Review of model drawings and specifications shall indicate conformance with the system voltage level and with the electrical safety protection system of the intended class or range of applications. To verify adequacy of the insulation systems, Test TE.AR.M.10 (Dielectric Voltage Withstand Test), leakage current tests (in preparation), and insulation resistance tests (in preparation) shall be conducted on representative samples both before and after environmental exposures.

Commentary. The insulation system shall be compatible with the intended class or range of applications of the module (including system safety provisions such as array grounding, lightning protection, and ground fault detection/interrupters) and with its installation, operation, and maintenance procedures. A fundamental requirement of the encapsulation and insulation system of photovoltaic devices is that it withstand the voltage imposed on it in service throughout its design life. To ensure the adequacy of the insulation system and provide a margin for degradation from aging, it is common practice to select a test voltage level for the Dielectric Voltage Withstand Test that is somewhat higher than the expected service condition. Test levels commonly used by institutions such as Underwriters Laboratories (UL) are:

- 1000 V plus twice the maximum rated voltage of the insulation system for systems with rated voltage levels above 50 V; and
- 500 V for insulation systems with rated voltage levels below 50 V.

As a measure of the extent to which the Dielectric Voltage Withstand Test has stressed the insulation system, a maximum allowable leakage current of 50 µA during the test is usually specified.

Insulation resistance tests are typically conducted with the module insulation system subjected to a test voltage equivalent to the system operating voltage. The required minimum insulation resistance of 50 kΩ is consistent with UL recommendations for keeping shock sensation below "let-go" current levels.

MO.S.2 Flammability

Criterion. Modules and arrays forming or attached to roofs shall not reduce the required fire resistance of roof covering materials.

Evaluation. UL Standard 790, Tests for Fire Resistance of Roof Covering Materials, shall form the basic test procedure.

Commentary. UL 790 does not specifically detail the testing of a photovoltaic array as part of the roof covering, although the types and methods of fire exposure and the conditions of acceptance for classification may be applied to a particular PV assembly. A proposed UL Standard 1279, Standard for Solar Collectors, will contain information on testing solar collectors that may be applicable to photovoltaic arrays.

MO.S.3 Toxic Materials Release

Criterion. A PV module, under operating conditions, shall not release toxic substances which result in chemical concentrations exceeding those specified by OSHA 29 CFR 1910 Table Z, or the American Conference of Governmental Industrial Hygienists Threshold Limit Values (TLVs) [19].
Evaluation. Module designs should be analyzed to determine what toxic substances in what concentrations might be released during operation or failure.

Commentary. It is not anticipated that current module designs will give off dangerous quantities of toxic substances or harmful materials. The release of materials would most likely occur in the event of fire. Present module designs are such that fires are not spread from module to module, but are restricted to the burning module. Future designs, however, may incorporate materials in either cell or module fabrication which could release toxic components. Two examples of this are the possible release of $\text{As}_2\text{O}_3$ or CdS in the event of a fire involving GaAs or CdS modules, respectively. Care should be taken in the design to minimize release of toxic substances under catastrophic failure conditions. Since modules are used in an outdoor environment, the concentration of released materials will be low due to rapid dilution. Analyses should be made to protect servicing personnel during normal operating conditions and to warn people such as firefighters of potential dangers during catastrophic failure. An excellent review of industrial- and installation-related toxic materials generation is contained in Ref. 20. Toxic effects of cadmium are discussed in Ref. 21.

Durability/Reliability Attributes

MO.D.1 Temperature Cycling

Criterion. Modules shall be capable of withstanding the stresses induced by temperature cycling for their design life without significant degradation of module performance.

Evaluation. Satisfactory long-term performance under in-use conditions shall be documented. When adequate information is unavailable, engineering analysis or the Tests TE.AR.M.3 (Temperature Cycling Test—Flat-Plate Modules) or TE.AR.M.4 (Temperature Cycling Test—Concentrator Modules) shall be used to evaluate thermal cycling degradation. The characteristics to be evaluated for determining temperature cycling withstand capability include output power degradation and altered physical appearance.

Commentary. Modules encounter temperature cycling stresses as a result of diurnal and climatic excursions. Susceptible parts of the module include the encapsulant system, cells, interconnects, and bonding materials.

MO.D.2 Solar Weathering

Criterion. Modules, receivers, concentrator optics, and their components and materials shall not be affected by exposure to solar irradiance in service to an extent that will significantly impair their function during their design life.

Evaluation. Documentation of satisfactory long-term performance under in-use conditions, acceptable test results, or engineering analysis shall be required. Where adequate documentation is unavailable, Tests TE.AR.D.1 (Solar Radiation Weathering Tests—Materials and Components) and TE.AR.D.2 (Solar Radiation Weathering Tests—Modules) may be used. The characteristics to be evaluated for determining solar weathering capability include output power degradation and physical appearance alteration. A test method is being developed for concentrator receivers.
Commentary. Conformal polymeric encapsulants, organic potting materials, adhesives, and organic adhesion-promoting treated materials are particularly susceptible to solar ultraviolet-induced weathering under prolonged exposure. Field observations have shown the occurrence of delamination of cell-encapsulants substrate-superstrate, encapsulant-substrate and encapsulant-cover interfaces, carbonation, cell-cracking, encapsulant discoloration, and contact corrosion.

Moisture (rain, dew, high humidity, condensation) and dust, in combination with solar ultraviolet radiation, are principal agents in producing adverse synergistic degrading effects in materials. This has led to the inclusion of water spray and moisture cycles in accelerated and simulated exposure test methods.

The use of diagnostic tests, including baseline photographs, transmittance data of cover materials, and electrical performance characteristics ($I_{sc}$, $V_{oc}$, I-V curves, $P_m$, etc.) are usually required to estimate the effects of exposure-induced degradation in reducing module efficiency and operating characteristics.

MO.D.3 Humidity

Criterion. Modules, receivers, concentrator optics, and tracking controls shall be capable of withstanding the stresses induced by humidity for their design life without significant performance degradation.

Evaluation. Documentation of satisfactory long-term performance under in-use conditions shall be required. When adequate documentation is unavailable, engineering analysis or Test TE.A.R.D.4 (Humidity Test—Array Elements) shall be used to evaluate humidity degradation. The characteristics to be evaluated for determining humidity withstand capability include output power degradation and physical appearance alteration for modules and receivers, optics obscurity or altered alignment for concentrator optics, and functional performance degradation for tracking control.

Commentary. Humidity, which is one form of atmospheric water vapor, can significantly degrade the performance of photovoltaic equipment as a result of moisture migration and penetration. High relative humidity at elevated temperature can be especially stressful.

Corrosion can be accelerated by humidity. Hygroscopic materials are sensitive to moisture and may deteriorate rapidly under humid conditions. Absorption of moisture by many materials results in swelling that destroys their function and causes loss of physical strength and changes in other important mechanical properties. Insulating materials that absorb moisture may suffer degradation of their electrical and thermal properties. Cycling temperature and humidity may cause condensation of moisture inside the equipment that could cause malfunctions resulting from electrical shorts. Such cycling may cause (1) dulling or obscuring of reflecting or transmitting optics; or (2) corroding of cell metallizations or terminals.

MO.D.4 Rain

Criterion. Modules, receivers, and concentrator optics shall be capable of withstanding exposure to rain for their design life without significant performance degradation.
**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions shall be required. When adequate documentation is unavailable, engineering analysis or the Rain Test (in preparation) shall be used to evaluate rain tolerance. The characteristics to be evaluated for determining rain withstand capability include output power degradation and altered physical appearance.

**Commentary.** Rain can degrade the performance of modules and receivers because of moisture penetration. Absorption by many materials results in swelling, which may degrade performance, cause loss of physical strength, and affect other important mechanical properties. Insulating materials that absorb moisture may suffer degradation of their electrical and thermal properties.

**MO.D.5 Electrical Terminals (See MO.E.2)**

**Installation, Operation, and Maintenance Attributes**

**MO.I.1 Physical Interchangeability**

**Criterion.** Modules of the same model by the same manufacturer shall be physically interchangeable.

**Evaluation.** Drawings and specifications of the module shall be reviewed to see that modules are interchangeable.

**Commentary.** The intent of this criterion is to provide reasonable assurance that modules placed in the field can be installed, replaced, and operated with a minimum amount of handling by field personnel. Tolerance on all external module dimensions shall be maintained at a level consistent with module interchangeability. Surfaces, mounting holes, and any attachment interfaces shall be maintained within the tolerance specified in the interface control drawings.

**MO.I.2 Access for Maintenance (See SY.I.3)**

**MO.I.3 Field Monitoring (See AR.I.6 and SY.I.2)**

**MO.I.4 Electrical Interchangeability**

**Criterion.** Installation or replacement modules of the same model in an array source circuit shall not cause circuit power performance to fall below specified levels due to electrical incompatibility. (See also MO.E.4.)

**Evaluation.** Electrical interchangeability shall be determined by engineering analysis of electrical drawings, specifications, and electrical output data. Test TE.ARE.1 (Electrical Performance Test—Flat-Plate Cells, Modules, and Arrays) shall be used to provide electrical output data. The test methods for concentrator modules are in preparation.

**Commentary.** This criterion is intended to provide assurance that modules connected into an array circuit source either as original equipment or as replacements will not
adversely affect array performance. Unless modules are electrically interchangeable, current limiting, hot-spot heating, and catastrophic failure of the array source circuit could result.

Acceptable electrical interchangeability of modules within array source circuits of flat-plate array fields is obtained by the following procedure:

- At module acceptance inspection, current-voltage (I-V) characteristics are evaluated and each module is assigned to a short circuit current group. The current range for each group is an incremental percentage of the nominal short circuit current ($I_{sc}$), typically 5%. This group is further separated into incremental current subgroups, typically 2-1/2%, at the acceptance test voltage, usually the nominal operating voltage.
- At the time of field installation, only modules from the same subgroup are wired into any single string array source circuit.
- When an array source circuit is made up of multiple strings of modules that are paralleled at intervals integral to the array source circuit, all of the modules in each string within a series block should be of the same subgroup, but the other strings of that series block do not have to be the same group or subgroup as long as the total parallel current of that series block is equivalent to the array source circuit current.

CONCENTRATOR OPTICS/RECEIVER PERFORMANCE CRITERIA

Electrical Attributes

CR.E.1 Receiver Electrical Output

**Criterion.** A receiver, under given illumination, shall satisfy specifications for electrical output.

**Evaluation.** The electrical output of a receiver is characterized by certain electrical output parameters determined from the current-voltage (I-V) characteristic curve of the receiver. Test TE.AR.E.2 (Electrical Performance Test—Concentrator Solar Cells) shall be used to determine either the entire curve or some portion thereof.

**Commentary.** The electrical output parameters of a receiver include the short-circuit current ($I_{sc}$), the open-circuit voltage ($V_{oc}$), the maximum power ($P_{m}$), the voltage and current at maximum power ($V_m, I_m$), the cell electrical conversion efficiency ($\eta_C$), the curve fill factor (FF) and, for some purposes, the output current at a specified voltage ($I_v$).

The active area of a receiver for computation of efficiency is the area designed to be illuminated. This includes interior grids, contacts, and gap between cells. The active area may exclude the area of the cells covered by contacts at the outer edges of the receiver, provided that it is reasonable to expect the optical system to avoid illuminating these areas. Both the active area and the total area of the receiver should be included in the report.

Receiver output parameters vary with temperature and with the intensity and the spectrum of the irradiance. Receiver electrical performance reporting conditions are being developed.

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CR.E.2 Electrical Terminals (See MO.E.2)

CR.E.3 Module and Receiver Fault Tolerance (See MO.E.3)

Mechanical/Structural Attributes

CR.M.1 Attachment Provisions

**Criterion.** The provisions for attaching a replaceable receiver to the support structure shall not cause significant out-of-focus distortions of the receiver when it is subjected to the operating mode structural load.

**Evaluation.** Documentation of satisfactory long-term experience under in-use conditions shall serve as the primary evaluation method. When adequate information is unavailable, design drawings, specifications, and engineering analyses shall be used to evaluate the receiver attachment provisions with respect to the aforementioned criteria.

**Commentary.** Receiver attachment provisions must accommodate the various structural specified loading conditions. In particular, these attachment provisions shall minimize the constraint forces acting on the receiver because of temperature changes and any other differential movement between the receiver and the support structure. Since the field removal and replacement of a defective receiver can be anticipated at some time during the life of the system, these attachment provisions shall be designed to permit expeditious replacements, without disturbing the operation of other modules in the field.

CR.M.2 Off-Axis Survival of Concentrator Module and Receiver (See MO.M.11)

CR.M.3 Materials Compatibility (See MO.M.12)

CR.M.4 Physical Deterioration of Gaskets, Sealants, and Polymeric Coupling Hoses

**Criterion.** Gaskets, sealants, and polymeric coupling hoses, whether dry or in direct contact with heat transfer fluids, shall not have their physical properties adversely affected by contact with these fluids to the extent that their functioning is significantly impaired during their design life.

**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be required. Acceptability of gaskets and sealants shall be determined by the methods outlined in ASTM D 3667-78 and in Appendices B and C of NBSIR 77-1437. Where adequate information is unavailable, coupling hoses may be tested using methods that meet the criterion.

**Commentary.** Gaskets, sealants, polymeric coupling hoses, and similar organic materials frequently swell when exposed to liquids and, thus, may lose their ability to function.

The joints near coupling hoses are a potential source of leakage; therefore, the selection of coupling hoses and clamps is quite critical. Many failures have been noted with clamping hoses having screw or spring-type clamps. The hose tends to harden beneath the clamp when the hose is exposed to high temperatures, causing it to lose resiliency and leak. Further tightening of the clamps temporarily stops leakage but aggravates hardening. This results in a hard, nonresilient ring under the clamp that can no longer be...
tightened. Silicone rubber hoses and EPDMs (Ethylene-Propylene-Diene Monomers), if properly vulcanized, tend to maintain their resiliency. The silicone rubber hoses, however, tend to be so pliable that if screw-type clamps with perforated bands are used, the material is extruded through the perforations in the band. In this case, smooth band clamps also should be used.

CR.M.5 Compatibility of Materials with Heat Transfer Fluids

**Criterion.** Materials designed to be used in contact with heat transfer fluids shall not be corroded or otherwise adversely affected by these fluids to the extent that their function will be significantly impaired under in-use conditions during their design life.

**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be required. Acceptability of gaskets and sealants shall be determined by the methods outlined in Appendix B of NBSIR 77-1437. Where adequate information is unavailable, materials may be tested using methods that meet the criterion.

**Commentary.** Corrosion of metals by heat transfer fluids could be a serious problem in solar energy systems. The Society of Automotive Engineers (SAE) Standard J447, "Prevention of Corrosion of Metals," provides guidance in preventing corrosion. Experience indicates that tight closed-loop systems help.

Any use of inhibitors should be keyed to the characteristics of all elements of the energy transport system to which they are exposed, including collectors, piping, connectors, tanks, pumps, valves, and heat exchangers. With nontoxic heat-transfer fluids, inhibitors should be selected to maintain desired fluid properties. (See CR.M.6.)

CR.M.6 Corrosion by Leachable Substances

**Criterion.** Chemical substances that can be leached by moisture from any of the materials within the system shall not cause corrosive deterioration of solar components or building elements that would significantly impair their function over their design life.

**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be required. Where adequate information is unavailable, testing methods that meet the criterion shall be used.

**Commentary.** Salts that can be leached by moisture from some types of glass fiber and mineral wool insulation or from organic components may cause corrosion of nearby system components. Chlorides or sulfates are of particular concern in regard to metallic corrosion. Corrosion of solar components can also be caused by substances leached from roofing materials.

CR.M.7 Deterioration of Fluids or Phase-Change Materials

**Criterion.** Fluids or phase change materials shall not freeze, give rise to excessive precipitation, lose their homogeneity, boil, change absorptivity, or change pH or viscosity beyond design ranges when exposed to their maximum and minimum service temperatures and pressures during design life.
**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions or engineering analysis shall be required. Where adequate information is unavailable, testing methods that meet the criterion shall be used.

**Commentary.** Although boiling can be prevented by pressurization, excessive temperature can break down some constituents of the fluid to form organic acids. Buffers can counter the pH balance but only until they are exhausted. Some changes in pH are acceptable, but when the allowable range is exceeded, the transfer fluid or the buffers must be renewed. This can be an acceptable maintenance requirement.

Thermal cycling may cause precipitation to occur that may lead to a build-up of solids in pump seals and valve seats and cause a malfunction.

If they are taken into consideration in the design, viscosity changes may lead to pumping problems (such as excessive pumping power requirements or overheating).

**CR.M.8 Effects of Decomposition Products**

**Criterion.** Chemical decomposition products that are expelled from solar components or building elements under in-use conditions shall not cause the degradation of solar components or building elements to an extent that would significantly impair their function over their design life.

**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions shall be required. Where adequate information is unavailable, engineering analysis or testing methods that meet the criterion shall be used.

**Commentary.** Although components and materials such as gaskets, sealants, and coatings may yield degradation products during their service life without impairing their function or aesthetic properties, these degradation products could significantly impair the performance of other components in the system.

Heat transfer fluids, including inhibited water, may decompose and cause scale build-up that may cause deterioration. This is particularly true of hot water heaters where supply water is heated directly in the collector and dissolved solids (calcium salts) precipitate.

**CR.M.9 Interconnect Stress Relief (See MO.M.7)**

**CR.M.10 Piping for Pressurized Fluids (See SY.M.3)**

**Durability/Reliability Attributes**

**CR.D.1 Temperature-Humidity Cycling Stresses**

**Criterion.** Receivers shall be capable of withstanding the stresses induced by temperature-humidity cycling for their design life without significant performance degradation.

**Evaluation.** Documentation of satisfactory long-term performance under in-use conditions shall be required. When such documentation is unavailable, the Test TE.ARM.7 (Temperature/Humidity Cycling Test—Concentrator Receiver) shall be used to evaluate receivers. The characteristics to be evaluated shall include output power degradation and altered physical appearance.
**Commentary.** Receivers will encounter the combined effects of temperature-humidity cycling stresses as a result of diurnal and climatic excursions. Temperature and humidity may combine to produce effects that could not be caused by either one alone. These include temperature- and moisture-induced expansion of plastics and freeze-thaw effects. Susceptible parts of the receivers include cells, interconnects, encapsulant systems, and bonding materials. To determine satisfactory long-term performance under in-use conditions, a five-year minimum of actual environmental evaluation is suggested.

**CR.D.2 Electrical Terminals (See MO.E.2)**

**CR.D.3 Solar Weathering (See MO.D.2)**

**CR.D.4 Humidity (See MO.D.3)**

**CR.D.5 Rain (See MO.D.4)**

**CR.D.6 Temperature Cycling (See MO.D.1)**

**Installation, Operation, and Maintenance Attributes**

**CR.I.1 Field Monitoring (See AR.I.6)**

**ARRAY/ARRAY FIELD PERFORMANCE CRITERIA**

**Electrical Attributes**

**AR.E.1 Array Electrical Output**

**Criterion.** An array, under given illumination, shall satisfy specifications for electrical output.

**Evaluation.** The electrical output of an array is characterized by certain electrical output parameters that are determined from the current-voltage (I-V) characteristic curve of the array. Test TE.AR.E.1 (Electrical Performance Test—Flat-Plate Cells, Modules, and Arrays) shall be used to determine either the entire curve or some portion thereof.

**Commentary.** The I-V curve is used to determine a large number of array electrical parameters. These include the short-circuit current (I_sc), the open-circuit voltage (V_oc), the maximum power (P_mp), the voltage and current at maximum power (V_mp, I_mp), the array electrical conversion efficiency (\(\eta_c\)), the curve fill factor (FF), and, for some purposes, the output current at a specified voltage (I_v). The entire front area of the array, including the frame, is used in efficiency calculations.

The parameters measured also may be used in the sale or purchase of arrays, the matching of arrays for assembly into array fields, and the detection of array degradation. The array may represent a source of high power output, and, as such, it may be impractical to measure a complete I-V curve. To interconnect arrays and match them to a given load, it is often desirable to determine the current at a single voltage level.
The values of the array output parameters vary with the temperature and irradiance conditions. For comparison of flat-plate arrays, output parameter values are normalized to and reported at the electrical performance reporting conditions specified in Table TE.A.R.E.1-a of Test TE.A.R.E.1. Reporting conditions are being developed for concentrator arrays. The physical size of many arrays precludes indoor measurement of the output parameters and, hence, these parameters are often determined under outdoor illumination.

**AR.E.2 Array Field Electrical Output**

**Criterion.** An array field shall have an electrical output under illumination that satisfies specifications.

**Evaluation.** The electrical output of an array field is characterized by certain electrical output parameters that are determined from the current-voltage (I-V) characteristic curve of the array field. This curve, or some portion of it, may be determined from a direct measurement of the array field according to Test TE.A.R.E.1 (Electrical Performance Test—Flat-Plate Cells, Modules, and Arrays) or from engineering analyses of the I-V curves of measurable portions of the array field. The test method for determining current-voltage characteristics of concentrators is in preparation.

**Commentary.** The electrical output parameters of an array field include the short-circuit current ($I_{sc}$), the open-circuit voltage ($V_{oc}$), the output current at a specified voltage ($I_v$), the maximum power ($P_m$), the voltage and current at maximum power ($I_m, V_m$), and the electrical conversion efficiency ($\eta_C$). The area used in conversion efficiency calculations to reflect land utilization is defined by the line connecting the outer bounds of the arrays in the array field projected on the horizontal.

These electrical output parameters may be used to monitor performance, detect any degradation of the array field, and compare performance with other array fields. Because the array field represents a source of high power output, it may be impractical to measure a complete I-V curve. In this case, an I-V curve may be determined from measurements or data from individual branch circuits or other measurable parts of the array field.

The values of the electrical output parameters of an array field vary with temperature and irradiance. For comparison of flat-plate arrays, output parameter values may be normalized to and reported at the electrical performance reporting conditions specified in Table TE.A.R.E.1-a of Test TE.A.R.E.1. The physical size of the array field requires the electrical parameters to be measured outdoors. The methods presently available to normalize the measured or determined parameters to the standard reporting conditions may not be accurate.

**AR.E.3 Lightning Protection (See SY.E.8)**

**AR.E.4 Array Capability (See SY.E.4)**

**AR.E.5 Mismatch Losses in Modules and Arrays (See MO.E.4)**
Mechanical/Structural Attributes

**AR.M.1 Flat-Plate Array Structural Adequacy**

**Criterion.** Flat-plate arrays shall support all loads expected during the design life of the system without structural failure or significant performance degradation.

**Evaluation.** The structural adequacy of the array structure for a given application shall be demonstrated by structural analysis. Documentation of satisfactory long-term performance under in-use conditions shall be considered contributory evidence of structural adequacy.

**Commentary.** The loading criteria to be used in evaluating the array structure are primarily dependent on geography, use, and construction. Wind loading is recognized as a primary structure cost driver for photovoltaic arrays. In some applications it may be cost-effective to take advantage of the reduced wind loading due to boundary layer effects near the ground, shielding from adjacent rows or arrays, or wind shielding devices, provided that the increased cost of supporting analysis and documentation is defrayed by decreased structural costs.

**AR.M.2 Concentrator Array Structural Adequacy**

**Criterion.** In any sun-tracking operating mode, the PV concentrator array shall safely support operating design loads (dead weight, wind, and constraint loads) without structural failure or performance degradation beyond that accounted for in the energy loss budget for the system. When in a nonoperating mode or position, the concentrator array shall support all loads expected during the design life of the system without structural failure or subsequent performance degradation when the system is returned to an operating condition.

**Evaluation.** The structural adequacy of the array structure for a given application shall be demonstrated by structural analysis. Documentation of satisfactory long-term performance under in-use conditions shall be considered contributory evidence of structural adequacy.

**Commentary.** The loading criteria to be used in evaluating the array structure are primarily dependent on geography, use, and construction. Wind loading is recognized as a primary structure cost driver for photovoltaic arrays. In some applications it may be cost-effective to take advantage of the reduced wind loading caused by boundary layer effects near the ground, shielding from adjacent rows of arrays, or wind shielding devices, provided that the increased cost of supporting analysis and documentation is defrayed by decreased structural costs. In connection with concentrator arrays, it is appropriate to distinguish between operating and nonoperating loads. The operating loads are those that occur while the array is in a sun-tracking operating mode. Operating loads cause structural deformations which affect the ability of the concentrator array to accurately track the sun. Operating wind loads might be significantly lower than nonoperating wind loads because studies have shown that virtually all of the sun's insolation occurs at relatively low wind speeds. Nonoperating loads occur at any time during the design life of the array. In addition to withstanding these loads without structural failure, permanent deformations of concentrator array structures should not reduce excessively the ability of the array to collect solar energy.
AR.M.3 Off-Axis Survival of Field Components (See AR.S.1)

AR.M.4 Piping for Pressurized Fluids (See SY.M.3)

Safety Attributes

ARS.1 Off-Axis Survival of Field Components

**Criterion.** Field components shall be capable of tolerating concentrated sunlight traversing off the normally illuminated area during normal operating conditions (e.g., sun acquisition or steering operations) or abnormal operating conditions (e.g., power failure of tracking motors) without significant degradation.

**Evaluation.** Off-axis survival shall be demonstrated by engineering and safety analyses during field layout and design. The characteristics to be evaluated are adequate spacing of components and use of shields or barriers, redundancy in component design, use of noncombustible materials, and use of materials that will not soften or melt.

**Commentary.** Concentrators can impose complex steady-state and transient thermal loads on adjacent structures during off-axis pointing. Depending on the specific concentrator, optics, and field layout, the energy distribution on adjacent structures can be highly nonuniform and may reach very high levels of concentration in localized areas. The nature of the off-axis condition—that is, whether the array is moving or stopped—determines the extent to which adjacent structures may be exposed to intense energy concentrations for extended periods of time.

Linear focusing concentrators, while tracking, inherently concentrate light off the receiver at the ends of the trough during normal operation; the effect of this concentrated light must be accounted for in field layout.

ARS.2 Safety Procedures (See SY.S.1)

ARS.3 Flammability (See MO.S.5)

Durability/Reliability Attributes

ARD.1 Humidity (See MO.D.3)

Installation, Operation, and Maintenance Attributes

AR.I.1 Access for Maintenance (See SY.I.3)

AR.I.2 Array Spacing for Shadowing (See SY.B.1)

AR.I.3 Installation, Operation, and Maintenance Manual (See SY.I.1)

See below for additional commentary warranting particular attention.
Commentary.

Protection from Concentrated Light. Safety practices shall be provided for protecting personnel from harmful exposure to concentrated light. Exposure to concentrated light can cause permanent blindness or other serious personal injury. People near concentrating equipment may include one-time-only visitors or operating and maintenance personnel for either the concentrating equipment or nearby equipment, e.g., condenser for building air conditioning system. Safety practices must protect people from the harmful effects of instantaneous and cumulative exposure.

The greatest potential harm from instantaneous exposure is to unprotected eyes. Eye protectors having low transmittance of ultraviolet are essential when working with concentrated light. Metallized sun glasses can be effective against accidental burning of the retina by concentrated infrared but must still exhibit attenuation of ultraviolet light. ANSI standards on eye protection for welding and for lasers provide additional guidance (e.g. ANSI-Z 136.1-1980, "Safe Use of Lasers").

Exposed skin may be harmed by long-term frequent exposure to concentrating sunlight. Experience in working with concentrator array fields over periods of ten or more years has shown a tendency for susceptibility to cumulative effects of sunlight on unprotected skin (arms, neck, face, etc.). The danger from cumulative effects relates most importantly to the increased susceptibility to skin cancer. Workers should be encouraged to wear protective clothing covering arms and neck areas, and with proper education, to use ultraviolet light inhibitors for sensitive skin areas such as lips and face. Long-sleeved, light-weight white shirts are helpful in protecting against the harmful effects of cumulative concentrated sunlight. Possible safety procedures include routine physical examination.

Servicing concentrating equipment should be done in a way that minimizes the exposure to concentrated light. Suitable techniques are to service at night, to point the equipment in a direction opposite the sun leg (e.g., in the northern hemisphere point toward the northern horizon), or to shade the equipment. During operation, examining or servicing equipment at the focus should be avoided unless proper precautions are taken. Safety practices should include warnings posted in critical areas; visitors should be cautioned about the hazards. Areas surrounding concentrating equipment may require restricted access.

Since experience with large numbers of concentrators in various applications is just beginning to be reported, other precautions may be required in the future.

Cleaning Flat-Plate Modules and Panels. The installation manual shall instruct that, prior to installation in an array field, a module's or panel's front surface may need to be cleaned in accordance with the manufacturer's recommendations. Normally when a module is received from a manufacturer, its front surface is clean and no further cleaning is needed. However, modules are often left in unprotected storage racks or are used in one array field and then relocated to another. It is easiest to clean these modules individually prior to installation. The appropriate cleaning agent must be compatible with the front surface encapsulating material. For dust on a stored module, the most effective cleaning cleaning agent is normally a solution of detergent and water. For embedded dirt particles, the cleaning techniques outlined below are more appropriate. If any doubt exists about the compatibility of a cleaning agent and a module's front surface, a safe but not necessarily effective technique is to use warm water and a soft cloth.
The manual for maintenance shall include a recommended procedure for cleaning the front surface to remove dirt accumulations which reduce electrical output. The appropriate cleaning technique depends on the module's front surface material and the type of dirt present plus the environmental conditions at the time of cleaning. Representative cleaning procedures used by various organizations that have proven effective are described below.

- **Procedure 1**
  - Modules are thoroughly rinsed with tap water. A cleaning solution of heavy-duty water-based degreaser (Franklin Formula 707 or equivalent, 62.25 cm³/L of water) is applied with a sponge. For badly soiled modules, a bug sponge is used. The modules are then rinsed and dried with a squeegee and thoroughly wiped with a chamois.

- **Procedure 2**
  - A detergent solution (Alconox-Tide or equivalent) is prepared and applied with a scrub cloth; this is followed by light hand scrubbing until the scrub cloth appears clean. The modules are rinsed well with tap water and then dried.

- **Procedure 3**
  - A detergent solution (Alconox or equivalent) is prepared and applied with a sponge or a washcloth. The modules are rinsed with tap water, using a hose. A squeegee is used for drying.

- **Procedure 4** (for modules with silicone rubber top cover).
  - The module surfaces should be sprayed with a solution of hot water (130°-150°F) and detergent. The water should be heated in a steamer and sprayed with a nozzle onto the module surfaces.
  - Soft brushes should be used to rub the resulting soapy solution over the module surfaces.
  - Modules should be rinsed with water (either hot or cold).
  - Pumice (a mild abrasive) should be sprinkled on soft brushes and then rubbed over the module's surfaces immediately after rinsing.
  - Modules should be immediately rinsed with water (either hot or cold) to prevent filming.

**AR.I.4 Installation Plan (See SY.I.6)**

**AR.I.5 System Maintainability (See SY.I.2)**

**AR.I.6 Field Monitoring**

**Criterion.** Modules, receivers, tracking and control apparatus, and arrays shall provide monitoring capability for evaluating electrical and thermal performance.

**Evaluation.** Drawings, specifications, and the operating/maintenance manuals shall be reviewed to determine that appropriate accessible and monitoring points (e.g., electrical terminals) have been incorporated.
Commentary. The location of accessible and appropriate sensors will permit array-related parameter monitoring and expedite the maintenance and repair of equipment. Periodic monitoring of modules (arrays, concentrators, etc.) is sometimes necessary to check for hot-spot heating, power degradation, etc. Test points at the appropriate element are useful for monitoring the above conditions.

Building and Site Attributes

AR.B.1 Avoidance of Array Field Soiling (See SY.B.4)
REFERENCES


19. TLVs (Threshold Limit Values) for Chemical Substances in Workroom Air. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio; 1979.


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SECTION 4.0
POWER CONDITIONING SUBSYSTEM

INTRODUCTION

The power conditioning subsystem comprises the power conditioning units (PCU) and power routing switches required to link one or more power sources to one or more loads. It also provides necessary subsystem supervisory functions and signal wiring. The power conditioning subsystem may be controlled by the system monitor and control unit through the power conditioning monitor and control subsystem, which responds to both internal and external signals for supervision of PCU operation. To avoid conflicts, all signals to and from PCUs and power routing switches should be routed through the power conditioning monitor and control subsystem. The system monitor and control unit is described in Section 2.0; the power conditioning monitor and control subsystem is described in Section 5.0.

An inverter is a PCU which changes a DC input to an AC output and may be used in two types of systems: stand-alone (SA) and utility interactive (UI) systems.

An SA system is one in which the inverter operates independently of a utility line; it never operates in parallel with the utility line. The output voltage of an SA inverter is fixed; the output current drawn is determined by the loads. Generally, all load requirements (real, reactive, transient) must be supplied by the inverter. It is possible to draw supplementary power, if needed, by disconnecting the load from the inverter and connecting the load to the utility (if available) by electronic or mechanical switching. A DC power supply can be used to provide supplementary power to the DC input of the inverter. A diesel generator or other supplementary energy source such as a chemical storage battery, can be used in a stand-alone system.

A UI system is one in which the inverter or system operates in parallel with a utility line to supply a common load and may supply power to that line. The output voltage of the UI inverter is set by the utility line; the inverter controls the output current by phasor adjustment. Contrast this capability with that of the SA inverter described previously. The power supplied by or to the utility is the difference between that supplied by the PV system and that used by the load. Transient overloads, such as those required for starting a motor, would normally be supplied by the utility. Proper function of the inverter may or may not depend on the connection to the utility line.

A UI system could be designed so that power is never delivered to the utility. In this case, the PV power system must operate in a load-following mode whenever array capability is greater than the load, thus not using all available energy. Alternatively, another discretionary load (battery charger/battery or water heater, for instance) may accept excess PV power available. A UI system may also employ equipment to operate the array at the maximum power point (see glossary). In this case, a sufficient load must always be available to absorb all available array power.

Both stand-alone and UI systems may include an energy storage device to store PV and/or off-peak utility energy for use at night or when load demand exceeds available PV power.

Performance criteria in this section are applicable to both SA and UI applications unless otherwise indicated. In some cases, specific comments relative to one or the other are
made in the commentary statements, as appropriate. Later editions of this document will include performance criteria for other types of power conditioning units, as described in the glossary. Amendments and updates to Sec. 4.0 on utility intertie considerations will be issued as technical committee work progresses. Test methods referred to in this section with the code designation TE.PC. are in Volume II.

PERFORMANCE CRITERIA

Electrical Attributes

PC.E.1 Input Voltage Specification

Criterion. The PCU shall perform as specified for any applied DC input voltage within the input voltage and environment operating range specified.


Commentary. It is recommended that PV array voltage ranges be standardized so that PCUs need not be custom designed for each application. For SA and transformer-isolated UI units, 100 V to 300 V have been used for up to 50-kW ratings in both single and three-phase systems. Other voltages may become desirable as new power switching devices are developed. Recently, UI inverters for up to 10 kW have been designed for the 160 V to 240 V input voltage range. If line-commutated UI inverters are to be used without transformer isolation, the input voltage range should be consistent with restrictions on maximum DC input voltage; e.g., 90% of the RMS AC utility voltage for single-phase units and 135% (6 pulse) and 141% (12 pulse) of the RMS AC line-to-line utility voltage for three-phase units. Similar restrictions apply to self-commutated inverters without transformer isolation.

PC.E.2 Input Ripple Current Ratio

Criterion. The input ripple current ratio for the PCU shall be less than that value specified for the unit for a specified range of input impedances.


Commentary. Measurement system bandwidth is restricted so that switching transients that have little practical effect on loads (other than EMI considerations) will not produce misleading measurements.

Ripple superimposed on the average current drawn from the PV array can reduce average array output power and, if excessive, can cause the inverter to malfunction. At the maximum power point the PV array impedance (for small changes) can be approximated by a resistor numerically equal to the maximum voltage divided by the maximum current. Generally this incremental resistance is minimal when the array maximum power point voltage is lowest (either by design or because of high-temperature operation), leading to the worst ripple currents for a given PCU. The effects on a PV array of ripple current drawn by a connected load is discussed in Ref. 1. In systems with storage, the effects of
ripple current are still under investigation. Inverter commutation circuitry should be sized to commutate at peak load current, taking into account ripple components.

An analysis of how the inverter input ripple current is affected by the instantaneous power balance and the input filter circuitry is also shown in Ref. 1. As described in this reference, the input filter strongly affects the amount of ripple fed back to the source. Array nonlinearity can also introduce additional harmonics. Filters, if required, should be placed at the input to the PCU to prevent conduction of internally generated signals to the PV array, from which they could cause electromagnetic interference (EMI). If electrolytic capacitors are used in filters, correct ripple current ratings should be adhered to.

**PC.E.3 Input Current-Voltage Characteristics**

**Criterion.** The input current drawn by the inverter as a function of applied input voltage shall satisfy the input current-voltage characteristics as specified for a given set of output load and voltage conditions.


**Commentary.** The current-voltage input characteristics of the inverter are important because they provide insight into system performance under variable conditions of PV array output and system load.

If a closed-loop maximum power point tracker is included in the PCU package, it must temporarily be overridden in order to measure input characteristics.

**PC.E.4 Output Voltage for Stand-Alone Inverter**

**Criterion.** The output voltage of an SA inverter shall satisfy specifications for amplitude adjustment range and response speed.

**Evaluation.** To be prepared for a future addendum.

**Commentary.** Inverters designed for SA systems applications should provide a nominal AC output voltage at one of the electric utility standards, such as 120/240 V single-phase or 120/208 V three-phase. It will usually not be necessary or desirable to adjust the output voltage by means of front panel controls, because most loads are able to operate within nominal utility tolerances. An internal adjustment range of ±10% of nominal is common.

Since most loads that would be connected to the inverter can operate with utility power, they will tolerate the normal fluctuations found on a utility line. This level of regulation should, therefore, be sufficient except for special cases. Voltage regulation aspects are the static and dynamic input/output response characteristics of the inverter.

If the inverter can handle momentary overloads, such as motor starts, the manufacturer should specify regulation characteristics under such conditions if they differ from normal operations. Some inverters, such as those used for variable-speed AC motor drives will require additional specifications.
PC.E.5 Output Characteristics for Utility-Interactive Inverter

**Criterion.** The UI inverter shall be capable of operating with specified output characteristics when connected to a utility line of specified characteristics which constrains the inverter output voltage and frequency and presents a specified impedance at fundamental frequency to the inverter.


**Commentary.** In a UI system, the output of the inverter is connected directly to the utility line; therefore, output voltage and frequency are fixed. The inverter should be able to operate over a range of output voltages and frequencies that are compatible with the utility line characteristics. The nominal output voltage, frequency, and operational range, expressed as a percentage of nominal, shall be specified.

For UI inverters operating in parallel with utility sources of comparable capacity, as in small diesel-powered systems, protective measures and a description of adjustments (if applicable) should be provided to prevent the voltage or frequency of the combined power system from exceeding safe levels.

For inverters using a three-phase utility connection, the manufacturer should state the allowable phase voltage imbalance and phase deviation from nominal.

A standard U.S. test line impedance for single-phase residential UI inverters will be determined (see Ref. 3). Line impedances substantially different from the standard test impedance may affect inverter specifications, such as harmonic current injection and device stability. A range of line impedances should be considered in the design of the equipment. Line commutated inverters rely on the utility line to supply commutation energy for proper circuit operation if no filter is present.

PC.E.6 Unbalanced Load for Stand-Alone Inverter

**Criterion.** The inverter shall be able to sustain an unbalanced load equal to a maximum stated level.


**Commentary.** In a three-phase system, modern utility-supplied loads usually exhibit some imbalance among phase loads. The same is true for two sides of a 240-V single-phase center tap system. A PCU should be able to operate in these unbalanced loads and should protect itself and the load if the imbalance limits are exceeded.

PC.E.7 Intermittent (Inrush) Capability of a Stand-Alone Inverter

**Criterion.** The inverter shall be capable of providing reactive and real power output in excess of its rated output power consistent with its overload specification.

Commentary. Overload capability is the ability of the PCU to provide output in excess of specified ratings. This may be required to put high inrush current loads into operation. Overload capability may be a necessary performance requirement. Application of a load within the specified overload rating of the PCU shall not activate protective devices, turn off the PCU, or damage internal components.

Where necessary, SA systems should be specified to supply sufficient rated or overload capacity (including reactive currents) to provide inrush currents to start equipment such as compressors, motors, and tungsten-type loads. If the power system does not include storage, then the real (nonreactive) portion of the overload capability may be limited by the PV array. If storage is provided, then real power will likely be limited by the overload rating of the PCU. These overload ratings may permit high inrush currents for short times and a longer time for overload capability (e.g., for motor starting and inertial loads). Note that higher-than-necessary overload capability may decrease efficiency and increase the cost of the PCU. Overload capability is load specific and part of a complex trade-off against efficiency and cost; therefore, increased overload capability is not necessarily a benefit.

PC.E.8 Load Power Factor for Stand-Alone Inverters

Criterion. All inverter output specifications shall be met when the load displacement power factor is within its specified maximum allowable limit.


Commentary. Displacement or fundamental power factor has traditionally been the parameter used to specify inverter reactive power capability. As the use of nonlinear loads increases, such as AC-powered switching power supplies, the effects of harmonic currents drawn from inverters become more important. The effects of nonlinear loads and limitations on them shall be stated.

A power transfer map (as defined in the glossary) may be used to specify the allowable load power factor.

PC.E.9 Output Power Factor or VARs for Utility-Interactive Inverter

Criterion. Output total power factor or VARs shall be within specifications over the full rated range of operation of the inverter.


Commentary. When an inductive load is connected to a utility line, the current (defined into the load) lags the voltage. This condition is a lagging power factor or a consumer of reactive volt-amps as defined in utility terminology.

Conversely, a capacitive load presents a leading power factor which supplies reactive volt-amps. To prevent confusion, the UI inverter should be treated as any other utility load, and the direction of the current reference should be toward the inverter. If the power factor is adjustable, its range should be specified.
PC.E.10 Output Voltage Harmonic Content for Stand-Alone Inverter

**Criterion.** The output voltage harmonic content shall be equal to or less than that specified over the full rated range of operation of the inverter.


**Commentary.** The amount of voltage distortion that can be tolerated depends on the equipment connected to the inverter and the susceptibility of this equipment to nonsinusoidal waveshapes. Most loads have been designed to operate from utility lines that have a low harmonic content. Some loads are sensitive to waveform distortion. The total harmonic voltage distortion accepted for powering critical computer loads is 5%; no more than 3% is in any one harmonic.

Allowance of higher distortion may permit the design of higher efficiency or lower cost equipment or both. The PCU output waveform may be purposely nonsinusoidal (such as a square wave) in some specialized applications. See Ref. 2 for additional information.

PC.E.11 Output Current Harmonic Content for Utility-Interactive Inverter

**Criterion.** Output current harmonic content shall be equal to or less than that specified over the full range of operation of the inverter while operating with a utility line of specified characteristics.


**Commentary.** The amount of voltage distortion that can be tolerated on the utility lines depends on the susceptibility of the equipment connected to it. The measurement and specification of voltage harmonic content is therefore preferred at the utility system level. The UI inverter can be modeled as a generator of harmonic currents. Measurements of these harmonic currents are required to calculate the effects of the inverter on the distribution system. Measurements of the individual harmonics are desirable to help select suppression techniques, because the amplitudes actually generated frequently differ from those indicated by simplified theory. The resultant voltage harmonics at the point of equipment connection, and at other points in the utility distribution system, will depend on system impedances at harmonic frequencies and inverter harmonic current. Care should be taken to avoid both series and parallel resonance. The ability of the utility to absorb these harmonic currents without damage and with acceptable resultant voltage harmonics may be specific to the site. Adequate information about the line impedances at harmonics at residential and other locations on low voltage distribution lines is not yet available, but relatively large amounts of harmonic current may be acceptable for the near term. As the number of UI inverters in a particular residential distribution area increases, a more restrictive inverter specification (or distribution systems modification) could become necessary, consistent with utility standards which may be developed. A standard U.S. test line impedance for single-phase residential UI inverters will be determined. See Ref. 3 for additional information.

Intermediate PV power systems may be large enough to make custom filters economically feasible. Measurements made on an individual installation will determine the filter required. Similar comments apply to central power applications, which use custom designed filters.
PC.E.12 Output Frequency of a Stand-Alone Inverter

**Criterion.** The output frequency of an SA inverter shall satisfy specifications for nominal value and stability.

**Evaluation.** A frequency measuring instrument with an accuracy and readability of 0.1 Hz shall be used. The frequency range (if adjustable) shall be checked at nominal input voltage and full rated load. The frequency shall then be set at the nominal operating frequency and the unit allowed to stabilize its temperature.

Any frequency change shall be noted, and the frequency shall again be set to its nominal value. The input voltage and load power shall be varied over the full specified operating range and the frequency shall be recorded. If required, the frequency shall be measured at environmental extremes. If it can be shown that the frequency is independent of output load, testing may be confined to the individual circuit or card that contains the elements determining frequency.

If the inverter contains provisions for phase lock to an external reference, phase error shall be recorded as the external reference frequency is varied between specified limits. The locking capture range is defined as the range of reference frequencies within which the inverter can achieve phase lock.

If the specification includes a requirement for a maximum rate of phase change, this shall be measured by using instrumentation which provides an abrupt change of phase into the reference frequency terminals.

**Commentary.** Most loads to be used with an SA inverter have been designed for operation at either 50, 60, or 400 Hz. A majority of these loads can tolerate at least a 5% deviation from nominal, but some loads, such as clocks, require long-term frequency accuracy.

PC.E.13 Turn-on Characteristics

**Criterion.** The inverter shall be capable of satisfying the specified turn-on characteristics of input or output voltage, current, or power, after input power has been applied to the inverter, or when the inverter is recovering from a load or source fault condition.

**Evaluation.** The turn-on input or output transients shall be recorded by an oscilloscope equipped with a camera or a suitable chart recorder. Turn-on shall be checked at several combinations of low and high input voltage and no load to full load as specified in Test TE.PC.E.1 (Power Conditioning Unified Test Procedure for Solid-State Inverters). If applicable, short circuits (or overloads) shall be applied to the inverter and photographs taken of the recovery transient.

**Commentary.** Power system equipment is usually designed to turn on gradually, or "walk in" to minimize transients in the AC or DC side of the power system by allowing power flow to change slowly. This "walk-in" capability should also operate in remote-controlled units when switching from the standby mode to the operate mode. "Walk-in" capabilities are especially important in UI PV applications because of the limited power available during morning turn-on procedures.
If an inverter requires a power surge when it is turned on, or when it is connected to the utility, then this transient power requirement limits the system's useful power range.

PC.E.14 Efficiency

**Criterion.** The conversion efficiency shall be no lower than the values specified over the stated range of electrical and environmental conditions.


**Commentary.** Efficiency is the fraction of input power converted into useful output power. Two efficiency definitions have been established by the Institute of Electrical and Electronics Engineers (IEEE) Industrial Application Society (IAS) and are as follows:

- **P428-D1 2.3.11 Total Efficiency.** The ratio of the total output power to the total input power including the contribution of all harmonics, i.e., ripple component.

- **P428-D1 2.3.12 Fundamental Efficiency.** The ratio of the fundamental output power to the fundamental (DC) input power.

Generally, harmonics of the fundamental frequency do not contribute useful power to a load and may cause undesirable heating effects in load equipment such as motors and transformers. However, for loads such as incandescent lights and resistance heating elements, harmonics can contribute useful power.

Electrodynamometer power meters will measure total power to at least 1 kHz. The same measurement can be made with Hall effect multipliers or electronic analog multipliers. The derivation of the fundamental component of voltage and current prior to multiplication would unnecessarily complicate efficiency measurements. It is therefore recommended that the total efficiency shall be measured since suitable equipment is generally available. If total harmonic distortion is low, the differences are negligible.

The system designer should bear in mind that, in general, the inverter will not operate at maximum rated output. If an oversized inverter was chosen to accommodate transient loads but will normally operate at partial load, then the specification should cover the partial load efficiency and not the full load efficiency.

PC.E.15 Input Undervoltage/Overvoltage Survival Capability

**Criterion.** The PCU shall survive specified overvoltage and undervoltage conditions at its input without damage.

**Evaluation.** Satisfactory performance of a reference unit shall be determined in a qualification test which subjects the unit to undervoltage and overvoltage. The unit shall automatically disconnect from the input source, or otherwise take protective action, when input voltage falls outside the design range. Restart of the inverter shall provide operation within specifications.

**Commentary.** When a PCU is operated directly from a PV array, an undervoltage condition will occur when more power is demanded from the array than is available at the
maximum power point, perhaps due to high temperature and/or low insolation. An overvoltage may occur in cold weather when insufficient power is drawn from the PV array.

Input overvoltage may damage an inverter; thus, a disconnection or short-circuit (crowbar) between the PV source and the inverter may be necessary. With an undervoltage condition present, the inverter may not provide the specified output power quality and the inverter must be safely turned off or the load disconnected. The inverter should be capable of surviving any input undervoltage condition without damage to itself or the load.

The input voltage design range requires a complex trade-off against such items as efficiency and cost. Inverters of various designs will have different short- and long-term capabilities regarding input under- and overvoltage. The manufacturer should supply applicable information.

If the under/overvoltage circuitry acts to trip an input circuit breaker, and if such circuitry senses input voltage after the circuit breaker, some additional circuitry (such as time delays) must be provided to permit reliable turn-on of the unit.

For unattended operation, an inverter in a system without energy storage should be capable of automatic turn-on or turn-off at sunrise and sunset. In addition, large power fluctuations, such as those caused by transient cloud cover, should not cause system malfunction.

PC.E.16 Output Undervoltage/Overvoltage

**Criterion.** An SA inverter shall disconnect or otherwise protect the inverter or load, and/or activate an alarm when the output voltage is beyond specified limits.

A UI inverter must disconnect from the utility line as specified when the utility voltage is beyond specified limits yet to be determined.

**Evaluation.** A recommended test procedure will be prepared for a future addendum.

**Commentary.** This performance criterion may not be required for all SA applications. Output undervoltage could be caused by inverter malfunction or output overload. Output overvoltage in SA inverters is usually the result of inverter malfunction.

Since overvoltage to the load is potentially harmful to that load, some protection may be afforded by an automatic load disconnect. While failure in the overvoltage mode is common in DC power supplies, it is uncommon in AC inverters; therefore, the need for protection must be weighed for each type of inverter design and application.

For UI inverters, the output voltage of the inverter when it is connected to the utility line is determined solely by the utility since the utility power capability will usually far exceed that of the inverter. An undervoltage or overvoltage condition from the utility indicates a serious utility problem. A UI inverter must be disconnected from the utility to protect the inverter and utility personnel when an out-of-specification condition exists. The undervoltage/overvoltage sensing may also be an inherent part of an inverter's protective design in sensing that the utility voltage has disappeared. System restart, after shutdown due to utility removal, can be manual, or if restart is automatic, the utility power first must be restored and stable.
Many options exist for residential and intermediate load center power systems. The system could be designed so that, should utility failure occur, the system disconnects from the utility and reverts to SA operation to supply local loads as much as possible. Loss of utility in central power applications precludes further operation, and manual restart will probably be required.

PC.E.17 Output Underfrequency/Overfrequency

Criterion. The inverter shall provide an alarm or automatically disconnect to protect the load or inverter in the event of output under- or overfrequency.

Evaluation. An evaluation procedure shall be performed if the inverter contains an out-of-frequency alarm/shutdown circuit. Inverter frequency may be varied or an external variable signal may be applied to the frequency detecting circuitry (whichever is appropriate). Trip/alarm frequencies shall be compared to specifications.

Commentary. In an SA application, an under- or overfrequency output indicates failure within the inverter. Such failure, if severe, can cause damage to the inverter or the connected load. In most inverter designs, failure in frequency regulation is unlikely; therefore, this protection may not be required.

For UI applications, the output frequency (when the inverter is connected to the utility) is determined solely by the utility since the utility power capability will far exceed that of the inverter. Any under- or overfrequency condition indicates a serious utility problem.

Thermal Attributes

PC.T.1 Overtemperature

Criterion. If the equipment is provided with such protective devices, automatic shutdown shall occur or remote alarms shall become operative when the unit operating temperature is beyond its specified range.

Evaluation. The temperature sensors shall be heated or cooled with a suitable source and monitored while temperature and shutdown/alarm signals are monitored.

Commentary. Electronic equipment is designed to operate within specified temperature ranges. Critical components, usually semiconductors, are provided with minimum cooling consistent with long-term reliability and economic considerations. An overtemperature condition may be the result of blockage of air passages or loss of forced air.

Mechanical/Structural Attributes

PC.M.1 Operational Temperature, Pressure, and Humidity

Criterion. PV inverters shall be capable of operating over the specified range of ambient temperatures, pressures, and humidity conditions.
Evaluation. Satisfactory thermal performance of a representative complete unit shall be determined in a qualification test capable of producing the range of specified temperatures for the unit. Pressure and humidity specification conformance shall be determined by test or experience and design analysis.

Commentary. Like any piece of electrical equipment, the inverter must perform satisfactorily over the ranges of temperature, humidity, and pressure to which it will be subjected in operation. The pressure range should include the barometric pressures at all locations at which the unit might be installed.

Special consideration is necessary if unit operation below 0°C is required, because components may be affected by these temperatures.

Although the unit may be installed in a temperature- and humidity-controlled room, unit failure should be avoided if the building HVAC system should fail. One possible set of operating conditions might be:

- Ambient temperature: 0°C to 40°C
- Relative humidity: up to 96%, noncondensing
- Barometric pressure: 69.3 kPa to 101.3 kPa (520 to 760 mm Hg).

If required, the inverter should be provided with internal cooling fans and proper cooling air flow paths to maintain satisfactory performance over the specified temperature, pressure, and humidity ranges.

Safety Attributes

PC.S.1 Safety

Refer to performance criterion SY.S.1. See below for additional commentary warranting particular attention.

Commentary. In addition to the issues mentioned in SY.S.1, the following characteristic should be considered.

Charged capacitors represent a safety hazard to service personnel. Permanently connected parallel bleeder resistors will discharge the capacitors, but they lower system efficiency; therefore, a trade-off must be made, balancing safety against efficiency. Another method of discharging capacitors is by using a discharge button and a voltage indicator, or a safety interlock system. These methods, although somewhat more costly, optimize both safety and efficiency.

The system generally should be designed so that the voltage across the input capacitors falls to below 30 VDC within one minute after power is removed from the inverter, or upon access to the inverter for servicing.

See also SY.I.1, Installation, Operation, and Maintenance Manual, for further information.
PC.S.2 Burn Hazard (see SY.S.7)

PC.S.3 Fire Safety (see SY.S.5)

PC.S.4 Electrical Isolation and Insulation

**Criterion.** Input and output power connections shall meet the specifications for electrical isolation from equipment ground. If the input and output power leads are stated to be electrically isolated from each other, the isolation shall meet its specifications.

**Evaluation.** The dielectric withstand voltage shall be tested in accordance with Method 301 of MIL-STD-202.

- The magnitude of the test voltage should be as specified in Table 4-1. The peak voltage that may be present between conductors shall be considered when computing test voltages. Test voltages greater than 1000 V RMS shall be applied gradually at a rate not exceeding 500 V RMS/s.

<table>
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<tr>
<th>Working Voltage (V)</th>
<th>RMS Test Voltage (V)</th>
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<tr>
<td>Less than 25</td>
<td>50</td>
</tr>
<tr>
<td>26-50 incl.</td>
<td>100</td>
</tr>
<tr>
<td>51-100 incl.</td>
<td>300</td>
</tr>
<tr>
<td>101-175 incl.</td>
<td>1000</td>
</tr>
<tr>
<td>176-700 incl.</td>
<td>2.8 x working voltage</td>
</tr>
<tr>
<td>Greater than 700</td>
<td>1.4 x working voltage + 1000</td>
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*The working voltage is defined as the maximum instantaneous voltage stress that may appear under normal rated operation across the insulation being considered. This insulation may be between conductors or between a conductor and case.*

- The nature of the potential is AC.
- The duration of the application of the test voltage is a minimum of 5 s.
- The points of application of the test voltage are:
  - (a) The DC input leads are tied to chassis, and the test voltage should be applied between the AC output leads and the chassis. The transformer lamination should be connected to chassis and all means of disconnection activated.
  - (b) The AC output leads are tied to the chassis, and the test voltage should be applied between the DC input leads and the chassis.
(c) If it is proposed to apply the test voltage between the DC input leads and
the AC output leads, these tests need not be made if the test voltages in (a)
and (b) are greater than that proposed for (c). Two sources of test voltage
shall be used, proportioned, and phased so that the input-to-output test volt-
age satisfies Table 4-1, but the input-and-output-to-chassis voltage does not
exceed that used in (a) and (b).

- The high voltage source shall supply a minimum of 0.5 kVA for voltages over
1 kV.
- Examination during and after the test shall determine evidence of arcing, flash-
over, breakdown of insulation, and other damage.

The insulation resistance of the inverters shall be tested in accordance with Method 302
- The test condition Letter B, 500 V.
- The points of measurement shall be as in the withstand voltage test described
above.
- The electrification time shall be 1 min.

Note: The measurements may be made at any temperature above 20°C and at
ambient room humidity, but rejections shall be based on measurements made at
25°C (+10°C, -5°C) and at a relative humidity not greater than 80%. The insulation
resistance shall be a minimum of 10 MΩ.

Commentary. Ungrounded power systems can be a safety hazard, and for that reason it
may be desirable to provide both AC and DC grounds. A decision must be made as to
whether to ground the electrical system; if the decision is positive, then the inverter AC
and DC connections must be electrically isolated from each other, usually by a trans­
former, which may increase costs and power losses. If the input and output are not elec­
trically isolated from each other, then either the DC or the AC side must be ungrounded.

Equipment grounding, in contrast with system grounding, relates to the manner in which
nonelectrical conductive material, which encloses electrical equipment, is to be inter­
connected and grounded. The inverter should have no connection between the power
input/output connections and the equipment chassis or case (see NEC Article 250,5).

The dielectric withstand and insulation resistance tests are used to prove the integrity of
the insulation on all transformers that interface the DC and AC circuits, as well as the
insulation of heat sinks and other components.

The withstand voltage test is a go/no-go test. Successful completion of the test gives
some assurance that no gross defect is present in the insulation structure. The ability of
a withstand test to expose incipient faults is less certain, therefore this test is often sup­
plemented by the measurement of insulation characteristics such as insulation resistance.

This test was written with reference to MIL-STD-202 because it was available, not
because of a requirement for a highly reliable military construction.

IEEE STD 62-1978 provides a good discussion of grounded systems. It refers to the fol­
lowing standards, which may be more suitable for these criteria. Refer also to Test
TE.AR.M.10.
Whenever ungrounded lines are connected to an exterior element, such as a solar array, a voltage limiting device should be connected from each line to ground to prevent possible static charge build-up or lightning-induced voltages in excess of the capabilities of the insulation. In addition, refer to SY.S.1, SY.S.2, and SY.S.3.

A good discussion of these subjects can be found in IEEE Std. 142-1972, Recommended Practice for Grounding of Industrial and Commercial Power Systems.

Installation, Operation, and Maintenance Attributes

PC.I.1 Installation, Operation, and Maintenance Manual

Refer to performance criteria SY.I.1. See below for additional commentary warranting particular attention.

Commentary. The service manual shall provide detailed directions for discharging capacitors, and applicable warning notices shall be displayed on the equipment chassis.

PC.I.2 Maintainability (see SY.I.2)

PC.I.3 Accessibility (see SY.I.3)

PC.I.4 Local Monitoring

Criterion. Malfunction and alarm conditions shall be suitably displayed as specified. Indicators or test points shall be available as specified to enable maintenance personnel to verify equipment operation and facilitate corrective procedures.

Evaluation. Review drawings and equipment to determine conformance with criterion.

Commentary. Proper equipment operation can be displayed with the use of status lights or meters that display input and output voltage, current, and power. Alarm display lights can indicate impending failure and failure display lights can indicate the cause of equipment shutdown/disconnect. As equipment reliability is demonstrated in the field or as installation circumstances warrant, local monitoring devices may be removed for economic reasons in small installations. Larger systems may retain extensive instrumentation where operating personnel are on duty.
PC.I.5 Local/Remote Controls

**Criterion.** Adjustments and controls located on or inside the equipment shall be marked according to their function as specified. If remote control can be exercised, then switches and indicators shall be available to disable such remote operations.

**Evaluation.** Local controls and adjustments shall be exercised to verify their operation. The remote control operation shall be similarly exercised, and it shall be verified that the disable function removes the remote control capability. Repeat the procedures after the equipment is installed.

**Commentary.** Some examples of functions which may be remotely controlled are UNIT ON/OFF, OUTPUT VOLTAGE, and OUTPUT POWER. Even though normal system operation includes the capability for remote control, it is desirable to provide means for local control to facilitate troubleshooting and service. To protect service personnel, the remote control function must be locked out or otherwise disabled.

The remote control interface should be standardized as soon as possible. A suggested interface is an external contact closure in Class 2 control circuits. Optoisolated digital inputs may also be used.

PC.I.6 Local/Remote Monitoring

**Criterion.** Local and remote status monitoring shall be as specified.

**Evaluation.** Drawings and equipment shall be reviewed. Remote indicators that are compatible with the specified interface shall be connected; operation, including alarms, shall be verified. Repeat the procedures after the equipment is installed.

**Commentary.** The remote monitor interface should be standardized as early as possible.
REFERENCES


# 5.0 POWER CONDITIONING MONITOR AND CONTROL SUBSYSTEM

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SECTION 5.0

POWER CONDITIONING MONITOR AND CONTROL SUBSYSTEM

INTRODUCTION

The power conditioning monitor and control subsystem supervises power conditioning subsystem operation in response to internal and external signals. Such a subsystem may be described by levels, types, and functions. Because of the large number of possible combinations of monitor and control configurations, the scope of this section encompasses designs ranging from simple switch-operated subsystems to highly complex microprocessor/minicomputer-operated subsystems. The following paragraphs describe several facets of control systems including levels, types, and functions of control, and other considerations.

There are two monitor and control levels in a typical PV power system. The highest level is the photovoltaic power system monitor and control unit, which receives information from and sends information to the thermal and power conditioning subsystems through their monitor and control units. Typically the operator interacts with this unit, and performance criteria are located in Section 2.0.

At the next lower level is the power conditioning monitor and control subsystem. This subsystem monitors the operation of the power conditioning subsystem, controls the subsystem directly, receives and carries out commands from the system monitor and control unit (if there is one), and ensures the safe operation of the subsystem. The subsystem elements may be distributed among various PV components instead of being a discrete unit.

Types of control may be categorized as switch-activated, electromechanical, and electronic. A switch-activated control, typically manual, is the most basic type. It connects various components within the power conditioning subsystem or connects subsystems, such as battery storage, to the power conditioning subsystem. Electromechanical control is typified by relays—electrical and mechanical couplings—that open or close. Electronic control includes microprocessors or the equivalent that use analog or digital signals for use in startup, shutdown, and optimization of the power conditioning subsystem.

Control functions can be divided into three broad categories: operating mode selection, startup, and shutdown. The control signals from the monitor and control system to the equipment and devices controlled indicate the type of action to be taken. The signals may be either digital or analog; analog outputs may be provided for continuous control. Voltage, current, and bandwidth ratings of the control elements must be compatible with signal and termination requirements.

To operate the monitor and control subsystem properly, interface signalling must provide accurate and reliable transfer of information. Consideration should be given to the operator interface, to ensure effective communication between operator and subsystem. An acceptable interface must perform satisfactorily in the presence of electrical noise and other adverse environmental conditions. Default operation created by interface failure should be recognized and defined. Standardization of control interfaces is important for compatibility.
Electrical interference may be a problem wherever there is close coupling between power conditioning and control systems. Electrical interference is any spurious voltage or current arising from external or internal sources that appears in a circuit. When these voltages or currents become too large, the system is adversely affected and malfunctions. Circuits can be separately characterized by their susceptibility to such interference and by their generation of such interference. Electromagnetic compatibility with the electrical environment must be assumed at all times.

Software is a very important part of any design utilizing processor control. With availability of low-cost microprocessors increasing, the inclusion of software control can be expected to increase correspondingly. Just as any system is only as good as its weakest link, so any monitor and control system is as weak as its control algorithm. It is important to outline the crucial interaction between hardware and software considerations in a system. Much effort should be spent in selection of a system, its components, and analysis of system algorithms to ensure that the system operates efficiently, safely, and with only the amount of operator involvement intended.

Computers, including microprocessor-based systems, are normally susceptible to "crashing" where electrical transients, lightning, induced surges, or RF noise can force an address or instruction error that will cause the stored program to jump into an unallowed and often repetitive mode. Under such a condition anything can happen, and the problem is usually manifested in a hard or soft system failure. Until the system is reset (reinitialized) or the program is reloaded, malfunctioning will continue. Adequate safeguards (usually for both hardware and software) must be included to ensure maximum operating time for the system. Crash-proof systems are usually designed for a specific application with a fixed amount of code and logic elements immune to noise.

Testing residential PV equipment is important and must often be performed by persons with backgrounds in heating, ventilation, and air conditioning or by electricians who work with conventional systems.

A prospective manufacturer should compare the cost of appropriate test equipment with the amount of time saved by service personnel because of ease of repair and the increased need for service. Because of the cost of service to the residential customer, service test procedures should be streamlined to eliminate field repairs as much as possible. Test procedures should be comprehensive to ensure safety.

Monitor and control provide a central means for running special tests on other parts of the power conditioning and associated subsystems, such as the electrical storage element and the array. Such tests could be used to vary operating conditions to reveal problems not otherwise apparent, and could be undertaken in conjunction with direct access to appropriate parts of the subsystem. Self-testing capabilities could be included.

PERFORMANCE CRITERIA

Electrical Attributes

MC.E.l Pre-Startup Conditions

Criterion. The monitor and control subsystem should provide for proper startup of the system after all pre-startup conditions have been met.
**Evaluation.** Signals to and from the monitor and control unit should provide the sequence and type of signals that are consistent with the designed startup procedure.

**Commentary.** Circumstances exist (such as failure of a component, overheating of part of the system, and no voltage being supplied by the array) under which startup should not be initiated because of system and personnel safety. In a manually operated system, the operator may have a checklist to complete before operating the switch that turns on the system. In an automated system, the monitor and control unit may have built-in precautions that prevent initiation of startup until all necessary conditions are met. Once the necessary conditions are met, either manual or automatic startup initiation should result in a properly functioning system.

**MC.E.2 Startup (Automatic or Manual)**

**Criterion.** When startup is properly initiated, the electrical parameter levels between subsystems should fall within the specified limits.

**Evaluation.** A check for compatibility of equipment specifications should be performed. Anywhere a transient signal caused by startup might interfere with the operation of a component or subsystem, monitoring of electrical levels may also be a necessary test.

**Commentary.** All startup modes should satisfy voltage and current constraints imposed by the components involved. Startup is a control action that allows energy to flow in the power conditioning unit(s). All configurations of any power conditioning unit should be tested for:

- possible failure of each component and startup inhibition;
- compliance with specified electrical constraints for each component involved in startup; and
- possible effects on other interconnected components or subsystems to determine safe operation.

**MC.E.3 Manual Shutdown**

**Criterion.** Manual shutdown shall be possible.

**Evaluation.** System shall be inactivated when manual shutdown procedure is followed.

**Commentary.** Some means of manually shutting down the monitor and control subsystem is important for all systems. This procedure may range from simple switch shutdown or other power disconnection for small systems to more elaborate master shutdown provisions in large systems.

**MC.E.4 Automatic Shutdown**

**Criterion.** If automatic shutdown is included, it shall occur if operation is attempted outside specified levels for either the system or the subsystem.
**Evaluation.** Analysis of possible failure modes of each component shall demonstrate that any abnormal operating mode can safely achieve shutdown. Failure mode and effect analysis (FMEA) are applicable. The FMEA should include data on component/functional assembly, failure mode, failure effect, compensating feature or control, and severity index.

**Commentary.** Protective control actions operate to shut down the unit automatically upon detection of abnormal operating conditions, such as high temperature, unbalanced operation (for three-phase systems), overvoltage or undervoltage, overcurrent, and loss of synchronism.

This criterion may not be required on small systems. Many control configurations are possible for specific modes of operation. Failure of one or more of the components may result in safe shutdown of the unit or an appropriate part of it.

Failure of systems interconnected with the unit shall result in shutdown of the unit if unsafe operation is possible. If shutdown is not required for transients, such as voltage dips on the utility line, transients shall be shown to cause no damage to equipment or operators. If automatic restarting is included, then it must pass the same tests applied to the startup function.

**MC.E.5 Power Supply Voltage Level and Range**

**Criterion.** The monitor and control subsystem shall operate in the manner specified when connected to a power source whose supply voltage is within the specified range of input voltages for the subsystem.

**Evaluation.** The subsystem must operate properly at maximum and minimum power supply output voltages and frequencies.

**Commentary.** Power supply inputs should be compatible with available sources. Standard input voltages are dictated by the location of the system. In the United States, the commonly available residential voltages are 120 VAC or 240 VAC single-phase, or 208 VAC three-phase, 60 Hz. It is desirable that outputs of control system power supplies be compatible with present industrial practice, (e.g., ±5 VDC, ±12 VDC, ±15 VDC, and ±24 to +28 VDC). In some cases (e.g., stand-alone applications), power supplies may not be required if the appropriate DC levels are available for logic and controls.

**MC.E.6 Power Consumption**

**Criterion.** Power consumption of the monitor and control subsystem shall not exceed its specified limit.

**Evaluation.** Power consumption should be measured over the full specified operating range.

**Commentary.** The supply's power consumption should be specified so that it can be properly wired into the system and its effect on system efficiency can be determined. The consumption of this power supply should be minimized to keep overall system efficiency high. Most DC supplies operate most efficiently at full load; therefore, if the supply
rating is not much greater than the system requirement, the power supply losses will be minimal. However, reliability considerations might dictate a specification of a power supply with a considerably higher rating, causing a trade-off between conflicting reliability and efficiency requirements. Because the monitor and control power supply requirements are likely to be relatively small compared to the system output power, the supply efficiency will probably be a minor concern.

MC.E.7 Interference Susceptibility

**Criterion.** Within the interference levels specified, the monitor and control operation shall not be affected adversely by electrical interference.

**Evaluation.** The monitor and control subsystem shall be subjected to electrical interference to ascertain proper operation under the influence of the specified limits of interference.

**Commentary.** For interference to affect performance, its source must be electrically coupled to the instruments' circuits magnetically, capacitively, conductively, or by a combination of these.

Unwanted voltages enter an electrical signal transmission system by:

- inductive pickup for AC fields electromagnetic coupling;
- electrostatic or capacitive coupling with other circuits;
- direct coupling with other circuits by ground current loops, a common return lead for more than one circuit, or leakage current paths; or
- thermoelectric and corrosion voltages generated by dissimilar material combinations.

These conditions should be considered in the design (refer to IEEE, FCC, or Verband Deutsche Electrotechnica and the International Special Committee on Radio Interference standards for further information).

Safety Attributes

MC.S.1 Safety Control

**Criterion.** Control equipment shall allow for manual and/or automatic shutdown in the event of an emergency.

**Evaluation.** System plans and schematics should conform to this provision.

**Commentary.** One of the prime reasons for having control equipment is safety; this equipment should be capable of shutting down the system to avoid damage to equipment and injury to personnel. Where applicable, indications of unsafe operation should be provided. A safety control can be implemented directly from a central unit or in a distributed manner by interlocks and disconnects. As the size of the system increases, it is desirable to increase the number of emergency shutdown locations. In some cases, the safety control equipment can provide additional hazards. For example, lower voltage
ranges are desirable in safety control lines and are less hazardous. Therefore, the safety control equipment and control algorithms should be designed carefully for both adequate performance and reduced risk.

**Durability/Reliability Attributes**

**MC.D.1 Cabling and Connectors (see CA.D.1)**

**Installation, Operation, and Maintenance Attributes**

**MC.I.1 Installation, Operation, and Maintenance Manual**

Refer to performance criterion SY.I.1. See below for additional commentary warranting particular attention.

**Commentary.** The following additional items should be included in the manual where applicable:

- Software program instructions should be listed in tabular form and be complete, accurate, and clear.
- All programs should be represented diagrammatically in standard flow-chart symbols to depict sequential program operation.
- Software should be divided into functional elements or modules. Modularized programs generally can be useful in both their development and usage. Proper modularization is an asset in troubleshooting and modification and a very important consideration in large programming structures.
- Programs should be written in an acceptable programming language, and program debugging routines should be available.
- Calibration requirements should be identified and minimized as much as possible. The stability of equipment should ensure that system calibration is seldom (preferably never) required under normal conditions and operations. Ideally, customer service organizations should not be required to maintain special calibration facilities (except those of a minimal nature) to check test instrument calibration. However, where calibration is necessary, facilities should be provided for it.

**M.C.I.2 Manual Control Panels**

**Criterion.** Control panels included in the system should present explicit information and provide control in a manner easily comprehended by the operator.

**Evaluation.** Design review and visual inspection shall be performed.

**Commentary.** Since the control panel of any photovoltaic system is the interface between the machine and the operator, it is important that all display and control functions (including master and subsystem control panels) be legible. A control panel should
also provide explicit indication of both normal operating and emergency or failure conditions and present system operating information in a manner easily comprehensible to the operator. An entire collection of design information on human factors has been developed over many years, and all control panels and other human/machine interfaces should be developed by personnel whose knowledge of human-factor design criteria is sufficient to provide a control panel easily read by persons with minimal training. This is particularly crucial in residential and small-scale operations. Proper attention should be paid to the use of standard colors for standard functions, such as red for danger. It is desirable that all control panels appropriately announce failure or impending failure, both visually and audibly, and warn of dangerous situations such as equipment overheating, fire, and other conditions that may jeopardize system integrity. To keep costs of residential units low, attention should be given to using standard enclosures; the importance of ease in servicing cannot be overstated.

MC.I.3 Maintainability

Refer to performance criteria SY.I.2. See below for additional commentary warranting particular attention.

**Commentary.** The following items should also be considered for ease of maintenance:

- Built-In Test Equipment (BITE) may be used wherever justified by cost, ease of service, or other conditions.
- The level of technical analysis required by service personnel should be identified as a significant part of test procedures. BITE equipment should be used wherever justified since extensive on-site analysis requirements can be expensive. The manufacturer may provide service personnel with test boxes to locate failures. Use of these test boxes should provide positive results, eliminating any ambiguities in equipment servicing. It is often less costly to replace a more expensive module than to analyze and locate ambiguous problems. A well-designed control system for some applications may include an internal microprocessor to perform continual analysis, provide normal control functions, and indicate problems.
- If desired, a manual internal test may provide system operation information.

MC.I.4 Accessibility (see SY.I.3)

MC.I.5 Environment

**Criterion.** All equipment must operate in and withstand expected environmental conditions.

**Evaluation.** Appropriate test procedures shall confirm operation and tolerance to specified environmental conditions.

**Commentary.** For each application, a corresponding set of environmental requirements must be satisfied to ensure reliable operation. Even where installations are made in relatively benign environments, tolerance must be provided for vibration and shock encountered in shipping and handling. Operation must tolerate temperature ranges which may be broadened by installations away from human habitation or in enclosed, nonventilated...
areas where unexpectedly high temperatures can occur. For monitor and control systems, humidity is pertinent primarily because of corrosion and because it can cause premature system failure if not given adequate consideration. Cellar installations and salt-air coastal environments could be particularly vulnerable.

Elevation is a factor primarily related to air cooling. Equipment designed for sea level operation is generally designed for operation to 1500 m, and higher elevation must be accounted for or excessive heating may result. For low power control systems, this should be less significant than for associated power conditioning equipment.

Cleanliness may be an important factor for monitor and control systems where low-level, high-impedance signaling is involved, and they may depend on many plug-in, low-current contacts that cannot tolerate dirt.
## 6.0 STORAGE SUBSYSTEM

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SECTION 6.0

STORAGE SUBSYSTEM

INTRODUCTION

Without storage, solar energy must be used when it is received. However, because many power requirements are not coincidental with available sunlight, solar energy must be stored. With storage, solar energy can provide power to system loads regardless of time and weather.

The wide range of solar photovoltaic (PV) energy applications for energy storage requires that different types and amounts of energy be stored for varying lengths of time. Energy storage requirements are associated with basic differences in energy storage subsystem sizes, applications, regional variations, and time frames for implementation of such systems. At present, commercially available batteries, such as lead-acid and nickel-cadmium, are used to provide storage in PV applications. Research is being conducted to develop other storage devices; e.g., advanced batteries and electrochemical systems, chemical and thermal systems, and magnetic and mechanical systems (flywheels). For further information on long-term development programs, see Refs. 1, 2, and 5.

The typical storage battery is an electrochemical apparatus comprising one or more connected cells that convert chemical energy into electrical energy. The cell is the smallest unit of a battery system. Cells are connected in series and/or parallel to obtain a desired battery voltage, power, and capacity. The essential parts of a cell are two dissimilar electrodes (anode and cathode) immersed in an ionic conductor called an electrolyte. The cells are enclosed in a leak-proof container and provided with binding posts to which electrical connections are made. Detailed information on the specific chemistry and chemical action of the storage battery can be found in Refs. 3, 4, 5 and 8.

The battery energy storage subsystem is used to store electrical energy collected by the PV array and to supply energy to the load during periods when the PV array is not producing enough power. In certain system designs, the battery storage subsystem may also be used to store energy supplied by an electric utility or other supplemental energy system, such as a diesel generator. Refs. 5, 6, and 7 should be useful in selecting the appropriate battery.

Battery characteristics are governed by the type of cell (e.g., lead-acid, nickel-cadmium). However, many design variations are commercially available for each battery type which must be considered in selecting an appropriate battery. For example, a charge-retaining lead-acid battery designed for low-rate discharge would be destroyed by the duty cycle typical of residential systems. Thus, it is essential that the system designer be familiar with battery characteristics or solicit the aid of a battery manufacturer in specifying the optimum battery for a given PV system design.

Key characteristics useful in gauging battery performance include capacity, efficiency, and expected (or warranted) life. However, these characteristics are functions of operating parameters such as temperature, voltage range, and charge and discharge rate. Meaningful specification of key battery characteristics must include a delineation of operating or test conditions. Information on lead-acid battery charging methods is contained in Ref. 9.
Battery characteristics such as physical size (dimensions) and weight can be specified and checked by conventional methods. Certain other characteristics (e.g., gas emission) require equipment that is available but generally not used except by the battery manufacturer in its design process. At this time, there are no tests for battery life except destructive testing of the cell. Thus, type qualifying or random testing may be used where cell life is to be verified.

The performance criteria in this section are intended to point out information that must be provided to allow proper battery selection and utilization. Included in some of the commentaries are applications to remote-site, intermediate load centers and central generating stations. Battery design for PV applications is a unique branch within battery development programs, and many design criteria are yet to be developed. While the performance criteria addressed in this section refer, for the most part, to lead-acid and nickel-cadmium batteries for residential PV systems, it is not intended that development and use of new cell types in PV systems be constrained. Test methods referred to in this section with the code designation TE.ST. are in Volume II.

PERFORMANCE CRITERIA

**Electrical Attributes**

**ST.E.1 Battery Capacity**

**Criterion.** After complete plate formation cycles, the capacity of the battery storage subsystem shall be equal to or greater than the capacity specified for given test conditions.

**Evaluation.** For motive power, lead-acid batteries, NEMA STDs Pub. No. IB 2-1974, Sec. 1.03-1.04, may be used when appropriate.

For large, lead-acid storage batteries, as used in generating stations and substations, IEEE STD 450-1975, Sec. 5.1-5.5, may be used when appropriate.

Test TE.ST.E.1 (Test Procedure for Measuring Battery Capacity and Round-Trip Efficiency) may be used for determining the capacity of lead-acid or nickel-cadmium batteries.

In cases where the above circumstances do not apply, refer to the manufacturer's instructions.

**Commentary.** The capacity of a battery storage subsystem can be expressed in ampere-hours (coulombic capacity), or watt-hours (energy capacity), or both, at a specific discharge rate.

A test of capacity may be made prior to installation in the form of an acceptance test and after installation in the form of a service or performance test. Tests may be repeated periodically according to the requirements of the user. When the battery begins to deteriorate, testing will indicate whether the battery has failed (defined by industry as a capacity below 80% of the rated capacity). Implicit in this is a need to be absolutely sure that all parties concerned are referring to the same capacity; i.e., new or end-of-life.
A new battery may require several charge/discharge cycles to attain its full capacity (cycling up) if plate formation is incomplete.

The capacity of any battery is a function of discharge rate, final discharge voltage, and temperature. Capacity decreases with increasing final discharge voltage and discharge rate, and increases with temperature. Thus, these operating parameters must be included in capacity specifications.

Tests may be conducted under standard operating conditions, under conditions typical of the application, under expected extreme operating conditions, or all of these. The essential element is that there be agreement between the vendor, the purchaser, and the end user about the appropriate test method and operating conditions.

Tests of capacity do not relate to safety; therefore, they generally should be conducted at the discretion of the purchaser or end user to verify specified performance. Questions of warranty may also require battery capacity tests. At present many capacity tests are conducted as part of experimental or demonstration projects to provide data for future designs. This latter situation is different from a purely commercial installation and generally warrants more testing in all areas.

**ST.E.2 Battery Efficiency**

**Criterion.** The efficiency of a new battery storage subsystem shall be equal to or greater than the efficiency specified for given test conditions.

**Evaluation.** For round-trip efficiency, use TE.ST.E.1 (Test Procedure for Measuring Battery Capacity and Round-Trip Efficiency). For total in/out efficiency, use TE.ST.E.2 (Test Procedure for Measuring Total Battery In/Out Efficiency).

**Commentary.** Efficiency may be measured in terms of ampere-hour (coulombic) efficiency, watt-hour (energy) efficiency, or voltage efficiency. Generally, the watt-hour efficiency is more useful in system design, whereas the ampere-hour efficiency is more common in battery design terminology. Voltage efficiency is rarely used.

As with capacity, efficiency is a function of the battery operating parameters. Thus, specification of efficiency should include the operating parameters under which the test is conducted. The energy efficiency is lower at high rates of discharge. It is also a function of cell temperature, which must be considered during the design of the battery storage subsystem. Efficiency may decrease as the cell ages. Generally, efficiency is specified only for new cells.

Note the difference between round-trip and total in/out efficiency. The round-trip or cycle efficiency is useful for comparisons among batteries, and the total in/out efficiency is useful when examining a battery's performance within a PV system. The in/out efficiency will most likely not be measured once commercialization begins; however, for designer evaluating purposes, this test evaluation has been included.

From a system point of view, it is often desirable to have a battery efficiency that reflects the fraction of input energy available to the load over long periods of time. Parasitic losses within a PV system would not necessarily appear in a simple round-trip efficiency test. Parasitic losses can include the energy used to operate a battery ventilating system and air-lift pumps, the energy lost through self-discharge, or through...
equalization. The in/out efficiency test method reflects these parasitic losses by calculating the efficiency over numerous battery discharge/charge cycles.

ST.E.3 Voltage Window

**Criterion.** The battery shall provide the specified capacity when operated within the specified PV system's voltage window.

**Evaluation.** Compliance of this criteria with specifications can be evaluated by use of Test TE.ST.E.1 (Test Procedure for Measuring Battery Capacity and Round-Trip Efficiency).

**Commentary.** The voltage window is the range of voltages over which the battery is to be operated within the PV system. This window will usually be limited by the system's inverter; therefore, the battery manufacturer must be aware of the limitations to determine the most suitable voltage window. The decision should be made only after consultations between the battery and inverter manufacturers and the PV system designer.

The battery voltage is affected by the state of charge, charge/discharge rate, and temperature. The PV system designer must make certain that the battery will perform as desired, within the specified voltage window, under the full range of operating conditions. The PV system's voltage window should be chosen such that at low discharge rates the battery will not be overdischarged, and at high discharge rates a usable capacity (amount of energy) can be supplied to the loads.

ST.E.4 Discharge Rates

**Criterion.** The battery shall perform as specified when operated over the specified range of discharge rates.

**Evaluation.** This criterion's compliance with specifications can be evaluated by use of Test TE.ST.E.1 (Test Procedure for Measuring Battery Capacity and Round-Trip Efficiency). This test may be repeated at both the highest and the lowest discharge rates.

**Commentary.** If the PV system is to be used over a wide range of discharge rates (i.e., the application has a wide range of loads), a capacity test may be desirable at both the high and the low rate to cover both "worst case" conditions.

Normally, the high discharge rate is used to determine the final discharge voltage. However, if the lead-acid battery is operated at very low discharge rates, it is possible to over-discharge the battery to the extent that the specific gravity of the electrolyte is converted to a level below the recommended limit, making it extremely difficult to recharge. Therefore, the discharge rate must not be overlooked when designing the PV system.

ST.E.5 Equalizing Charge

**Criterion.** The capacity of the battery shall be restored to its specified value after completion of the specified equalizing charge procedures.
**Evaluation.** The battery shall be equalized as specified by the manufacturer. Battery current and terminal voltage shall be recorded throughout the equalizing charge. In the last hour of the equalizing period, each cell voltage shall be taken and recorded. At the end of the equalizing charge, each cell's specific gravity and cell temperature shall be read and recorded. Readings shall be checked for any large variations in specific gravities and voltages; i.e., if the specific gravity variation is greater than 0.020 g/cm³ or the voltage variation is greater than 0.100 V/cell, then the battery manufacturer should be notified, further checks or tests should be made on the suspect cell, and the equalizing period might have to be performed more often or for longer periods of time.

**Commentary.** Individual cells in a lead-acid battery often exhibit different self-discharge rates, capacities, and efficiencies. The purpose of the equalizing charge is periodically to bring all cells to a common state of charge and thereby minimize deterioration of certain cells. This is most important at the beginning of battery life in order to fully form the cells.

A second purpose of equalization in lead-acid batteries is to mix the electrolyte in the cells by generating gas bubbles. This eliminates stratification, which otherwise occurs during charging. Batteries with other mixing methods (such as mechanical stirring or airlift) do not need equalization.

The lead-acid battery manufacturer normally specifies a voltage, higher than that used for normal charging, of 2.60-2.75 V/cell for 5-10 V/cell hours. The equalizing charge may be carried out weekly, biweekly, or less often depending upon the particular application and use of the battery.

Not all batteries require an equalizing charge. For example, those that are on a float charge rarely need to be equalized. Nickel-cadmium batteries also rarely need to be equalized. If the battery's cells have a wide variation of capacities, then a normalization* may be desirable. This can be accomplished by a complete discharge to 1.0 V/cell followed by an overcharge, returning to the battery approximately 140% of its capacity.

**Thermal Attributes**

**ST.T.1 Battery Operating Temperature**

**Criterion.** The battery shall provide the specified capacity when operated within the specified cell temperature range.

**Evaluation.** This criterion's compliance with specifications can be evaluated by the use of TEST.E.1 (Test Procedure for Measuring Battery Capacity and Round-Trip Efficiency). This test should be performed at the expected temperature extremes with the manufacturer's recommended cell modifications (larger case, modified specific gravity, etc.). A table of "Cell Size Correction Factors for Temperature" can be found in ANSI/IEEE STD 485-1978, Table 1.

*Normalization is the term generally used by the nickel-cadmium industry for equalization.
Commentary. The charge/discharge characteristics as well as efficiency, capacity, lifetime, and final discharge voltage are functions of battery or cell temperature. Thermal management of the battery storage subsystem in the form of adequate heating and cooling must be provided to avoid excessively low and high temperatures, respectively (see also IEEE STD 484-1975, Sec. 4.1.1(4)). The battery electrolyte can be tailored to suit the temperature environment; however, lifetime and capacity are often reduced.

As the electrolyte temperature decreases, the battery's capacity falls off. Below 0°C (32°F) the reduction in capacity is somewhat greater per degree than that between 25°C and 0°C. At very low temperatures, a lead-acid battery is susceptible to damage by freezing electrolyte, especially at low states of charge. Nickel-cadmium batteries are not affected by freezing.

As the electrolyte temperature increases above 25°C, the battery's capacity increases, within certain limits. High temperatures also increase the general rate of deterioration in a battery. Electrolyte temperatures up to 52°C (125°F) can be compensated by decreasing the cell's specific gravity without serious reduction in the useful life of the battery. For further information see Ref. 8.

Mechanical/Structural Attributes

ST.M.1 Battery Structural Adequacy

Criterion. The batteries shall be supported throughout the design life of the system without structural failure (including those subsystems subject to seismic disturbances).

Evaluation. The structural adequacy of the battery supports shall be demonstrated by structural analysis.

Commentary. Battery supports are generally found in the form of "racks" or "feet" by which the batteries are slightly elevated to provide insulation, to allow access for the forks of a lift truck or lifting device, or to provide air circulation for ventilation and cooling. In some cases, the battery may be designed to sit on the floor.

Refer also to IEEE STD 484-1975, Secs. 4.1.3 and 4.2.1.

Safety Attributes

ST.S.1 Battery Electrolyte

Criterion. Provisions for personnel safety in the event of an electrolyte spill shall be located in or next to the battery area.

Evaluation. Review of the battery design and battery equipment list or maintenance manual shall be performed.

Commentary. Leakage of the sulfuric acid electrolyte of a lead-acid battery or the potassium hydroxide in a nickel-cadmium battery must be considered in the design. Standard techniques for protection of personnel and administrative procedures must be
followed to comply with the minimum requirements of OSHA. This is not required for residential applications. For lead-acid batteries, these techniques are outlined in Title 29, Part 1910, Subpart I: Personal Protective Equipment and in Subpart G: Occupational Health and Environment Control.

Recommended protective measures include respiratory, eye, and face protection as primary measures, and electrolyte handling gloves (rubber) and other clothing for protection of the body. The installation of electrolyte-resistant flooring in the vicinity of the batteries might be considered. To augment these protective measures, see also ST.B.1.

Burns caused by lead-acid battery electrolyte should be treated according to NAVSHIPS Manual 9623-907. Safety precautions to be followed while designing and installing lead-acid battery facilities are described in IEEE STD 484-1975, Secs. 3.0 and 4.1.1.

Residential systems must be constructed to keep children and unauthorized personnel safely away from electrolyte and high-voltage areas.

**ST.S.2 Battery Voltage and Current**

**Criterion.** The battery shall be provided with adequate protection against high battery voltage and current.

**Evaluation.** Review the battery design and electrical connections for adequate provisions of insulation, current interrupting devices, and grounding. (See also SY.S.3 and SY.S.4.)

**Commentary.** IEEE STD 484-1975 provides information on protective equipment and procedures for safe handling of the battery (Sec. 3.0), mounting of the battery and grounding the racks (Sec. 4.1.2), and alarms recommended for generating stations (Sec. 4.1.5).

All terminals and intercell connectors in PV battery systems over 60 V should be covered with a nonconducting material (dead top) to avoid accidental contact. For residential systems, it may be prudent to configure designs that permit minimal contact by the homeowner with any electrical portions of these systems. For large systems, access is likely to be restricted to knowledgeable technicians. However, this does not reduce the need to design a safe system.

Further protective measures include:

- Maintenance on batteries should be performed with the batteries open-circuited and isolated from ground. Such isolation should be tested before any maintenance is performed that requires electrical contact with a battery terminal. Personnel may be insulated from ground by using protective clothing, or a rubber sheet over parts of the floor and walls with which contact might be made, or both.

- Battery terminal covers should not interfere with the work immediately in progress. Care should be taken to avoid dangling conductive test items or other material which could cause a short circuit.

- Electrical shock hazard may be reduced by arranging the cell layout so that voltage differences between adjacent cells or rows of cells are minimal. Also, the batteries may be separated into individual groups by disconnect switches (National Electric Code, Article 480-6).
- Only qualified personnel should be allowed into the battery room, and the battery terminals should be designed for safety or to prevent contact by personnel.
- Only insulated tools and nonmetallic flashlights should be used near a battery or bus system. Extreme care should be taken never to short circuit any part of the battery since there are no circuit breakers in the cells to open a short, and no switches that can be thrown to deenergize the battery terminals.
- Rings, metallic watch bands, etc., should be removed when working near bus bars or batteries.
- Conductive support structures (racks) shall be insulated from cell and battery terminals with insulators rated for the full system voltage. Such structures shall be electrically grounded, as should conductive battery cases, for systems above 60 V.

**ST.S.3 Hazardous Gas Concentration**

**Criterion.** The battery area shall be provided with adequate protection against hazardous concentrations of flammable or toxic gases of any kind.

**Evaluation.** Battery chemistry, system ventilation, and the nearby environment should be analyzed.

The concentration of hydrogen in the battery area shall not exceed the flammability point of hydrogen (4% by volume). The minimum ventilation required is obtained by

\[
Q = \frac{0.027}{C} \cdot (I)(n)
\]

where
- \(Q\) is the ventilation rate required in cfm;
- \(C\) is the maximum allowable hydrogen concentration expressed as a percentage;
- \(I\) is that portion of the charging current passing through the cells which generates free hydrogen; and
- \(n\) is the number of cells in the battery.

Generally, the concentration used in that calculation is taken to be 2% to provide a margin of safety. See IEEE STD 484-1975, Sec. 4.1.4.

**Commentary.** The battery area must be designed to preclude any build-up of flammable or toxic gases. This is accomplished mainly by ventilation, either natural or forced. Batteries designed for low gassing levels over the operating voltage range often do not need active ventilation provisions where normal room air infiltration is adequate, while those designed for other criteria may require forced ventilation.

The possible effect of additional air circulation on the thermal management of the batteries should also be carefully reviewed. Where this could impede the battery's performance, it may be necessary to precondition the air or to limit the ventilation to only the charging cycle.

Also, consideration should be given to the possibility of a gas build-up in a dead air space (such as a false ceiling). Although it is nearly impossible to contain hydrogen, it may be possible for a temporary accumulation to occur that would exceed its flammability level, especially during a heavy gassing period.
Where practical, hydrogen recombiners can be used to reduce hydrogen build-up. They also help reduce the need for watering since most of the electrolyzed water is reclaimed. However, they add to the cost of a system and some types are prone to fouling. Lead-antimony batteries cannot use recombiners economically as they become poisoned by the antimony's gases. Progress is being made on filters for these batteries.

Flame arresters should also be considered as an additional safety feature on any battery system. These devices prevent any flames that might exist outside of the battery from getting inside the battery, causing it to explode. However, a wise safety precaution is to never permit smoking, arcing, or open flames near the batteries or the battery area. (Refer to IEEE STD 484-1975, Secs. 3.2(4) and 4.1.1(8).)

The use of antimony in the plates of a lead-antimony battery increases the hydrogen evolution because of higher charging currents. They also produce trace quantities of the toxic gases arsine and stibine; toxic levels are set by OSHA. However, these gases should easily be within acceptable limits if sufficient ventilation for hydrogen is provided and prolonged high charging rates are avoided. The battery manufacturer should be consulted regarding gassing rates and optimum charging voltages for specific cell designs.

**ST.S.4 Fire Protection**

Refer to performance criterion SY.S.5. See below for additional commentary warranting particular attention.

**Commentary.** Establish firefighting procedures and use extinguishers suitable for electrical fires. Pouring water on a battery fire may cause currents to flow. Hydrogen and oxygen may be released, which could lead to an explosion.

Ensure unobstructed aisles for quick exit from battery area in emergencies.

**ST.S.5 Battery Shelter**

**Criterion.** Adequate shelter shall be provided to protect the battery from harmful environments.

**Evaluation.** Review the battery shelter (building) and location. The shelter shall conform with state and local building codes.

**Commentary.** Battery shelters shall protect the battery from the environment to conform with the operating environment specified by the manufacturers. This includes limiting the battery's ambient temperature to a specified range while maintaining adequate ventilation.

In a harsh climate, a residential battery enclosure might be indoors, perhaps in a dry garage or basement area with suitable ventilation and thermal provisions. It might be a simple rain shelter or enclosure in a mild climate. Battery racks are optional and generally are used only to minimize space requirements. Many batteries are designed to sit directly on the floor in insulated cases. Corrosion protection if metal were exposed to acid spills and gases should be considered.
Durability/Reliability Attributes

ST.D.1 Battery Life

Criterion. The battery capacity shall remain above the specified value for the stated life when it is operated within its specified operating conditions.

Evaluation. Battery life cannot be evaluated without destroying the battery. Therefore, it is only practical to perform accelerated testing of the particular battery types and lots, and to evaluate in-field experiences. There is no universal manner or procedure for life testing.

Commentary. The life of a battery is determined by its construction and its operating conditions. The dominant effects and predicted change in battery capacity should be specified by the vendor for an appropriate range of operating conditions.

Lead-acid batteries often show a small initial increase in capacity with cycling, followed by a long period of nearly constant capacity, followed by a final decrease. Different mechanisms operate in the cell to affect its life. Some forms of battery abuse and misuse are as follows:

- Undercharging lead-acid cyclic batteries over a considerable period is one of the most common and most destructive forms of misuse. Due to the formation of excessive amounts of lead sulfate, the positive plates tend to expand and break up, and the negative active material hardens and loses capacity.
- Overcharging lead-acid cyclic batteries is another form of abuse that can have a serious effect on battery life; however, its effects are not as immediately obvious as those of undercharging.
- Overdischarging degrades battery life, and, if combined with undercharging, the effects are intensified. Strictly speaking, a battery is not overdischarged at any particular rate unless more than its capacity at that rate (the total charge in coulombs) has been taken out. For example, with deep discharge lead-acid batteries, it is highly undesirable and uneconomical to take out more than 80% of its rated capacity as a daily routine.
- A lead-acid battery left for a considerable period at a low state of charge will also have a reduced lifetime. The causes are the same as those for undercharging.
- High-temperature operation will increase the general rate of deterioration in a cell because of higher rates of undesirable chemical actions. This is due to an intensified interaction between the electrolyte and the active material.

Installation, Operation, and Maintenance Attributes

ST.I.1 Installation, Operation, and Maintenance Manual

Refer to performance criterion SY.I.1. See below for additional commentary warranting particular attention.
Commentary. In addition to the issues mentioned in performance criterion SY.I.1, the following procedures specifically pertaining to storage should be included in the manual:

(1) Installation: Although specifically directed toward large lead storage batteries, IEEE STD 484-1975, Secs. 5.1 and 5.2 provide a wide coverage of receiving, storage, and assembly procedures that can be applied to any battery. The battery manufacturer should be consulted if there is doubt about the applicability of parts.

(2) Maintenance: Although specifically directed toward large lead storage batteries, ANSI/IEEE STD 450-1975 covers a wide range of maintenance, testing, and replacement procedures that can be applied to most batteries. The battery manufacturer should be consulted if there is doubt about the applicability of any parts. Additional comments on maintenance procedures are listed below:

- Access to battery areas should be restricted either by room enclosure or electrical package enclosures. Normal maintenance procedures should not be dangerous if carried out by the appropriate personnel using specified procedures for the intended application. The design of the facility should reflect the expected levels of training of maintenance personnel. Installation qualifications shall be specified by the vendor in accordance with local building codes.
- Always exercise care when working around open cells to keep foreign material from falling into the cells.
- When frequent performance inspections are made, it is common practice to use pilot cells. Pilot cells are randomly selected (usually one in six); their performance is assumed to be representative of the battery's performance. If this technique is used, complete inspections should still be performed occasionally. (If any adverse conditions are found, a complete inspection should be considered prudent.)
- Normal usage of most batteries requires periodic addition of water to replace losses due to gassing and evaporation. Permanently sealed cells are exempt from this requirement. Water addition is necessary to maintain proper electrolyte specific gravity and to ensure that all plates are completely immersed. The interval for water addition depends on duty cycle, site environment, and battery type. The water added should meet or exceed purity requirements specified by the battery manufacturer (otherwise the battery may be damaged, have its life shortened, or the warranty may be voided). Low humidity may require more frequent watering and hence increase the maintenance requirements. This could be significant in increasing the life-cycle costs at remote sites.

(3) Disposal, Refund, and Return: Disposal of batteries represents a logistics and environmental problem unless properly done. Since battery metal (mainly lead) has significant salvage value, return to the metal scrap salvage dealer or battery reclaimer is a reasonable alternative. Refund policies (if any) must be stated, and a return method described.

(4) Warranty: To establish that a warranted battery fails to perform, it may be necessary to measure its capacity. Refer to Sec. ST.E.1.

ST.I.2 Maintainability

Refer to performance criterion SY.I.2. See below for additional commentary warranting particular attention.
Commentary. In addition to the issues mentioned in performance criterion SY.I.2, the following storage-specific comments should be considered:

- Batteries can be heavy and filled with corrosive electrolytes; therefore, they require appropriate equipment for installation and maintenance. Before installation, the handling equipment shall be inspected for its capacity. Repair and/or replacement of deficient equipment is mandatory to ensure handling safety.

- In any installation where the weight of a battery exceeds that which an installer can easily lift [23 kg (50 lb)], slings and lifting equipment are required. They shall be sufficient in size and capacity so that the procedure can be safely undertaken. Sling spreaders may also be necessary.

- There shall be sufficient operating space around the battery supports (racks, trays, or platforms) to permit safe movement of the lifting equipment (and the personnel necessary to operate it) without worry of damaging other batteries. The personnel involved in the installation shall be protected from possible electrolyte spills by goggles, gloves, aprons, etc., as appropriate to the facility. See manufacturers' recommendations and existing standards (IEEE 484-1975, for example).

Building/Site Attributes

ST.B.1 Plumbing

Criterion. Appropriate plumbing and drainage for personnel safety shall be located in the battery area.

Evaluation. Review the building design and installation drawings.

Commentary. Special safety showers and/or eyewash fountains may be provided in the battery room for use by personnel in the event of an electrolyte spill. Portable units may be preferable in small installations. If a shower is provided, care must be taken so the water from the shower does not splash onto the batteries.

A floor drain in the battery area may be provided, especially if the area contains a shower. The drain must not be connected to the normal plumbing but have a separate flow and containment.

An amount of neutralizing chemical sufficient to deal with any electrolyte spillage should be provided. In addition, electrolyte-resistant flooring in the battery area should be installed.
REFERENCES


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SECTION 7.0

CABLING

INTRODUCTION

Photovoltaic applications pose no different selection requirements for cabling than any other electrical power source. Technical requirements such as voltage, current to be carried, external thermal conditions, voltage regulation, and other special requirements need to be considered. A study of the conditions that the cable will have to meet, and a study of cable types available and their recommended applications, may determine a sole candidate. If several types are suitable, however, then usually the most economical one is chosen.

After the appropriate type of cable is chosen, the conductor size can be determined. The information needed to determine proper size includes four criteria:

- the current required by the intended load;
- the maximum ambient air temperature;
- the distance from the source of supply to the intended load; and
- the voltage drop.

Because of the wealth of information that already exists on cabling practices for other power system types, which will not have to be amended for PV installations, this section is relatively brief, but further information may be obtained from Refs. 1 and 2. Further information on the ampacity of cables is contained in National Electrical Code (NEC) Article 310.

PERFORMANCE CRITERIA

Electrical Attributes

CA.E.1. Cable Conductor Sizing

Criterion. The cable conductor size shall be such that electrical losses resulting from cabling shall be within the specified energy loss budget of the system.

Evaluation. Cabling design shall be analyzed to determine that wire sizing satisfies the energy budget of the system. This procedure generally will satisfy any NEC requirements that consider wire heating rather than efficiency. Nevertheless, compliance with the provisions of Article 310 of the NEC shall be assured. Maximum current of modules for this analysis shall be short-circuit current.

Commentary. Wires have a finite resistance corresponding to the length, size (diameter), and material of the wire. Power losses may be expected because of this resistance, and these losses should be kept within the system energy budget. (It may be necessary to balance the economics of wire size costs against the gains in power output of larger
In addition, the NEC has defined acceptable current-carrying capacities for wires of different sizes and materials. These represent a safety feature and should be examined to ensure operation within acceptable limits, including short-circuit conditions if no overcurrent protective devices are provided. In no case shall the wires be continuously loaded under normal or fault conditions beyond NEC stipulations that describe acceptable current loading as a function of wire size, ambient temperature, and temperature rating of the wire for three conductors in a raceway, or cable, direct-earth burial.

In choosing a cable for an intended load, its environment should not cause it to exceed its temperature-to-voltage limits as specified by the Insulated Power Cable Engineers Association (IPCEA). Tables of current-carrying capacities based on heating for various sizes and types of cable have been issued by IPCEA and the NEC.

**Safety Attributes**

**CA.S.1. Cable Flammability**

**Criterion.** The cabling used in photovoltaic systems shall not propagate flames beyond their area of original occurrence.

**Evaluation.** The cabling used shall be rated VW-1 per UL 44 Rubber Insulated Wire, et al.

**Commentary.** If flaming of a segment of a photovoltaic array does occur, all attempts should be made to confine it to the area of original occurrence. The use of wiring rated as described above will help accomplish that result.

**CA.S.2. Clearances**

**Criterion.** Clearances between overhead supply cables and all other cables and structures should conform to Sec. 23 of ANSI C2.

**Evaluation.** Conformity to instructions contained in ANSI C2. Review of installation drawings and specifications.

**Commentary.** It is important to maintain safe distances between operating cables.

**CA.S.3. Fire Codes and Standards**

**Criterion.** Cable assemblies and their installations shall comply with local and nationally recognized codes and standards for fire safety.

**Evaluation.** Drawings and specifications shall be reviewed for conformity to local and nationally recognized codes and standards for fire safety, including but not limited to applicable sections of NFPA 89M, FFPA 90A and 90B, NFPA 211, NFPA 54, NFPA 30, NFPA 31, NFPA 256, the NEC and HUD standards. In cases where sufficient engineering information is not available, testing to show compliance may be required. Potential heat, rate of heat release, ease of ignition, and smoke generation will be considered in assessing potential fire hazards.


**Durability/Reliability Attributes**

**CA.D.1. Cabling and Connectors**

**Criterion.** Cabling and connectors shall be sufficiently rugged and long-lived to withstand all system operating conditions for the expected life of the system.

**Evaluation.** Specifications review, visual inspection, and high potential (hi-pot or Megger) testing, where applicable, shall verify conformance to this criterion.

**Commentary.** Cables must provide: adequate electrical isolation under all expected environmental conditions, long-term insulation integrity, and sufficient physical strength to allow installation under difficult conditions of bending and flexing. Attention must also be given to providing freedom from cable cross talk coupling within cable wiring, and prevention of excessive electromagnetic interference radiating from the cable system. Cables should be protected from damage by animals or vermin, particularly buried cabling. Appropriate NEMA or IEEE standards should be consulted.

**CA.D.2. Cable Loading Requirements**

**Criterion.** The cabling shall not be damaged by expected in-field ice and wind loading.

**Evaluation.** Drawings and specifications shall be reviewed in conjunction with weather data for the intended application site to determine adequate load capabilities.

**Commentary.** ANSI C2 governs the approved criteria for ensuring that cable systems maintain their structural integrity under in-service conditions. The strength requirements of cable support structures (if any) should be calculated using the data provided in Sec. 26 of the National Electric Safety Code, ANSI C2.

**CA.D.3. Solar Degradation**

**Criterion.** Cable components or materials shall not be adversely affected by in-service exposure to sunlight to an extent that their life-cycle function is impaired significantly.

**Evaluation.** Evaluation includes documentation of satisfactory long-term performance under certain use conditions, or engineering analysis.

**Commentary.** Some organic materials used in cabling may be particularly susceptible to solar degradation under prolonged exposure. When cable components or materials are exposed to UV radiation with or without an intermittent water spray at their maximum service temperature, there should be no signs of excessive deterioration such as cracking, crazing, embrittlement, loss in flexural strength, or any other changes that would significantly affect performance.

**CA.D.4. Moisture Resistance**

**Criterion.** Cable chosen for a specific application shall not be adversely affected by exposure to moisture to an extent that its function during its lifetime is impaired significantly.
**Evaluation.** This includes documentation of satisfactory long-term performance under usage conditions, or engineering analysis. Where adequate information is unavailable, methods that demonstrably meet the intent of the criterion should be used.

**Commentary.** Moisture is exhibited in several forms; e.g., rainfall, melting snow and ice, or condensation. The intent of this criterion is to ensure adequate performance of cable components or materials that probably will be exposed to moisture.

**Installation, Operation, and Maintenance Attributes**

**CA.I.1. Installation, Operation, and Maintenance Manual (see SY.I.1)**

**CA.I.2. Cabling Installation**

**Criterion.** Cable shall be installed according to accepted cabling installation practices, consistent with the level of complexity of the photovoltaic system.

**Evaluation.** Installation shall be evaluated by determining conformity to plans and specifications developed from accepted industrial practices.

**Commentary.** Because of the diverse applications for cable installation, it is not possible to specify every contingency. One excellent overall source, especially applicable to intermediate load center and central station applications, is Ref. 1. (See particularly Chapter 8, Cable Installation, and Chapter 9, Cable Joints and Terminations).

The complexity of any cable system and the way it is installed depend on its particular application. Remote applications might require a solitary cable buried in a shallow ditch, while central station applications would involve many diverse installation practices. As the size and complexity of the intended application increase, so do established standards and practices. For central station applications, the utility will issue standards to guide the installer, operator, or maintenance person in each specific task.

In utility interactive solar applications, the architect and engineer should discuss the primary needs of voltage and capacity with utility representatives, and from that discussion the utility will determine what type of cabling it needs to furnish to the work site. Also, depending on power requirements, it will specify to the architect and engineer the type of metering needed and whether a vault would be needed as well. The utility will furnish its cabling and ancillary equipment—without the meter in residential applications, and without the utilization transformer or vault in intermediate load center applications. The utility will also be available to advise the architect and engineer on matters pertaining to cabling and concomitant equipment that connect to the utility lines, within the confines of the intended application. In stand-alone solar applications, the architect and engineer should devise installation procedures according to the complexity of the intended application. Various standards and standard operating procedures exist, and help is available from the distribution division of the nearest utility. Another source of assistance is the field service personnel of the cable manufacturer.
CA.I.3. Cable Maintenance

**Criterion.** The maintenance manual for the system shall specify inspection intervals for system cabling. (See also SY.I.1.)

**Evaluation.** Evaluation will determine conformity to inspection and maintenance procedures developed from accepted industrial practices.

**Commentary.** The frequency of inspections and maintenance varies according to the complexity of the intended application, and is usually determined locally from operating experience. Refer to Ref. 1, Chapter 11, Cable Testing, Fault Location and Cable Identification, and Chapter 12, Records, Repairs and Maintenance.

Cables are tested at the factory, but they can be damaged before put in service, and their life expectancy can be shortened in service. Cables interconnect various apparatus that are often great distances apart, which subjects them to many hazards. Cables may be installed in hard-to-reach locations such as underground, under floors, under water, on poles, or in conduits; therefore, they are not readily accessible for periodic inspection. They are frequently installed and forgotten until something goes wrong. Accessibility to all cables, particularly at termination points, is recommended.
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SECTION 8.0
POWER DISTRIBUTION SUBSYSTEM

INTRODUCTION

The power distribution subsystem is the electrical and physical interface between a power conditioning subsystem and electrical loads. It also contains the interface between a utility power source and the electrical loads and power conditioning subsystem. The function of this interface is to provide:

- the electrical connection between a power source and loads;
- system overload and short-circuit protection; and
- manual circuit disconnect capability.

Power in the subsystem may be of three types: AC, regulated DC, and unregulated DC. Unregulated DC power is power delivered to a load at a variable voltage; for example, the power supplied directly from a bank of batteries. Regulated DC power is power delivered at a fixed voltage and/or current.

A power distribution subsystem consists of a protective cabinet containing breakers or relays for each separate load circuit and a main breaker for input conductor overcurrent protection. Manual disconnect capability is essential to provide safe conditions for servicing system components. The power distribution subsystem may be designed to contain electronic relays that accept control signals from a system monitor and control unit.

A residential power distribution subsystem may simply be the "fuse box" that currently exists in a residence. Additional control relays will be used in those systems utilizing load shedding or load switching as dictated by a system monitor and control unit. For all systems, the power distribution subsystem provides the access location for the physical interconnection to and control of the various load circuits. The power distribution subsystem may be designed to contain electronic relays that accept control signals from a system monitor and control unit.

PERFORMANCE CRITERIA

Electrical Attributes

PD.E.1. Power Distribution Power and Voltage Capability

Criterion. The electrical components of the power distribution subsystem shall be appropriate for the power type and load voltage level requirements.

Evaluation. Satisfactory review of electrical system drawings and component specifications shall indicate conformance.
PD.E.2. Utility Interface Design

**Criterion.** The power distribution subsystem to utility power interface shall be designed to conform with applicable codes and practices regarding safety and design considerations.

**Evaluation.** Review of the electrical connection drawings shall indicate conformity to the applicable portions of the National Electrical Code (NEC) and applicable practices of the local utility.

**Commentary.** The NEC contains the requirements for designing and installing the electrical interface between the utility and the application. These requirements, however, apply to receiving energy from, rather than sending it to, the utility (as would occur in a utility sell-back arrangement).

The portions of the NEC that apply to receiving energy from the utility are:

- Article 220 - sizing for the feeder (load) of the application;
- Article 230 - requirements for the electrical service (utility) connection and equipment for control and protection of the electrical service and installation requirements;
- Article 240 - overcurrent (circuit breaker) protection; and
- Article 250 - grounding.

If the application is a residence, NFPA No. 701A, an excerpted version of the electrical code, is available.

While it may be desirable to sell back the energy generated by the photovoltaic energy source to the utility, NEC requirements for that interface do not presently exist. If the existing service conductors are used, the current returned to the utility cannot exceed their capacity. Until national guidelines and requirements are established, users desiring to feed energy back to the utility should consult their local utility for an acceptable method.

**Safety Attributes**

PD.S.1. Power Distribution Safety

**Criterion.** Power distribution shall comply with existing codes or established procedures governing the installation, operation, and maintenance safety requirements of junction boxes, circuit breakers, and DC and AC circuits.

**Evaluation.** Code conformity shall be verified by review of drawings and component specifications.

**Commentary.** The power distribution subsystem typically consists of a corrosion-proof metal cabinet housing the circuit breakers and/or relay switches, load busbars, and associated wiring. All wiring must be accessible for inspection. The cabinet must be covered and placed to prevent moisture or water accumulation. There should be no combustible material adjacent to the distribution panel.
The circuit breaker status (on/off) should be clearly marked for both switch positions, and the current and voltage rating should be indicated. Once a trip point has been set, the breakers should be tamper proof.

The distribution panel must be sized according to the number of electrical connections it will house, and breakers sized according to the capacity of the current conductors.

NEC requirements that may be applicable to the power distribution subsystem are contained in Articles 370, 240, and 250. Similarly, Underwriters Laboratories Standard for Molded Case Circuit Breakers and Circuit Breaker Enclosures, UL 489-1972, may also be applicable. Because of the possibility of reverse power flow, the circuit breaker may need to be suitable for use with a reversed line-load connection.

**PD.S.2. Load Disconnect Capability**

**Criterion.** The power distribution shall have the capability of manually disconnecting the power source from the load.

**Evaluation.** Satisfactory review of electrical system drawings and component specifications shall indicate conformance.

**Commentary.** Manual disconnect capability is essential to provide safe conditions for servicing system components. The power distribution center may be designed to contain electronic relays that accept control signals from the system monitor and control.

**PD.S.3. Utility Interface Design (See PD.E.2)**
APPENDIX A

GLOSSARY
INTRODUCTION

This glossary is a collection of some terms and nomenclature used in this document and defined by the task groups who developed the performance criteria. In some instances, definitions need to be reviewed and many accepted definitions may not apply to photovoltaic applications; hence, some new definitions have been derived that apply to current technology.

**Algorithm**

A prescribed set of well-defined rules or processes for the solution of a problem in a finite number of steps; for example, a full statement of an arithmetic procedure for evaluating \( \sin x \) to a stated precision.

**Array**

A mechanically integrated assembly of modules or panels with a support structure and foundation, tracking unit, thermal control, and other components, as required, to form a DC power producing unit.

**Array Field**

The aggregate of all solar photovoltaic arrays generating power within a given system.

**Array Subfield**

A group of solar photovoltaic arrays associated by a distinguishing feature such as field geometry, electrical interconnection, or power conditioning.

**Battery**

Two or more cells electrically connected for producing electrical energy. Common usage permits this designation to be applied also to a single cell used independently.

**Battery Capacity**

Generally, the total number of ampere-hours that can be withdrawn from a fully charged cell or battery.

Ampere-Hour Capacity (Coulombic)—The number of ampere hours which a storage battery can deliver under specified temperature, rate of discharge, and final voltage.

Available Capacity—The total number of ampere-hours that can be withdrawn from a cell or battery for a specific set of operating conditions including discharge rate, temperature, initial state of charge, age, and cut-off voltage.
Installed Capacity—The total number of ampere-hours that can be withdrawn from a new cell or battery when discharged to the system-specified cutoff voltage at the system design rate and temperature (i.e., discharge to the system design specified maximum depth of discharge).

Rated Capacity—The rated capacity of a storage battery is the number of ampere-hours and/or watt-hours it is capable of delivering when fully charged and under specified temperature, rate of discharge, final voltage, and specific gravity.

Watt-Hours (Energy) Capacity—The total number of watt-hours (kilowatt-hours) that can be withdrawn from a fully-charged cell or battery. The energy capacity of a given cell varies with temperature, rate, age, and cutoff voltage. This term is more common to system designers than it is to the battery industry where capacity usually refers to ampere-hours.

Capacity Tests—
   a) Acceptance Test (lead storage batteries): A capacity test made on a new battery to determine if it meets specifications or manufacturer ratings.
   b) Performance Test (lead storage batteries): A capacity test made on a battery after being in service to detect any change in the capacity determined by the acceptance test.
   c) Service Test (lead storage batteries): A capacity test made to demonstrate the capability of the battery to meet the design requirements of the system to which it is connected.

Battery Cell
A storage cell (galvanic cell) for the generation of electrical energy in which the cell, after being discharged, may be restored to a fully charged condition by an electric current flowing in a direction opposite the flow of current when the cell discharges.

Battery Cycle Life
The number of cycles, to a specified depth of discharge, that a cell or battery can undergo before failing to meet its specified capacity or efficiency performance criteria.

   For example, with lead-acid batteries, end-of-life is generally taken as the point when a fully charged cell can deliver only 80% of its rated capacity. Beyond this state of aging, deterioration and loss of capacity begin to accelerate rapidly. Life may be measured in cycles and/or years, depending on the type of service for which the cell or battery is intended.

Battery Final Cutoff Voltage
The prescribed voltage at which the discharge is considered complete.

   The cutoff or final voltage is usually chosen so that the useful capacity of the battery is realized. The cutoff voltage varies with the type of battery, the rate of discharge, the temperature, and the kind of service. The term "cutoff voltage" is applied more particularly to primary batteries, and the term "final voltage" to storage batteries.
Battery Efficiency
The ratio of the output of the cell or storage battery to the input required to restore the initial state of charge under specified conditions of temperature, current rate, and final voltage.

Ampere-Hour (Coulombic) Efficiency ($\eta_{Ah}$)—The electrochemical efficiency expressed as the ratio of the ampere-hours output to the ampere-hours input required for the recharge of a storage battery.

$$\eta_{Ah} = \frac{\text{ampere-hours discharged}}{\text{ampere-hours of charge}} = \frac{\int_0^{t_d} i_d \, dt}{\int_0^{t_c} i_c \, dt}$$

where $i_d$ and $i_c$ are the discharging and charging currents, respectively, and $t_d$ and $t_c$ are the discharging and charging times, respectively.

Voltage Efficiency ($\eta_v$)—The ratio of the average voltage during the discharge to the average voltage during the recharge of a storage battery.

$$\eta_v = \frac{\text{avg. discharge voltage}}{\text{avg. charging voltage}} = \frac{\frac{1}{t_d} \int_0^{t_d} V_d \, dt}{\frac{1}{t_c} \int_0^{t_c} V_c \, dt},$$

where $V_d$ and $V_c$ are the discharging and charging voltages, respectively, and $t_d$ and $t_c$ are the discharging and charging times, respectively.

Watt-Hours Energy Efficiency ($\eta_w$)—The energy efficiency expressed as the ratio of the watt-hours output to the watt-hours of the recharge of a storage battery.

$$\eta_w = \frac{\text{watt-hours discharged}}{\text{watt-hours charged}} = \frac{\int_0^{t_d} i_d V_d \, dt}{\int_0^{t_c} i_c V_c \, dt},$$

where $i_d$ and $i_c$ are the discharging and charging currents, respectively; $V_d$ and $V_c$ are the corresponding voltages, and $t_d$ and $t_c$ are the discharging and charging time, respectively. The watt-hour efficiency is approximately equal to the product of the voltage and ampere-hour efficiencies.

Battery Self-Discharge (Local Action)
The loss of otherwise usable chemical energy by spontaneous currents within the cell or battery regardless of its connections to an external circuit.
Branch Circuit
A number of modules or paralleled modules connected in series to provide DC power at the system voltage.

Bypass Diode (shunt diode, shadow diode)
A diode connected in parallel with solar cells or groups of solar cells such that when one or more of the cells becomes shadowed, fractured, or fails in an open circuit mode, the diode becomes forward biased and permits current to flow around the affected cells.

Cell Bus
The portion of the cell contact that conducts current from the grid lines to the contact pads (see Cell Contact Elements, Figure A-1).

Cell Contact
Electrically conductive continuous or patterned coating on the surfaces of a solar cell to make contact with the cell or to collect cell current, or both (see Cell Contact Elements, Figure A-1).

Cell Efficiency (at peak electrical performance operating conditions, $\eta_C$)
The ratio of solar cell peak power at 28°C junction temperature to total irradiant power of RIS spectrum incident on the illuminated cell area. Flat-plate cells are normally referenced to 1000 W/m² RIS irradiance level; cells designed for concentrated sunlight applications are normally referenced to the RIS irradiance level expected in service.

Charge Rate
The current applied to a cell or battery to restore its available capacity.
The charge rate can be expressed in amperes (or watts if a constant power is applied) but is commonly normalized with respect to the rated capacity of the battery. For example, given the rated ampere-hour capacity $C$ and the actual charging current $I_c$, the charging rate is expressed as:

$$\frac{C}{C/I_c} = \frac{C}{T_N}$$

where $T_N$ is a nominal unit of time in hours.

Therefore, given a 500-ampere-hour battery being charged by a 50-ampere current, the charge rate becomes

$$\frac{C}{500/50}$$

or,

the C/10 rate.
Note that $T_N$ cannot be taken as the charging time. That is, the charge current cannot always be calculated by dividing $C$ by $T_N$ except when the recharge is started from approximately a 90% discharged status and the battery is then fully recharged. Ninety percent is commonly the ampere-hour efficiency of a lead-acid storage battery, and a full charge would therefore restore the battery to 100% of its rated capacity. For example, if less than 90% of the rated capacity were removed from a battery, then the time required to completely recharge would be less than what was indicated by $T_N$. Similarly, if greater than 90% were removed, the actual recharge time would be greater than $T_N$.

**Collector Efficiency** ($\eta_{CL}$)

Ratio of the total WRIS irradiant power incident on the receiver area divided by the total WRIS irradiant power incident on the module active aperture area.

In practice, the WRIS irradiant power is usually measured using a RIS spectrum and a measurement device with the same spectral sensitivity as the encapsulated cell to be used in service.

**Commutation**

The action of transferring current from one switching device to another in a power conditioning unit.

Stand-alone inverters must be self-commutated, but utility interactive inverters may make use of line commutation where the circuit operation depends on the utility line connection. Utility interactive inverters may also be self-commutated. Other types of commutation have been used, such as natural and load commutation, but generally in special applications.

**Concentrator**

A descriptor associated with elements of an array which generate DC power by direct electrical conversion of concentrated sunlight (e.g., concentrator cell, concentrator module, concentrator array).

**Concentrator Optics**

The optical concentrating portion of a module designed to operate with concentrated sunlight on the receiver.

**Concentrator Cell Assembly**

The smallest complete assembly of a solar cell(s) (which may be environmentally protected) designed to generate DC power under concentrated terrestrial direct sunlight.

**Contact Pad**

An area of the cell contact intended for attachment of cell interconnects; often a portion of the cell bus (see Cell Contact Elements, Figure A-1).

**Control Functions**

Control functions can be divided into three broad categories: permissive; protective; and optimization. Startup and automatic shutdown are permissive and protective functions, respectively.
**Depth of Discharge (DOD)**

The ampere-hours removed from a fully charged cell or battery, expressed as a percentage of rated capacity.

For example, the removal of 25 ampere-hours from a fully charged 100 ampere-hours rated cell results in a 25% depth of discharge. Under certain conditions, such as discharge rates lower than that used to rate the cell, depth of discharge can exceed 100%.

**Discharge Rate**

The current removed over a specific period of time from a cell or battery.

The rate can be expressed in amperes (or watts if the load is of constant power) but is sometimes normalized with respect to the rated capacity of the battery to comply with the charge rate terminology. For example, given the rated ampere-hour capacity \( C \) and the actual discharging current \( I_d \), the discharge rate can be expressed as:

\[
\frac{C}{C/I_d} = \frac{C}{T_N}
\]

where \( T_N \) is a nominal unit of time in hours (see Charge Rate). Again, it must be noted that \( T_N \) is not the discharge time. It is equal to the discharge time only when 100% of the rated ampere-hour capacity is removed from the battery. However, the final (end) voltage can interfere with the ampere-hour removal, hence an alternative expression to describe the rate is more commonly used. This rate is expressed as:

\[
\text{Actual number of hours taken to reach the rated end voltage} = \text{hour rate}
\]

For example, given that a battery's rated capacity is 500 Ah at the 5-h rate to an end voltage of 1.75 V/cell, the 3-h rate would be equal to the current (in amperes) necessary to discharge the battery to 1.75 V/cell in three hours. The 10-h rate would be the current necessary to discharge the battery to 1.75 V/cell in ten hours. Unfortunately, the battery's available capacity is not constant with discharge rate. Therefore, the discharge current cannot be calculated by dividing the rated capacity by the hour rate, except at the manufacturer's rating. For the above case, the current necessary to fully discharge the 500 Ah battery to 1.75 V/cell in 5-h would be 500/5 = 100 amperes. But the current at the 3-h rate might only be 145 A rather than 167 A, due to the fact that less than 500 Ah would be removed at the faster rate to the given end voltage of 1.75 V/cell. Similarly, at a slower rate, more than 500 Ah would be removed by the time the voltage reached 1.75 V/cell.
Electrolyte
A conducting medium in which the flow of electric current takes place by the migrations of ions.

The electrolyte for a lead-acid storage cell is an aqueous solution of sulfuric acid. (See Specific Gravity of Electrolyte.)

Encapsulation System (Flat Plate)
The portion of a module that consists of all the materials intended to protect solar cells and interconnects from environmental hazards, to provide electrical isolation, and to provide structural support for resisting structural loads such as handling and wind. The encapsulant system may consist of the following construction elements, two or more of which may be combined within the same material: Surface, front cover, pottant, porous spacer, dielectric, substrate, and back cover (see Encapsulation System Figure A-2).

Encapsulated Solar Cell Efficiency ($\eta_{EC}$)
Solar cell efficiency measured with protective encapsulation in place.

End-of-Charge Voltage
The cell or battery voltage at which the finishing charge is normally terminated by the charging source.

Equalization
The process of restoring all cells in a battery to an equal state of charge.
For lead-acid batteries, this is a charging process designed to bring all cells to 100% state of charge. Some battery types may require a complete discharge as a part of the equalization process.

Equalizing Charge
A continuation of normal battery charging, at a voltage level slightly greater than the normal end-of-charge voltage and at the finishing rate or less, to provide cell equalization of voltage and specific gravity within a battery.

Fill Factor (FF)
The ratio of the maximum power ($P_m$) to the product of the short circuit current ($I_{SC}$) and the open circuit voltage ($V_{OC}$):

$$FF = \frac{P_m}{I_{SC}V_{OC}}$$

Finishing Rate
The finishing rate for a storage battery is the rate of charge expressed in amperes to which the charging current for some types of lead batteries is reduced near the end of charge to prevent excessive gassing and increases in temperature.

Flat-Plate
A descriptor associated with elements of an array which generates DC power by direct electrical conversion of nonconcentrated sunlight (e.g., flat-plate cell, flat-plate module, flat-plate array).
Formation
The process, during manufacture or installation, by which the electrode or plate materials are transformed into the compositions required for cell operation.
A battery upon installation is not necessarily fully formed and could require several cycles before complete formation. The battery will be able to give its usable capacity, but not its rated capacity.

Gassing
The evolution of gas from one or more of the electrodes in a cell.
Gassing commonly results from local action (self-discharge) or from the electrolysis of water in the electrolyte during charging.

Geometric Concentration Ratio (R)
Module active aperture area divided by receiver area.

Grid Lines
The fine line portion of the cell contact that is used to collect electricity from the surface of the solar cell.

Illuminated Cell Area (A_{C})
The total surface area of the cell designed for illumination.
For flat-plate cells, it is the total cell area; for concentrator cells, bus areas not designed for illumination are excluded.

Illumination Mismatch Efficiency (\eta_{IM})
Ratio of cell efficiency under specified nonuniform illumination conditions to cell efficiency under ideal uniform illumination conditions.

Interconnect
Conductive element that electrically connects components of array elements.

Inverter
A unit which changes a DC input to an AC output.

Levelized Energy Cost
The cost of a PV system expressed as an equivalent uniform (levelized) annual amount, taking into account the time value of money divided by the annual energy generated by the PV system.

Maximum Power (P_{m})
The point on the I-V curve of a PV device where the product of current (I_{m}) and voltage (V_{m}) is maximum.
Maximum Power Point Tracker
A control strategy whereby system operation is always at or close to the PV array maximum power point.
Maximum power point tracking requires the presence of a load that can accept a variable power; for example, a storage battery, resistance heater, or a utility line connection.

Minimodule
A reduced-sized module with electrical components and connections identical to a full-sized module but differing only in size and electrical output.
Minimodules are constructed for the testing of characteristics (e.g., materials properties) not significantly affected by size and are utilized whenever testing of a full-sized module is neither physically nor economically desirable.

Mismatch Efficiency ($\eta_{\text{MIS}}$)
The ratio of the efficiency of a series/parallel assembly of cells or modules measured under uniform illumination conditions to the average efficiency of the individual elements (includes interconnect series resistance losses).

Module
The smallest complete, environmentally protected assembly of solar cells, optics, and other components (exclusive of tracking), designed to generate DC power under unconcentrated terrestrial sunlight.

Module Active Aperture Area ($A_A$)
That portion of the total aperture area of a concentrator module designed to contribute receiver illumination when the sun is on the optical axis.

Module Aperture Area Efficiency ($\eta_{\text{AA}}$)
Ratio of the active aperture area to the total aperture area for a concentrator module.

Module Packing Efficiency ($\eta_p$)
The ratio of the total active solar cell area to the total aperture area for a flat-plate module.

Module Total Aperture Area ($A_{\text{TA}}$)
Total module projected area normal to the optical axis.

Motive Power (Traction) Battery
A cell or battery that is intended to power electrically operated mobile equipment and is designed to be operated in a daily deep-cycle regime at moderate (C/6) discharge rates.
Net Present Value
The present value of all savings resulting from the PV system minus the present value of all costs associated with the PV system, including initial investment, replacements, and operation and maintenance (less salvage value).
Present value denotes the equivalent value at the present time of future cash flows; it is found by discounting future cash flows to the present to account for the time value (earnings potential) of money. The time value of money is indicated by a discount rate (interest rate) for which the value of a dollar received at some future time is equivalent to the value of a dollar received at the present time.

Nominal Operating Cell Temperature (NOCT)
The equilibrium solar cell junction temperature corresponding to nominal module service operating conditions in a standard reference environment of 800 W/m² irradiance, 20°C ambient air temperature, 1 m/s wind, and electrically open circuit.

Open-Circuit Voltage ($V_{oc}$)
The voltage value where the I-V curve crosses the voltage axis at zero current ($I=0$).

Optical Axis
A reference axis for a module or concentrator generally chosen as the module/illumination-source line which maximizes power output (often an axis of symmetry).

Overcharge (Overcharging)
To put into a storage cell or battery a charge in excess of that needed to return full capacity to the cell. Such overcharging can result in "gassing" or decomposition of the water in the electrolyte into hydrogen and oxygen gases.

Panel
A collection of modules fastened together, pre-assembled and wired, and designed to provide a field-installable unit.

Permissive Control Functions
Permissive control facilitates operation of the power conditioning unit, as well as the operation of the subsystems connected to it. In addition, permissive control determines the interconnections of the internal components within the power conditioning unit.
Permissive control actions allow the power conditioning unit to start up, synchronize, and interact with other systems, such as the utility. Closing a switch is a permissive control action since it allows interaction between connected components separated by the open circuit. Since permissive control actions allow specific components to interact, it is necessary, to ensure safe operation, that all possible control actions do not violate electrical/mechanical constraints specified by the manufacturer. Simple control actions such as closing a switch could cause damage to equipment, decrease the life of the system, and harm the operators. Transients caused by control actions shall be within the manufacturer's
specifications. Relays, like the under-voltage relay, initiate specific actions; these actions must not endanger other components, subsystems connected to the power conditioning subsystem, or the operator by creating electrical mismatches between components.

Photovoltaic Power System Monitor and Control Unit
The highest level of control that receives information from and sends signals to the thermal and electrical power conditioning subsystems through their monitor and control units.
Typically, the operator interacts with this functional unit.

Photovoltaic (PV) System
The total components and subsystems that combine to convert solar energy into electrical energy suitable for connection to an application load.
The major subsystems and their interfaces are the array, power conditioning, monitor and control, storage, cabling, and power distribution units. The auxiliary energy subsystem is not part of the PV system but is included in the total energy system. For a PV/thermal system, a thermal subsystem also is included.

Power Conditioning Subsystem Monitor and Control Unit
Second highest level of control that monitors and controls the components within, and the subsystems connected to, the power conditioning subsystem.

Power Conditioning Unit (PCU)
Equipment that pertains to a specific power conversion factor. A PCU is used to change input voltage level or waveform (or both) into a desired output voltage level or waveform.
The PCU can be specified and tested independently of the PVPS and generally includes all auxiliary functions required to control individual power handling devices, such as internal power supplies, error amplifiers, and self-protection features. A PCU will normally fall in one of the following general categories based on whether the input and output are primarily AC or DC:

DC-DC—Both input and output are DC. Power conversion may take place internally at high frequencies. Sometimes referred to as a converter.
DC-AC—The output is usually a single frequency sinusoid, while the input is DC. Usually referred to as an inverter.
AC-DC—The input is AC, usually sinusoidal, and the output is DC. Usually referred to as a rectifier, a DC power supply, or battery charger.
DC-AC/AC-DC—A bidirectional inverter that combines the functions of rectifier and inverter in a single unit.
AC-AC—The input is AC and the output is AC, usually sinusoidal, of a frequency different from that of the input. Usually called a frequency converter. One circuit that has been used to perform this function is a cycloconverter.
Power Factor
The ratio of real power (watts) to apparent power (volt-amps) in an AC circuit. Displacement power factor is the ratio of fundamental watts to fundamental RMS volts times RMS amps, excluding the effects of all harmonic components; it could be called fundamental power factor.

Power Transfer Map
A graphical means of presenting complex load characteristics which can be accommodated by a PCU.

Rated Module Electrical Efficiency (Flat-Plate, $\eta_{FPM}$)
The amount of electrical power (watts) generated by a module at its maximum power point and 1000 W/m$^2$, AM 1.5, NOCT divided by the product of 1000 W/m$^2$ and the gross module area (m$^2$).

Receiver
The component designed to operate under concentrated sunlight, incorporating the concentrator cell assembly, and providing thermal energy removal.

Receiver Active Cell Area ($A_{RC}$)
Total active solar cell surface area within the receiver area.

Receiver Area ($A_R$)
Total receiver surface area (not projected area) designed for illumination when the sun is on the optical axis and measured in the intended plane(s) of the solar cell outer surfaces.

Receiver Packing Efficiency ($\eta_{RP}$)
The ratio of the receiver active cell area to receiver area.
Reference Irradiance Spectrum (RIS)

Ripple Current Ratio
The ratio of the AC ripple component to the DC component (average) of the current at a PCU DC interface.

Ripple Factor
An expression of an AC ripple superimposed on a DC average value. IEC Standard 411-1, Power Converters for Electric Traction Part 1, Sec. 4.2 defines it as:

\[ RF = \frac{X_{\text{max}} - X_{\text{min}}}{X_{\text{max}} + X_{\text{min}}} \times 100\% , \]

where \( X_{\text{max}} \) and \( X_{\text{min}} \) respectively, represent the maximum and minimum values of the variable \( X \). This is equivalent to

\[ RF = \frac{X \text{ (peak-to-peak)}}{2X \text{ (average)}}. \]

Series Resistance \((R_s)\)
The idealization of the internal resistance occurring in series with the cell output and caused by distributed resistance elements (e.g., resistance of diffused layer, ohmic contacts, and semiconductor/contact interfaces). (See Equivalent Circuit of a Solar Cell, Figure A-3.)

Short-Circuit Current \((I_{sc})\)
The current value where the \( I-V \) curve crosses the current axis at zero voltage \((V=0)\).

Shunt Resistance \((R_{sh})\)
The idealization of the internal resistance occurring in parallel with the cell output and caused by cell leakage between the front and back contacts. (See equivalent circuit of a Solar Cell, Figure A-3.)

Solar Cell
The basic photovoltaic device, which generates electricity when exposed to sunlight.

Solar Cell Efficiency \((\eta_C)\) (See Cell Efficiency.)

Specific Gravity (of an electrolyte)
The ratio of the weight of a given volume of electrolyte to the weight of an equal volume of water at a specified temperature.
Stand-Alone (SA)
A PCU or system that operates independently of the utility lines. It may draw supplementary power from the utility but is not capable of providing power to the utility.

State of Charge (SOC)
The available capacity in a cell or battery expressed as a percentage of rated capacity.
For example, if 25 ampere-hours have been removed from a fully charged 100-ampere-hours cell, the new state of charge is 75%.

Substrate
A functional element of the encapsulation system designed to have structural load carrying capability which is positioned on the back of the cells.

Subsystem Monitor and Control Unit
Supervises the subsystem energy flow and storage state and controls the subsystem in a safe and timely manner in response to internal signals and external signals from other subsystems.
Each major subsystem typically will contain a Monitor and Control Unit which may or may not exist as a separate unit. This unit will inform the external controller of impending unsafe conditions and act independently if system control does not respond or if it commands an unsafe action. Refer to the Monitor and Control section of this document for details.

Superstrate
A functional element of the encapsulation system designed to have structural load carrying capability which is positioned on the front of the cells and is optically transparent.

System Power Rating
The rated power of the PV array at NOCT and an irradiance level of 1000 W/m² modified by cabling and power conditioning subsystem losses at this array power level.

Uninterruptible Power System (UPS)
A power system that has sufficient redundant power sources and backup configurations so that output power can be continuously supplied (uninterrupted) even though the primary source of power has failed (interrupted) or the equipment has failed.

Unlimited Interactive Source/Sink
An element that can act as a source or a sink and has unlimited capacity. An example of this type of element is a utility line connection.
Utility Interactive (UI)
A PCU system capable of operating in parallel with and supplying power to the utility line.

Voltage Window
The range of voltages over which the array, power conditioning unit, or battery is to be operated.

Weighted Reference Irradiance Spectrum (WRIS)
Convolution of reference irradiance spectrum and the short-circuit current spectral response of the particular solar cell.
Figure A-1. Cell Contact Elements

Figure A-2. Encapsulation System. Structuring, designations, and functions of various elements of one type of flat-plate module encapsulation system; any necessary primers and adhesives are not shown.

Figure A-3. Equivalent Circuit of a Solar Cell
APPENDIX B

TASK GROUP AND COORDINATING COUNCIL MEMBERSHIP
APPENDIX B

This document owes much to the time and talents of many people from photovoltaic-associated companies and technologies. Without the benefit of their efforts to apply their combined experience, knowledge, and insight, this report could not have been prepared. Appreciation is extended also to former Department of Energy staff members Leonard Magid and Richard Santopietro, who monitored this task and provided guidance and encouragement. Their contributions were many and important.

Members of each of the panels involved in the preparation of this document and the areas of responsibility for each panel are presented here.

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The above task group participants prepared the performance criteria in Section 3.0 and the test methods in Volume II that have the identification code TE.AR. that appeared in the first edition.

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B-3
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The Task Group Steering Committee (TGSC) coordinated the integration of task group activities and their products into a final document. A technical review and editing team was drawn from the TGSC to refine the document format and to edit the report for technical content, consistency, and clarity. This team included Harry Schafft (NBS) and SERI staff members Gary Nuss, Paul Longrigg, Steve Hogan, and Tom Basso.

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<td>Applied Solar Energy Corp.</td>
</tr>
<tr>
<td>John J. Fayed</td>
<td>NEMA (formerly)</td>
</tr>
<tr>
<td>Steve Forman</td>
<td>MIT/LL</td>
</tr>
<tr>
<td>Robert G. Harris</td>
<td>Underwriters Laboratories, Inc.</td>
</tr>
<tr>
<td>Gary Jones</td>
<td>Sandia National Laboratories</td>
</tr>
<tr>
<td>William Kaszeta</td>
<td>Solavolt International</td>
</tr>
<tr>
<td>James M. Marler</td>
<td>General Electric Company</td>
</tr>
<tr>
<td>William Masters</td>
<td>Acurex</td>
</tr>
<tr>
<td>Robert McGinnis</td>
<td>Photowatt International, Inc.</td>
</tr>
<tr>
<td>Michael Merchant</td>
<td>MCM Enterprises</td>
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<tr>
<td>Edward Passerini</td>
<td>University of Alabama</td>
</tr>
<tr>
<td>Steve Patrick</td>
<td>Wyle Laboratories</td>
</tr>
<tr>
<td>David Redfield</td>
<td>Institute of Electrical and Electronics Engineers (RCA)</td>
</tr>
<tr>
<td>Donald R. Roberts</td>
<td>Westinghouse Electric Corp.</td>
</tr>
<tr>
<td>Ron Ross</td>
<td>JPL</td>
</tr>
<tr>
<td>Joan Shorey</td>
<td>Solar Lobby</td>
</tr>
<tr>
<td>George Storti</td>
<td>Solarex Corporation</td>
</tr>
<tr>
<td>A. M. Wilson</td>
<td>Electronic Industries Association</td>
</tr>
<tr>
<td>William Yerkes</td>
<td>ARCO Solar, Inc.</td>
</tr>
<tr>
<td>Gene Zerlaut</td>
<td>American Society of Testing Materials (ASTM)</td>
</tr>
</tbody>
</table>

The Coordinating Council provided valuable support through coordination activities, guidance, recommendations, and review of this document.
## NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>ampere or amperes</td>
</tr>
<tr>
<td>AC</td>
<td>alternating current</td>
</tr>
<tr>
<td>Ah</td>
<td>ampere-hours</td>
</tr>
<tr>
<td>AM</td>
<td>air mass</td>
</tr>
<tr>
<td>ANL</td>
<td>Argonne National Laboratory</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>AR</td>
<td>antireflection</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>A_A</td>
<td>concentrator module active aperture area</td>
</tr>
<tr>
<td>A_C</td>
<td>illuminated cell area</td>
</tr>
<tr>
<td>A_R</td>
<td>receiver area</td>
</tr>
<tr>
<td>A_RC</td>
<td>receiver active cell area</td>
</tr>
<tr>
<td>A_TA</td>
<td>module total aperture area</td>
</tr>
<tr>
<td>BOCA</td>
<td>Building Officials Congress Administration</td>
</tr>
<tr>
<td>C</td>
<td>battery rated capacity</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>EIS</td>
<td>Environmental Impact Statement</td>
</tr>
<tr>
<td>EMI</td>
<td>electromagnetic interference</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>E_c</td>
<td>energy restored to a battery</td>
</tr>
<tr>
<td>E_d</td>
<td>energy removed from a battery</td>
</tr>
<tr>
<td>E_E</td>
<td>energy to equalize a battery</td>
</tr>
<tr>
<td>FF</td>
<td>current-voltage curve fill factor</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communication Commission</td>
</tr>
<tr>
<td>HUD</td>
<td>(U.S. Department of) Housing and Urban Development</td>
</tr>
<tr>
<td>I</td>
<td>current</td>
</tr>
<tr>
<td>IAS</td>
<td>Industrial Application Society</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IPC</td>
<td>Interim Performance Criteria</td>
</tr>
<tr>
<td>IPCEA</td>
<td>Insulated Power Cable Engineers Association</td>
</tr>
<tr>
<td>I-V</td>
<td>current-voltage</td>
</tr>
</tbody>
</table>
\[ I_v \] output current at a specified voltage
\[ I_m \] output current at maximum power
\[ I_{sc} \] output current at short circuit conditions
\[ i_c \] battery or cell charging current
\[ i_d \] battery or cell discharging current
\[ J \] irradiance
\[ JPL \] Jet Propulsion Laboratory
\[ LSA \] Low Cost Solar Array Project
\[ MIT/LL \] Massachusetts Institute of Technology/Lincoln Laboratories
\[ NASA \] National Aeronautics and Space Administration
\[ NBS \] National Bureau of Standards
\[ NEC \] National Electrical Code
\[ NEMA \] National Electrical Manufacturers Association
\[ NEPA \] National Environmental Policy Act
\[ NFPA \] National Fire Protection Association
\[ NOCT \] nominal operating cell temperature
\[ NTE \] nominal terrestrial environment
\[ NTIS \] National Technical Information Service
\[ OSHA \] Occupational Safety and Health Association
\[ PCU \] power conditioning unit
\[ PV \] photovoltaics
\[ PV/thermal \] photovoltaics/thermal
\[ P_m \] maximum power
\[ Q_c \] amount of charge restored to a battery
\[ Q_d \] amount of charge removed from a battery
\[ Q_e \] amount of charge to equalize a battery
\[ R \] module geometric concentration ratio
\[ RIS \] reference irradiance spectrum
\[ RMS \] root mean square
\[ R_S \] cell series resistance
\[ SA \] stand-alone
\[ SAE \] Society of Automotive Engineers
\[ Sandia \] Sandia National Laboratories
\[ SBCC \] Southern Building Code Conference
\[ SERI \] Solar Energy Research Institute

N-2
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC</td>
<td>state of charge of battery or cell</td>
</tr>
<tr>
<td>STD</td>
<td>standard</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
</tr>
<tr>
<td>T_B</td>
<td>battery electrolyte temperature</td>
</tr>
<tr>
<td>t_c</td>
<td>time interval to fully charge a battery</td>
</tr>
<tr>
<td>t_d</td>
<td>time interval to discharge a battery to its final voltage</td>
</tr>
<tr>
<td>t_e</td>
<td>recommended equalization interval</td>
</tr>
<tr>
<td>UBC</td>
<td>Uniform Building Code</td>
</tr>
<tr>
<td>UI</td>
<td>utility interactive</td>
</tr>
<tr>
<td>UL</td>
<td>Underwriters Laboratories, Inc.</td>
</tr>
<tr>
<td>UPS</td>
<td>uninterruptible power supply</td>
</tr>
<tr>
<td>V</td>
<td>volts or volt</td>
</tr>
<tr>
<td>VAR</td>
<td>volt-amperes-reactive</td>
</tr>
<tr>
<td>V_e</td>
<td>battery equalizing voltage</td>
</tr>
<tr>
<td>V_m</td>
<td>output voltage at maximum power</td>
</tr>
<tr>
<td>V_min</td>
<td>battery final discharge voltage</td>
</tr>
<tr>
<td>V_max</td>
<td>battery final charge voltage</td>
</tr>
<tr>
<td>V_oc</td>
<td>output voltage at open circuit condition</td>
</tr>
<tr>
<td>v_ave</td>
<td>wind velocity average</td>
</tr>
<tr>
<td>WRIS</td>
<td>weighted reference irradiance spectrum</td>
</tr>
</tbody>
</table>

**Greek Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>α</td>
<td>temperature coefficient for solar cell current</td>
</tr>
<tr>
<td>β</td>
<td>temperature coefficient for solar cell voltage</td>
</tr>
<tr>
<td>K</td>
<td>current-voltage curve correction factor</td>
</tr>
<tr>
<td>η</td>
<td>electrical conversion efficiency</td>
</tr>
<tr>
<td>η_AA</td>
<td>concentrator module aperture area efficiency</td>
</tr>
<tr>
<td>η_C</td>
<td>solar cell efficiency</td>
</tr>
<tr>
<td>η_CL</td>
<td>collector efficiency</td>
</tr>
<tr>
<td>η_E</td>
<td>battery energy efficiency</td>
</tr>
<tr>
<td>η_EC</td>
<td>encapsulated cell efficiency</td>
</tr>
<tr>
<td>η_FPM</td>
<td>flat-plate module efficiency</td>
</tr>
<tr>
<td>η_IM</td>
<td>cell illumination mismatch efficiency</td>
</tr>
<tr>
<td>η_MIS</td>
<td>mismatch efficiency</td>
</tr>
</tbody>
</table>
\( \eta_{\text{NOCT}} \quad \text{nominal operating cell temperature (NOCT) efficiency} \)

\( \eta_{\text{P}} \quad \text{flat-plate module packing efficiency} \)

\( \eta_{\text{Q}} \quad \text{battery round trip coulombic efficiency} \)

\( \eta_{\text{RP}} \quad \text{receiver packing efficiency} \)
SUBJECT INDEX FOR PERFORMANCE CRITERIA

Accessibility: SY.I.3

Antireflection coating: CE.M.1

Application-specific criteria/comments
   central station: CA.I.2
   intermediate load center: CA.I.2
   stand-alone: SY.E.5; SY.E.6; SY.E.7; PC.E.1; PC.E.4; PC.E.6; PC.E.8; PC.E.10;
       PC.E.16; PC.E.17; CA.I.2;
   utility interactive: SY.E.2; SY.E.3; SY.E.5; SY.E.6; PC.E.1; PC.E.5; PC.E.9;
       PC.E.11; PC.E.16; PC.E.17; CA.I.2; PD.E.2

Array/array field
   accessibility: SY.I.3
   capability for system (generic): SY.E.4
   cleaning tolerance: MO.M.10; AR.B.1
   concentrated light, damage by: AR.S.1
   design: SY.B.3; MO.M.12; AR.S.1; CR.M.10; AR.M.4; AR.B.1
   efficiency: AR.E.1; AR.E.2
   electrical output: AR.E.1; AR.E.2
   flammability: MO.S.2
   hail resistance: MO.M.8
   humidity stress: MO.D.3
   installation hazard: SY.S.6; SY.I.1
   lightning protection: SY.E.8
   loading (physical): AR.M.1; AR.M.2
   maintainability: SY.I.2
   manual: SY.I.2
   matching or modules and arrays: MO.E.4; MO.I.4
   monitor and control, provisions for: AR.I.6
   rain: MO.D.4
   safety procedures: SY.S.1
   soiling: SY.B.4; MO.M.9; AR.B.1
   shadowing: SY.B.1
   tracking and control: AR.I.6

Array subsystem (see also solar cell, module, receiver, array/array field)
   accessibility: SY.I.3
   capability for system (generic): SY.E.4
   design: SY.E.4; SY.E.8; SY.B.3
   handling: SY.M.2
   lightning: SY.E.8
   maintainability: SY.I.3
   output voltage range: PC.E.1
   PV/thermal design: SY.E.8; SY.E.9; SY.T.1; SY.M.3; SM.T.1; MO.T.2; MO.T.3;
       MO.T.4
   shadowing: SY.B.1
   shipping: SY.M.1

*For Performance Criteria Code: SY SM CE MO CR AR PC MC ST CA PD
See Document Section: 2 2 3 3 3 3 4 5 6 7 8
SUBJECT INDEX FOR PERFORMANCE CRITERIA* (continued)

Battery
abuse: ST.D.1
capability for system (generic): SY.E.6
capacity: ST.E.1
design: SY.E.5; ST.I.2
discharge rate: ST.E.4
efficiency: ST.E.2
equalizing charge: ST.E.5
fire protection: ST.S.4
hazardous gas: ST.S.3
life: ST.D.1
maintainability: ST.I.2
manual: ST.I.1
normalization: ST.E.5
operating temperatures: ST.T.1
plumbing: ST.B.1
safety: ST.S.1; ST.S.2; ST.I.2; ST.B.1
shelter: ST.S.5
shock hazard: ST.S.2
spills, protection against: ST.S.1
temperature, operating and extremes: ST.T.1
voltage window: ST.E.3

Cabling
clearance: CA.S.2
design: SY.E.8
fire codes and standards: CA.S.3
flammability: CA.S.1
grounding: SY.S.2
installation: CA.I.2
lightning: SY.E.8
loading (physical): CA.D.2
maintenance: SY.I.1; CA.I.3
manual: SY.I.1; CA.I.1
moisture resistance: CA.D.4
sizing, wire: CA.E.1
solar degradation: CA.D.3

Cleaning tolerance: MO.M.10; SY.B.4

Design aspects
array/array field: SY.S.6; SY.B.3; MO.M.12; AR.S.1; AR.M.4; AR.B.1
array subsystem: SY.E.4; SY.E.8; SY.B.3; MO.I.4
battery: SY.E.6; ST.I.2
cabling: SY.E.8
module: SY.E.8; SY.S.6; MO.E.2; MO.E.3; MO.E.4; MO.T.1; MO.T.2; MO.T.3;
MO.T.4; MO.M.1; MO.M.5; MO.M.6; MO.M.8; MO.M.9; MO.M.12; MO.M.18;
MO.M.19; MO.I.4; MO.S.3

*For Performance Criteria Code: SY SM CE MO CR AR PC MC ST CA PD
See Document Section: 2 2 3 3 3 4 5 6 7 8
SUBJECT INDEX FOR PERFORMANCE CRITERIA* (continued)

monitor and control (power conditioning) subsystem: MC.E.7; MC.S.1; MC.I.3
power conditioning subsystem: SY.E.5; SY.E.8; PC.E.2; PC.E.7
PV system: SY.E.8; SY.E.9; SY.T.1; SY.M.3; SY.I.4; SY.B.3; SY.B.4; ST.E.3; ST.E.4
PV system monitor and control: SM.E.1; SM.T.1
receiver: MO.E.3; MO.E.4; MO.M.7; MO.M.12; AR.M.4; CR.M.10

Efficiency
array/array field: AR.E.1
battery: ST.E.2
cell: CE.E.1; CE.E.2
module: MO.E.1; MO.I.4
power conditioning: PC.E.14
receiver: CR.E.1

Electromagnetic interference (EMI): SY.E.9; PC.E.2

Energy feedback (to utility): PD.E.2

Environmental impact: SY.B.2; MO.S.3

Environmental/use stress
  electromagnetic interference: SY.E.9
  general: MO.E.2; MC.I.5
  hail: MO.M.8
  humidity: CE.D.2; MO.D.3
  lightning: SY.E.8
  moisture: CA.D.4
  rain: MO.D.4
  soiling: MO.M.9
  solar weathering: MO.D.2; CA.D.3
  temperature cycling: CE.D.1; MO.E.2; MO.M.7; MO.D.1
  temperature-humidity cycling: CR.D.1
  temperature-voltage bias: CE.D.3

Fire
  codes and standards: CA.S.3
  protection: ST.S.4
  safety: SY.S.5

Flammability: MO.S.2; CA.S.1

Grounding: SY.S.2; SY.S.3; PC.S.4

Hail resistance: MO.M.8

Handling: SY.M.2; CE.M.2; CE.M.3

Harmonics: PC.E.10; PC.E.11

Hazards
  burn: SY.S.7; SY.I.3
  concentrated light: MO.M.11
  gas: ST.S.3

*For Performance Criteria Code: SY SM CE MO CR AR PC MC ST CA PD
See Document Section: 2 2 3 3 3 3 4 5 6 7 8

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SUBJECT INDEX FOR PERFORMANCE CRITERIA* (continued)

installation: SY.S.6; SY.I.1
shock: PC.S.1; ST.S.2
toxic materials release: MO.S.3

Hot spot heating: MO.E.3

Insurability: SY.I.4; SY.B.3

Interference susceptibility: MC.E.7

Loading (physical): MO.M.1; MO.M.2; MO.M.6; AR.M.1; AR.M.2; CA.D.2

Maintainability: SY.I.2; SY.I.3

Manual (installation, operation, and maintenance): SY.I.1; PC.I.1; MC.I.1; ST.I.1

Matching of cells, modules: MO.E.3; MO.E.4; MO.I.4

Material compatibility: MO.M.12; CR.M.4; CR.M.5; CR.M.6; CR.M.7; CR.M.8

Module

accessibility: SY.I.3
cleaning tolerance: MO.M.10
conscnpnted light, damage by: MO.M.11
design: SY.E.8; SY.S.6; MO.E.2; MO.E.3; MO.E.4; MO.T.1; MO.T.2; MO.T.3; MO.T.4;
MO.M.1; MO.M.5; MO.M.6; MO.M.8; MO.M.9; MO.M.12; MO.M.18; MO.M.19;
MO.I.4; MO.S.3
efficiency: MO.E.1
electrical insulation: MO.S.1
electrical interconnects: MO.M.7
electrical output: MO.E.1
environmental stress: MO.E.2; MO.M.7; MO.M.8; MO.D.1; MO.D.2; MO.D.3; MO.D.4
flammmability: MO.S.2
hail resistance: MO.M.8
handling: SY.M.2
hot spot heating: MO.E.3
humidity stress: MO.D.3
interchangeability: MO.I.4

matching of cells: MO.E.3; MO.E.4
material compatibility: MO.M.12; CR.M.4; CR.M.5; CR.M.6; CR.M.7; CR.M.8
monitor and control, provisions for: SY.I.2; AR.I.6;
loading (physical): MO.M.1; MO.M.2
PV/thermal: SY.E.8; MO.T.2; MO.T.3; MO.T.4
replacement: MO.I.1
rain exposure: MO.D.4
shipping: SY.M.1
soiling: MO.M.9
solar weathering: MO.D.2
support structure: MO.M.5; MO.M.6
temperature control: MO.M.18; SY.T.1
temperature cycling stress: MO.D.1

*For Performance Criteria Code: SY SM CE MO CR AR PC MC ST CA PD
See Document Section: 2 2 3 3 3 3 4 5 6 7 8
SUBJECT INDEX FOR PERFORMANCE CRITERIA* (continued)

terminals: MO.E.2
twist capability: MO.M.6

Monitor and control (power conditioning) subsystem
accessibility: SY.I.3
cabling: CA.D.1
capabilities for system (generic): SM.E.1
control panels: MC.I.2
design: MC.E.7; MC.S.1; MC.I.3
environment, tolerance to: MC.I.5
interference susceptibility: MC.E.7
maintainability: MC.I.3
manual: SY.I.1; MC.I.1
power consumption: MC.E.6
protective action: MC.E.4; MC.S.1
shutdown: MC.E.3; MC.E.4
software: MC.I.1
startup: MC.E.1; MC.E.2

Power conditioning subsystem
accessibility: SY.I.3
burn hazard: SY.S.7
capability for PV system (generic): SY.E.5
design: SY.E.5; SY.E.8; PC.E.2; PC.E.7
efficiency: PC.E.14
electrical characteristics
input: PC.E.1; PC.E.2; PC.E.3
output: PC.E.4; PC.E.5
fire safety: SY.S.5
frequency output: PC.E.12
grounding: PC.S.4
harmonics: PC.E.10; PC.E.11
insulation: PC.S.4
lightning: SY.E.8
maintainability: SY.I.2
monitor and control, provisions for: PC.I.4; PC.I.5; PC.I.6
operating conditions: PC.M.1
overload capability: PC.E.7
power factor: PC.E.8; PC.E.9
protective action: PC.E.15; PC.E.16; PC.E.17; PC.T.1
ripple, input: PC.E.2
shock hazard: PC.S.1
turn-on characteristics: PC.E.13
unbalanced load: PC.E.6
voltage regulation: PC.E.4

*For Performance Criteria Code: SY SM CE MO CR AR PC MC ST CA PD
See Document Section: 2 2 3 3 3 3 4 5 6 7 8
SUBJECT INDEX FOR PERFORMANCE CRITERIA* (continued)

Power distribution subsystem
  code conformity: PD.S.1
  electrical capability: PD.E.1
  manual disconnect: PD.S.2
  utility interface: PD.E.2

Protective action: SY.T.1; SM.E.4; SM.T.1; MO.T.1; MO.T.2; MO.T.4; PC.E.15; PC.E.16;
  PC.E.17; PC.T.1; MC.E.4; MC.S.1

PV system
  accessibility: SY.I.3
  auxiliary energy subsystem: SY.E.7
  burn hazards: SY.S.7
  codes, building, and safety: SY.S.1; SY.I.5
  computer simulation programs: SY.E.2
  design: SY.E.8; SY.I.4; SY.B.3; ST.E.3; ST.E.4
  economic performance: SY.E.3
  electrical interrupts: SY.S.4
  electromagnetic interference: SY.E.9
  energy performance: SY.E.2
  energy rating: SY.E.2
  environmental impact: SY.B.2
  fire safety: SY.S.5
  grounding: SY.S.2; SY.S.3
  handling: SY.M.2
  installation hazards: SY.S.6; SY.I.1
  insurability: SY.I.4; SY.B.3
  lightning protection: SY.E.8
  maintainability: SY.I.2
  manual: SY.I.1
  monitor: SM.T.1
  piping: SY.M.3
  power performance: SY.E.1
  parts replacement: SY.I.2
  power rating: SY.E.1
  reliability: SY.D.1
  safety: SY.S.1; SY.I.1; SY.I.2; SY.I.3
  shadowing: SY.B.1
  shipping: SY.M.1
  soiling: SY.B.4
  temperature control: SY.T.1; SM.T.1
  test locations: SY.I.2
  warranty: SY.I.1

PV system monitor and control
  capabilities of: SM.E.1; SM.T.1
  design: SM.E.1; SM.T.1
  electrical disconnects: SM.E.4; SM.E.5

*For Performance Criteria Code: SY SM CE MO CR AR PC MC ST CA PD
See Document Section: 2 2 3 3 3 3 4 5 6 7 8

I-6
SUBJECT INDEX FOR PERFORMANCE CRITERIA* (continued)

load management: SM.E.3
power flow control: SM.E.2
protective action: SM.E.4; SM.T.1

Receiver
concentrated light, damage by: MO.M.11
cleaning tolerances: MO.M.10
design: MO.E.3; MO.E.4; MO.M.7; MO.M.12
efficiency: CR.E.1
electrical interconnects: MO.M.7
electrical output: CR.E.1
humidity: MO.D.3
materials, compatibility of: MO.M.12; CR.M.4; CR.M.5; CR.M.6; CR.M.7; CR.M.8
monitor and control, provisions for: AR.I.6
piping: CR.M.10
rain: MO.D.4
replacement: CR.M.1; MO.I.4
soiling: SY.B.4; MO.M.9
solar weathering: MO.D.2
temperature control: MO.T.1; MO.T.2; MO.T.4
temperature cycling: MO.E.2; MO.D.1
temperature-humidity cycling stress: CR.D.1
terminals: MO.E.2

Replacement: SY.I.2; MO.E.1; MO.I.4; CR.M.1

Ripple: PC.E.2

Safety
acid spills: ST.S.1; ST.B.1
burn hazards: SY.S.7
cable clearance: CA.S.2
code conformance: SY.S.1; PD.E.2; PD.S.1; CA.S.3
concentrated light: AR.S.1
electrical interrupts: SY.S.4; SY.I.3; SM.E.4; SM.E.5; MC.S.1
fire protection/safety: SY.S.4; ST.S.5; CA.S.3
flammability: MO.S.2; CA.S.1
grounding: SY.E.8; SY.S.2; SY.S.3; PC.S.4
hazardous gas: ST.S.3
installation hazards: SY.S.6; SY.I.1
insulation: SY.E.8; MO.S.1; PC.S.4
manual: SY.I.1; PC.I.1; ST.I.1
manual/automatic disconnect: PD.S.2; MC.S.1
plumbing: ST.B.1
safety practices: SY.S.6; SY.I.1; SY.I.2; SY.I.3
shock hazard: PC.S.1; ST.S.2
toxic materials: MO.S.3

Shadowing: SY.B.1

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Shipping: SY.M.1
Software: MC.I.1
Soiling: SY.B.4; MO.M.9
Solar Cell
  antireflection coating: CE.M.1
  efficiency: CE.E.1; CE.E.2
  electrical output: CE.E.1; CE.E.2
  handling: CE.M.2; CE.M.3
  humidity stress: CE.D.2
  metallization (contact): CE.M.3; CE.D.1
  temperature cycling stress: CE.D.1
  temperature stress with voltage bias: CE.D.3
Storage subsystem (see battery)
Terminals: MO.E.2
Warranty: SY.I.1

*For Performance Criteria Code: SY SM CE MO CR AR PC MC ST CA PD
See Document Section: 2 2 3 3 3 3 4 5 6 7 8
These documents are a response to the Photovoltaic Research, Development, and Demonstration Act of 1978 (P.L. 95-590) which required the generation of performance criteria for photovoltaic energy systems. More than 100 experts in the photovoltaic field have contributed in the writing and review of the performance criteria. The performance criteria address characteristics of present-day photovoltaic systems that are of interest to manufacturers, government agencies, purchasers, and all others interested in various aspects of photovoltaic system performance and safety. The performance criteria apply to the system as a whole and to its possible subsystems: array, power conditioning, monitor and control, storage, cabling, and power distribution. They are further categorized according to the following performance attributes: electrical, thermal, mechanical/structural, safety, durability/reliability, installation/operation/maintenance, and building/site. Each criterion contains a statement of expected performance (non-prescriptive), a method of evaluation, and a commentary with further information or justification. Over 50 references for background information are also given. A glossary with definitions relevant to photovoltaic systems and a section on test methods are presented. Thirty test methods are included to measure performance characteristics of the subsystem elements.
HOW SOLAR CELLS WORK

A solar cell is a thin wafer of pure silicon crystal with minute amounts of phosphorous placed in the very thin top layer and boron in the thicker, lower layer. Narrow metal strips are plated on the top and a metal surface on the bottom. When the cell is exposed to sunlight, electrons, are dislodged within the crystal. The way in which the cell is made (in two layers) makes the electrons migrate upward in the top layer, into the metal strips, and out through an electrical circuit, forming a current. The electrons return through the lower metal surface to the cell. The sunlight dislodges a continuous stream of electrons into the circuit, maintaining a continuous electric current. Normally, many solar cells are connected together to produce a practical voltage level, and a power of about 10 watts per square foot of cell area.

FOR FURTHER INFORMATION

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Solar energy is one of the leading candidates among energy sources for the future, and direct (photovoltaic) conversion of sunlight to electricity is a leading technique in the solar energy field. Direct-conversion solar panels, made up of tens to thousands of small semiconductor cells made of crystalline silicon, have been used extensively in the space program and in many specialized, remote applications here on Earth.

They are simple — no moving parts — and reliable; their operations consume no fuel, emit no exhaust or noise. Silicon is one of the most abundant elements on the surface of the Earth. Unfortunately, they have been expensive — hundreds of dollars per watt of electrical power produced for spacecraft, and tens of dollars per watt in more recent Earth applications.

The Project

Caltech's Jet Propulsion Laboratory is at work on a ten-year project for the U.S. Department of Energy to make solar panels less expensive and more available for use. This Low-Cost Silicon Solar Array (LSSA) Project is working with a broad front of industry, universities, and government organizations, to simplify and speed production processes, improve the design and reduce the price of solar arrays, and stimulate the growth of the array industry.

JPL has awarded more than 75 contracts to the chemical industry, semiconductor electronics companies, solar-array manufacturers, and corporate and university research labs for process development, design studies, research, manufacturing, analysis, and testing. JPL itself is doing supplementary research, evaluation, and analysis in most areas.

Problems and Approaches

In order to improve the manufacturing of solar arrays we must attack every stage of the production chain. It begins with the silicon material from which the cells are made. Currently, it is expensive, highly purified, transistor-grade material. Some of the questions being investigated are: Will a lower, cheaper grade work well enough in solar arrays? Will mass production lower the price enough? Will new refining processes produce the correct grade in the required volume?

The next phase is providing the thin silicon wafers for solar cells. This is done at present by carefully growing long cylindrical crystals and slicing them like salami with a specially designed saw. Improvements to this method include faster and more mechanized crystal growth and multiblade saws. But there are also methods of growing thin, flat crystals — eliminating the sawing step, which wastes silicon and is time-consuming. These methods include a number of ways of producing silicon ribbon, from half an inch wide to several inches, and many feet long. Another approach may produce thin, large-area sheets, either grown directly or on a flat base material. Once the silicon wafer is produced, it must be made into a semiconductor solar cell. As many as 62 process steps may be required in this stage, with frequent handling of each silicon wafer. Many automation techniques are being analyzed, some based on wafers, others on ribbons or other sheet forms. Computer-controlled fabrication and assembly are also being studied.

Solar panels for space applications are provided with a thin glass filter for ultraviolet protection, but there are few other environmental hazards. Here on Earth, solar arrays must survive the attack of rain, hail, sea-spray in some uses, daily and seasonal temperature and humidity changes in any weather zone, winds up to hurricane force, blowing dust, smog, and the like. They must last for many years without special care. A semiconductor is a delicate device; should it be "hardened" or can it be hermetically sealed in transparent armor?

Design and Industry for Tomorrow

For cheap, mass production, the solar arrays must be manufactured in standard modules in the factory, and assembled to fit the user's needs at the site. We are working on standard designs to provide maximum adaptability and minimize expensive custom designing and assembly work in the field.

Finally, meeting the goals calls for rapid industrial change. The Project is working at several levels, from economic analysis to direct purchases of solar arrays from manufacturers, to understand this process and help it to occur with a minimum of difficulty. It appears to require cooperation and mutual understanding between scientific and engineering experts, business and industry entrepreneurs and managers, and government policy-makers. Ten years is a short time for this change to occur, especially when technical development is still going on.

The Low-Cost Silicon Solar Array Project is an element of the Department of Energy's Solar Photovoltaic Conversion Program, which is also studying and developing the total solar power systems, analyzing applications and new uses, and supporting research on new kinds of solar cells using different materials. The Program is supported by other Department of Energy and NASA Labs and contractors as well as by JPL, which is a NASA contract facility.