PERFORMANCE CRITERIA AND TEST STANDARDS FOR PHOTOVOLTAIC ARRAYS*

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ABSTRACT

This paper describes the purpose, rationale, and approach associated with the development of performance criteria and test methods for photovoltaic arrays as part of the Department of Energy's National Photovoltaic Program. These development efforts represent a new approach by the federal government to encourage and facilitate the development of technology in an infant industry. Included is a description of the forthcoming document, Interim Performance Criteria for Photovoltaic Energy Systems, and some examples of definitions, criteria, and test methods that are contained in that document.

1. INTRODUCTION

The objective of the United States Department of Energy National Photovoltaic Program is to bring photovoltaic systems--via research, development, and demonstrations aimed at achieving major cost reductions and market penetration--to the point at which they are able to supply a significant portion of the nation's energy requirements. To achieve significance as a renewable energy source, photovoltaic systems must be able to replace electrical energy currently being supplied by non-renewable sources. Thus, to enhance the likelihood of their eventual utilization, a key element in the overall photovoltaic program strategy is to support (1) the development of criteria to assess the performance of photovoltaic systems and (2) the development and documentation of testing methods for quantifying satisfactory performance (e.g., to measure electrical output or to determine environmental stress durability). Industry and user established performance criteria and test methodologies that gain wide acceptance in the photovoltaic community are essential for the protection of users (consumers), in promoting marketplace confidence, for comparing performance of different devices, and for ensuring reliable systems. These performance assessment needs were recognized in the provisions of the Photovoltaic Research, Development and Demonstration Act of 1978 (PL-95-590). Under that Act the Department of Energy, through the National Photovoltaic Program, has tasked the Solar Energy Research Institute (SERI) to develop an Interim Performance Criteria document for Photovoltaic Energy Systems. SERI established a Photovoltaic Performance Criteria and Test Standards Project whose overall objective is to stimulate the development and adoption of industry-established material, component, subsystem and system performance criteria and standards for the design, application, and operation of reliable and safe photovoltaic power systems.(1) In establishing this objective it was recognized that a traditional institutional framework for the development of consensus standards exists. One of the desired results of the project's efforts is the acceleration of the standards-setting process, which in turn can facilitate the widespread commercialization of photovoltaic technology.

2. PROJECT IMPLEMENTATION

To achieve the overall project goal four tasks were established: (1) definition of performance criteria and test methods, (2) development of laboratory accreditation/product certification guidelines, (3) development of validation methodologies, and (4) coordination of the efforts with consensus standards and code organizations. To accomplish these tasks various elements of the DOE photovoltaic program, the photovoltaic industry, public interest organizations, consensus standards groups, and others have been requested and are

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providing resources and expertise. It should be emphasized that the principal efforts to date--and the focus of this paper--is the first task, the definition of performance criteria and test methods.

The management structure for these efforts is given in Figure 1 together with the responsibilities of each management level. SERI began management of this project in 1978 with the establishment of the Coordinating Council. Its membership includes representatives from industry, voluntary consensus standards groups, public interest groups, independent test laboratories, prime contractors in the DOE photovoltaic program, and SERI. A steering committee made up of key program and project personnel oversees the development of performance criteria and test methodologies. The steering committee works through three task groups: Task Group 1 on the array subsystem led by the Jet Propulsion Laboratory; Task Group 2 on power conditioning, controls, storage, and cabling, led by the Massachusetts Institute of Technology/ Lincoln Laboratory; and Task Group 3 on the total system led by Sandia National Laboratory, Albuquerque. Major support to the task groups and to the overall project is being provided by persons from universities, and private industry, as well as from national laboratories such as Jet Propulsion Laboratory, MIT/Lincoln Laboratory, Sandia, National Bureau of Standards, and Solar Energy Research Institute.

The task groups' approach for developing is based on an iterative process whereby drafting assignments are given to individuals with

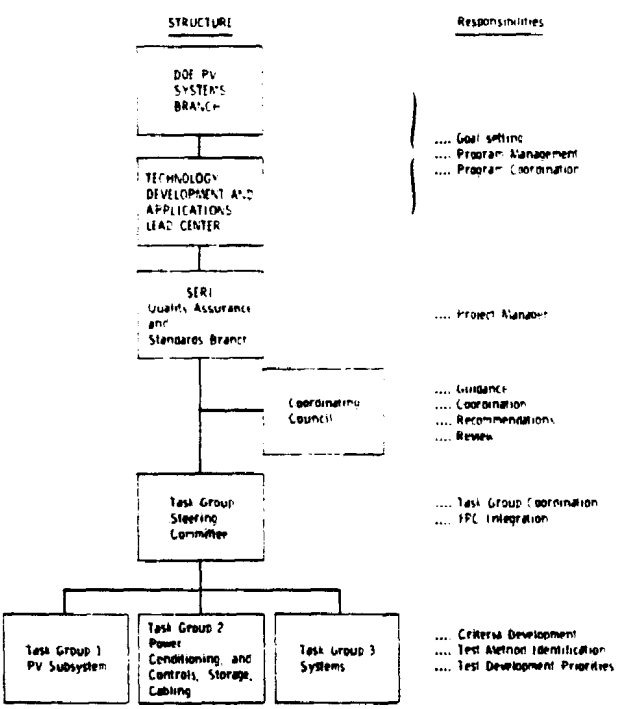

Fig. 1. Management Structure

appropriate expertise who prepare written drafts. These are then reviewed by the task group as a whole and are accepted, corrected, or redrafted. After achieving agreement on content and wording, the draft statement is forwarded to SERI for inclusion in the appropriate performance document.

3. PERFORMANCE CRITERIA DOCUMENT

One of the principal deliverables to the photovoltaic community by the Performance Criteria and Test Standards Project will be a document entitled "Interim Performance Criteria for Photovoltaic Energy Systems." The initial version of this document is scheduled to be published and distributed in mid-1980. The Interim Performance Criteria document provides performance and safety criteria and associated measurement techniques for criteria verification for terrestrial photovoltaic energy systems. This document is prepared from inputs to SERI developed by the task groups using the approach outlined above. Criterion is understood to be a characteristic (a distinguishing trait, quality, or property) of the photovoltaic system, subsystem, or component that is directly or indirectly related to performance and/or safety. Criterion verification refers to the techniques that can be used to measure performance and safety characteristics.

The objective of the Interim Performance Criteria document is to compile in a useful format criteria and test methods that can provide a technical resource for the entire photovoltaic community (industry, users, and government). The documentation of performance oriented criteria will establish a technical basis that can be used for procurement and evaluation programs for systems, subsystems, components, and materials; guidance for designers, producers, and the marketing and operation of photovoltaic energy systems; and a basis for the development of consensus standards; a basis for the development of more definitive performance criteria and test methods at a later date.

The Interim Performance Criteria document is organized on the basis of performance criteria for system and subsystems for terrestrial photovoltaic energy systems. The photovoltaic system and each of its subsystems are identified as chapters and by sections, which includes one or more elements (i.e., cell, module, etc.) of the system or subsystem. Each section containing performance criteria is further divided by eight performance attributes including: electrical; thermal; mechanical/ structural; safety; durability/reliability; installation, operation, and maintenance; and building and site.

All performance statement entries are presented in the criterion (characteristics), evaluation and commentary format. The criterion includes a qualitative statement(s). The qualitative statement(s) addresses the user need or expectation for the element (e.g., cell) being evaluated. It is a general statement of what the element will be able to do and what characteristic(s) are to be measured. The criterion does not establish the minimum and/or maximum levels for performance. Evaluation sets forth the methods of test and/or other information upon which an evaluative judgement or compliance with a criterion will be based. It states the standards, inspection methods, analysis, review procedures, historical documentations, and/or test methods which may comply with the criterion. It is expected, in some cases, that the review of documentation of in-use performance, or engineering analysis, will be used as evaluative tools in lieu of testing. Commentary provides background for the reader and presents the rationale behind the selection of specific data presented in the criterion and/or evaluation. It may also include, when desirable, a quantitative statement giving minimum and/or maximum levels of performance with supporting rationale. Test methods are given in the appendix of the document.

The Interim Performance Criteria document is intended to be a "living" document and will require updating as the photovoltaic technologies mature. For example, most of the field and laboratory experience to date has been with photovoltaic systems based on the use of single crystal silicon wafer technology. The initial version of the Interim Performance Criteria document is based on this history. Some of the criteria developed for single crystal silicon wafer technology will have to be modified before they can be applied to devices of other technologies. Additional performance criteria may have to be developed to properly evaluate systems based on these newer technologies.

Rule making bodies should recognize that most of the performance criteria included are not appropriate for use in codes.

4. EXAMPLES

To illustrate how definitions, criteria, and test methods used in the initial Interim Performance Criteria document evolved, three case histories for the array subsystem are examined below.

4.1 Terminology

The first problem to be addressed was the one of terminology. At the beginning of the standards activity a variety of terms was being used by the photovoltaic community for the same items or characteristics. Confusion relative to exactly what was meant by the terms "array," "panel," and "module" was abundant. The problem was approached by preparing a limited number of self-consistent nomenclature sets covering the complete hierarchy of photovoltaic array elements from the cell through the entire field of arrays. These candidate nomenclature sets were then debated and modified by the project's complete coordinating council at one of its early meetings. After considerable deliberation the terminology defined in Table 1 and illustrated in Figure 2 was accepted. These definitions encompass both flat-plate and concentrator array elements.

4.2 Cell Contact Metallization Integrity

An example of a mechanical/structural criterion and test method developed for solar cells is the one for contact metallization integrity. The purpose of this criterion is to ensure that the contact metallization of solar cells is capable of withstanding stresses due to the attachment of interconnects during manufacture and field use. Drafting responsibility was assigned to a solar cell manufacturer with broad experience in such testing associated with both terrestrial and space photovoltaic applications. The criterion statement is given in Table 2 and the test method in Table 3.

4.3 Module Thermal Characterization

An example of a thermal performance criterion and test method of widespread interest to the photovoltaic community is cell temperature control for flat plate modules. From the space program and early terrestrial experience it was well known that high cell operating temperatures adversely affect electrical performance and cause accelerated aging of the encapsulant. Based on JPL's experience in the assessment and testing of the thermal performance of flat plate modules, drafting responsibility for the criterion and test method was assigned to them. The resulting criterion statement is given in Table 4. The test method referenced is the procedure for determining the nominal cell operating temperature.

5. CONCLUSIONS

The development and dissemination of performance criteria and test methods for photovoltaic systems represents a portion of the activities of the federal government to encourage and facilitate the development of technology in this growing industry. The compilation of criteria and test methods provides a technical resource for the entire

Table 1 - Array Subsystem Definitions

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.

BRANCH CIRCUIT - A number of modules or paralleled modules connected in series to provide dc power at the system voltage.

ARRAY - A mechanically integrated assembly of modules or panels together with support structure and foundation, tracking, thermal control, and other components, as required, to form a dc power producing unit.

PANEL - A collection of modules fastened together, pre-assembled and wired, designed to provide a field-installable unit.

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.

CONCENTRATOR - The optical concentrating portion of a module designed to operate with concentrated sunlight on the receiver.

RECEIVER - The component designed to operate under concentrated sunlight, incorporating the concentrator cell assembly, and providing thermal energy removal.

CONCENTRATOR CELL ASSEMBLY - The smallest complete assembly of solar cell(s) (which may be environmentally protected) designed to generate dc power under concentrated terrestrial sunlight.

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

Table 2 - Solar Cell Contact Metallization Criterion

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 interconnectors during manufacture and service use.

EVALUATION. Contact metallization integrity shall be evaluated by using solar cell Contact Pull Strength Test (Method 303). For thin film solar cells, contact metallization integrity may best be determined by applying environmental stress to the completed module.

COMMENTARY. Solar cells used in flat plate or concentrator modules must have the basic capability of being connected together with an interconnector without loss of integrity of the cell contacts. Various interconnect attachment techniques and designs are likely to be used by the module manufacturer but in all cases the basic integrity of the cell contact is required. Since the above test is a destructive test, it is used as a qualification or in-process acceptance test on a sampling basis. The Contact Pull Strength Test used for discrete silicon cells will be suitable, in most cases, to evaluate the contact integrity of the provisions made for external contacts (terminals) to thin film devices.

Table 3 - Contact Pull Strength (Wire Pull Test) for Solar Cells

1. Purpose. The solar cell contact pull strength test is used to determine how well a contact is adhering to the cell surface and thus evaluate the integrity of interconnections to these contacts.

2. Apparatus. Pull tester equipped with a dynamometer for measuring pull force and a clamp for holding cell and the attached wire (Unitek Micropull Model 6-092-03 or equivalent); No. 26 gauge wire (Fed. Spec. QQ-W-343D or equivalent); soldering iron and solder.

3. Preparation.

Step 1 - Cut piece of No. 26 gauge wire (Fed. Spec. QQ-W-343D or equivalent) of sufficient length for clamping in tester.

Step 2 - Bend wire at .088 ± .013 cm (0.035 ± 0.005 inches) from end into a 90° ± 3° bend with a .025 cm (0.010 inch) radius.

Step 3 - Solder the bent wire tab onto the "N" contact (or "P" depending on the contact of test) of the cell so that the whole .089 cm (0.035 inch) dimension of the wire has a smooth uniform solder fillet. Position tab at 90° from cell surface according to Figure A.

4. Test Procedure.

Step 1 - Clamp cell with attached wire into pull tester.

Step 2 - Pull wire tab with increasing force until a predetermined acceptable contact strength level is reached (typically about 5 Newtons) or until a mechanical failure in the contact or the cell itself is experienced.

Step 3 - Record the maximum force achieved and the observed mode of failure.

5. Evaluation. If the solar cell contacts are able to withstand the predetermined minimum acceptable strength criteria, then the contact design and processes are acceptable and should have high reliability. If failure occurs below minimum acceptable and the mode of failure is contact peeling, then that manufacturing batch (or possibly that contact design) should be disqualified.

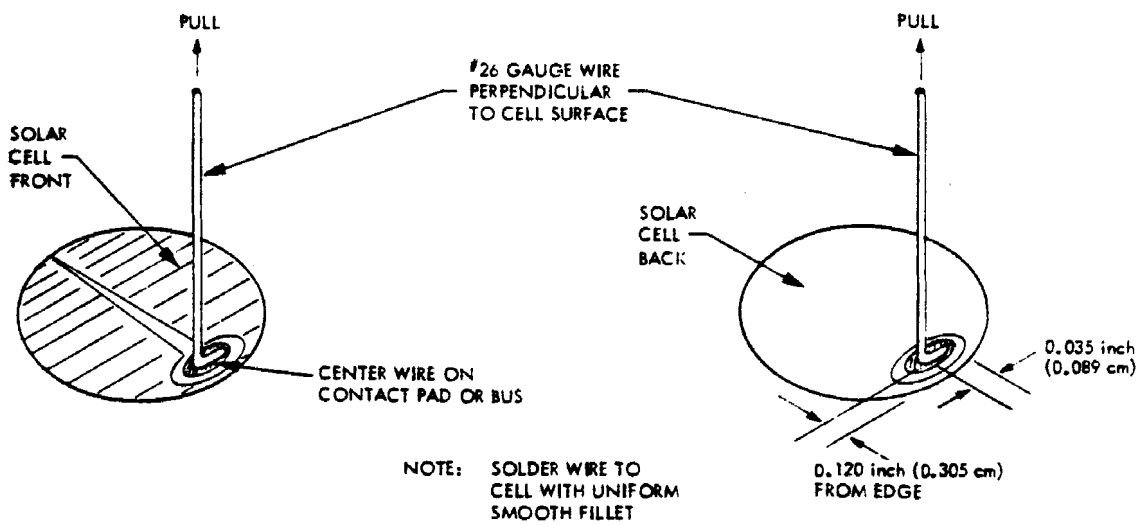

Fig. A. Solar Cell Test Position

photovoltaic community (industry, users, and government), and provides a basis for the development of consensus standards by consensus standards organizations, such as American Society for Test and Materials, the Institute of Electronics and Electrical Engineers, and others. Criterion and test methods are published in the Interim Performance Criteria document only after a critique and review by peers in the community.

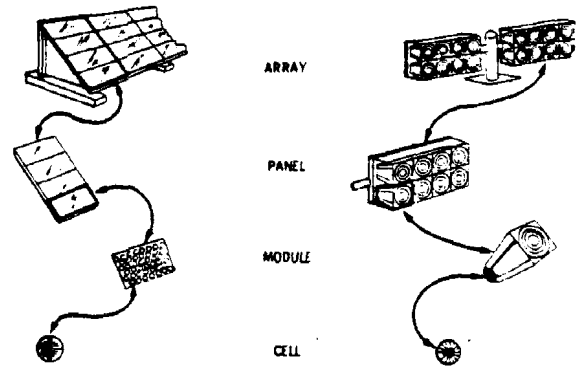

Fig. 2. Photovoltaic Array Terminology

6. REFERENCES

(1) Nuss, G. R., "Interim Implementation Structure for Development of Performance Criteria and Test Standards for Photovoltaic Systems," SERI/MR-61-270, Solar Energy Research Institute, Golden, Colorado, August 1979.

Table 4. Cell Temperature Control Criterion for Flat Plate Modules

CRITERION. Modules shall be capable of controlling electrical power loss and accelerated encapsulant aging caused by high cell operating temperatures.

EVALUATION. Test method 200.1 shall be used to measure the Nominal Operating Cell Temperature 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 M505, Solar Weathering.)

COMMENTARY. Electrical power output of PV solar cell modules decreases with increasing temperature (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 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 by avoiding an air gap between the front cover/encapsulant and the cells (i.e., avoid a "greenhouse" design).[1,2,3]

Fins give a slight advantage (less than 5°C temperature reduction), but are generally not cost effective. The effectiveness of fins for roof mounting applications depends strongly on 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. However, cooling with water is not expected to be cost effective unless the application already involves the use of the heated water, the pumping of the water, or unless a gravity water system is possible. At present, care in thermal design and cost considerations results in the NOCT for open back flat plate modules of 43°C to 48°C.

[1]Stultz, J. and Wen, L. C., "Thermal Performance Testing and Analysis of Photovoltaic Modules in Natural Sunlight," LSSA Project Task Report 5101-31 (JPL Internal Document), Jet Propulsion Laboratory, Pasadena, CA, 29 July 1977.

[2]Stultz, J., "Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight," LSA Project Report 5101-76 (JPL Internal Document), DOE/JPL 1012-78/9, Jet Propulsion Laboratory, Pasadena, CA, 31 July 1978.

[3]Stultz, J., "Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight," Journal of Energy, Vol. 3, No. 6, pp. 363-372, November-December 1979.