DESIGN TECHNIQUES FOR FLAT-PLATE PHOTOVOLTAIC ARRAYS*

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ABSTRACT

Numerous design requirements, design analysis and test methods, and design approaches have been identified and developed for flat-plate photovoltaic arrays and modules over the past few years as part of the National Photovoltaics Program. These technology developments have defined means of reducing the cost and improving the utility and reliability of photovoltaic arrays and modules for a broad spectrum of terrestrial applications. This paper integrates the results from a large number of these engineering studies in an attempt to provide an overview of the current state of the art and to provide a convenient reference to more detailed documentation in the literature. Emphasis is focused on the engineering aspects of array and module design, including system interface concerns, structural support, thermal design, safety, electrical circuit design, reliability and environmental endurance.

INTRODUCTION

As part of the Jet Propulsion Laboratory's Low-cost Solar Array Project, a comprehensive program is being carried out to define design requirements, design analysis and test methods, and design approaches for flat-plate modules and arrays. The objective of these studies has been to define means of reducing the cost and improving the utility and reliability of photovoltaic modules for the broad range of terrestrial applications. The approach to design improvement and cost reduction has been based on an iterative process, schematically illustrated in Figure 1, and involving:

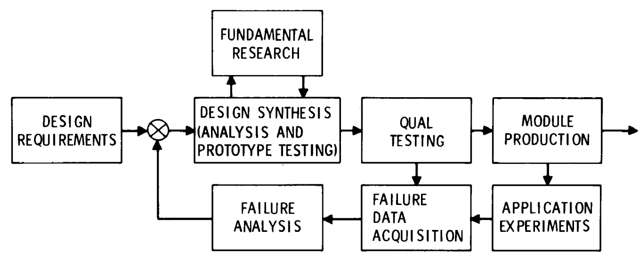

Figure 1. Schematic representation of the module and array closed-loop design process.

(1) Requirements specification.

(2) Design synthesis and optimization.

(3) Design debugging using qualification tests.

(4) Design testing in field applications.

(5) Generating improved design and test methods.

(6) Improving designs based on test data and improved methods.

Specific analyses have been conducted in the areas of structural design, series-parallel circuit design, thermal design, electrical isolation and safety, environmental protection, and others.

This paper addresses the need to integrate the results from these various studies by first describing the major design requirements that have been found to govern array performance at the subsystem level. The data presented summarize the findings in the areas of system integration, safety, reliability, and environmental endurance. Application-specific and site-specific requirements are broken out where appropriate, and techniques for deriving application-specific requirements are noted.

Next, array support-structure and module design requirements and approaches are reviewed. Integrated into the discussion are references to available analytical tools and test methods that have

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been found useful in designing array elements. Emphasis is placed on identifying those techniques that work and where techniques presently are lacking. An important objective of the paper is to serve as a road map to the numerous techniques identified and/or developed by the National Photovoltaics Program.

ARRAY SUBSYSTEM DESIGN

The term "array subsystem" is used to refer to the entire photovoltaic array that provides dc power to a power conditioner or load, and which is made up of solar cell modules, support structures, in-field wiring, safety features, and aesthetic features. Before module and component requirements are examined, it is useful to address the requirements at the subsystem level, where system, application and user needs are most easily defined and judged. The job of meeting the subsystem requirements is then divided up optimally among the subassemblies and components.

At the subsystem level the overall requirements can be organized into four categories:

(1) System interface functional requirements

(2) Safety requirements

(3) Aesthetic requirements

(4) Costs

System Interface Functional Requirements

The primary functional requirement of an array is to generate a specific level of electrical energy over time. This places requirements on the total rated power of the array, and the preferred tracking or fixed-tilt angle. Although the tilt angle of a fixed-tilt array has only a minor effect on total annual energy output, it can be efficiently used to select the time-of-year and time-of-day distribution of energy. In general, a steep tilt angle of about 60° gives the most uniform distribution during the year, with lower tilt angles providing an increasing fraction of the energy in the summer. East-West tilting provides a time-of-day bias. References provide excellent detail on the distribution of energy for a variety of fixed-tilt and tracking arrays for a number of locations in the U.S. (1, 2).

In order to control I^2R power losses in the power conversion equipment, or otherwise to satisfy the load, the array is also generally required to provide power at a specified voltage level. Small systems of up to a few hundred watts generally require 12 to 24 volts; residential and intermediate-load center systems from 5 to 100 kW generally require 100 to 300 volts, and large megawatt-level installations require a maximum of 1000 to 1500 volts. Because each solar cell generates roughly 0.4 volts, the array voltage requirement determines the number of cells to be connected in series, and the current requirement determines the number in parallel.

A second ramification of the voltage requirement is the increased sensitivity to open-circuit cell failures caused by the large numbers of series cells. In a 1000-volt array, for example, there will be approximately 2400 cells in series. If an array were made up of a number of such independent strings in parallel, and on the average one out of a thousand cells failed open-circuit, statistical analysis indicator that the array would be devastated, with a power loss of over 90%. In contrast, the power of a large 12-volt system made up of parallel branch circuits with 36 series cells, would be reduced by less than 4%.

This extreme sensitivity to circuit failures in higher-voltage arrays places important requirements on the array circuit design and redundancy features. Typical solutions involve the use of extensive series paralleling and bypass diodes at the module level, as discussed later in this paper. References describe means of evaluating the performance of various series-parallel circuit redundancy options and recommend preferred designs based on minimizing array life-cycle costs (3, 4, 5).

Subsystem Safety Requirements

An additional consideration for arrays with voltages higher than 30 volts is the requirement for protection from electrical shock hazards. Photovoltaic arrays are unique in that they cannot be switched off easily during hours of sunlight for installation or maintenance. In addition, the natural current-limiting character of solar cells makes the use of conventional circuit-fault interrupters such as circuit breakers and fuses unworkable.

The burden of providing electrical safety falls at all levels of the array, from the insulation within the module to the subsystem itself. The general philosophy of providing safety is based on minimizing the chance of a ground fault (short to ground) or exposed conductor at the component or assembly level, and then providing an independent backup system to ensure safety in the event of a breakdown of the primary system.

Key subsystem backup safety features include:

(1) Frame grounding--to prevent the array frame from reaching an unsafe high voltage in the event of a ground fault.

(2) Circuit grounding--to prevent the solar cell circuit from floating to a high voltage above ground and thus overstressing the primary insulation system. Typically, the negative bus or center voltage point of the array is either grounded or tied to ground through a high resistance.

(3) Ground-fault breaker--to sense a ground fault and stop the fault by either shorting the array or opening the array-circuit-to-ground connection. This is particularly important because a low-impedance short to ground is likely to generate a dc arc that can create a substantial fire hazard.

An additional critical safety concern is the generation of in-circuit arcs when a break occurs in an array circuit. Several such arcs have been discovered in present-day 200- to 300-volt applications and have resulted in severe burning and charring of the photovoltaic module. The conditions for such an arc are an open-circuit break in a high-voltage array circuit where the difference between the open-circuit voltage and the operating voltage leads to a voltage across the break that is sufficient (greater than about 70 volts) to maintain the arc (See Figure 2). Once started, such arcs have been known to burn for periods of hours. The only known remedy for in-circuit arcs in high-voltage arrays is the incorporation of redundant circuitry to prevent a complete open-circuiting of the branch circuit.

<u>Aesthetic Requirements</u>

Although aesthetics are highly subjective, they can be a major concern when dealing with arrays in residential or highly visible commercial settings. Support structures, field wiring, and modules all play interactive roles that should be addressed at the subsystem level first, and then allocated to the assembly level. Important ingredients include module size and aspect ratio, frame color and detailing, module surface gloss or texture, array tilt angle, and integration with an existing roof or other structure if one exists.

<u>Subsystem Cost Requirements</u>

In addition to providing power, being safe and looking acceptable, the complete array must also be competitively priced and inexpensive to maintain. It is important to consider price at the array level when considering cost-reduction alternatives because cost reduction in some assembly or component areas often leads to increases in other areas. This author has found life-cycle costing at the array level to be an indispensible tool for guiding array design optimization, particularly when performance degradation over time or distributed maintenance costs are involved (5, 6).

Key cost tradeoffs which have been found to be important at the subsystem level include:

(1) Designing the initial hardware to reduce site or application-specific engineering or rework, and to reduce field assembly and installation costs.

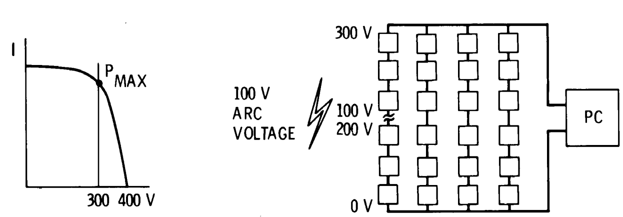

Figure 2. Voltage conditions that provide the potential for in-circuit arcing.

(2) Maintaining high solar cell and module electrical efficiency to control costs of area-related items such as support structures and module materials. Figure 3 illustrates the important subsystem cost tradeoff between module price and module efficiency to achieve the same array cost.

(3) Building in adequate reliability and life to control maintenance and replacement costs.

(4) Marketing complete modular or adaptable systems to reduce application engineering, procurement, system integration and installation costs.

ARRAY SUPPORT STRUCTURE DESIGN

The primary purpose of the array support structure is to support the photovoltaic modules at the chosen tilt angle and possibly to serve as a means of tying the module frames (if used) to ground potential. The cost of mass-produced structures, such as that pictured in Figure 4, is estimated to lie between $\$25/m^2$ and $\$50/m^2$, depending on the size of the application (7). This represents up to 40% of the total installed cost of a future array based on 70¢/watt photovoltaic modules and approximately equals the cost contribution of the solar cells themselves. Both material (structural member and foundation) and field installation costs are major cost contributors that must be addressed carefully. The array shown in Figure 4 achieves major cost savings by utilizing lightweight galvanized sheet-steel beams and treated wooden end trusses that are buried to eliminate the need for concrete foundations. References describe additional low-cost ground-mounted support structure concepts (8, 9, 10).

Because wind loading level is a cost driver for some support-structure designs, a major effort has addressed refining estimates of maximum aerodynamic wind loading levels to be expected in various field conditions. Results of an extensive wind

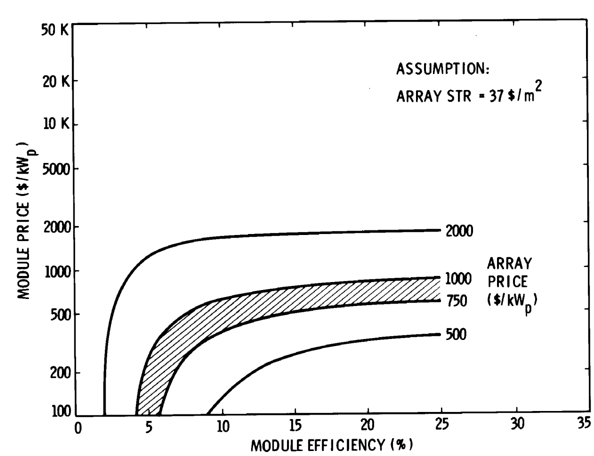

Figure 3. Module cost-effiency tradeoff for equal array related costs of $\$73/m^2$.

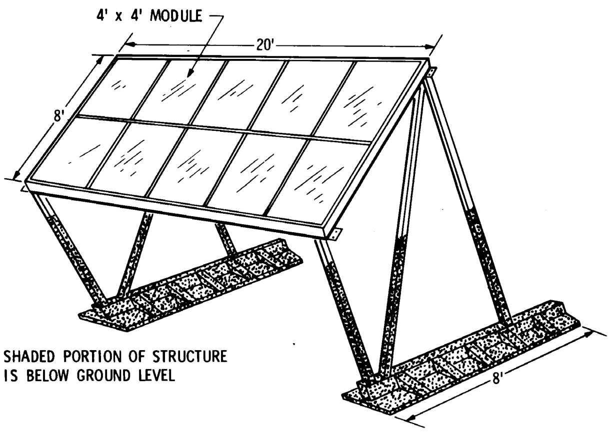

Figure 4. Low-cost support structure using buried wooden end-trusses.

tunnel test program indicate that wind loads in the interior of an array field, or behind a fence, are reduced to as little as 20% of the loads on a single array (11).

MODULE DESIGN

Addressed from the subsystem point of view, a module is a portion of the array electrical circuit that has been packaged in an easily handled unit. As such, it must embody the requirements of the overall array, and minimize the costs of shipping, installation and replacement. On the other hand, from the solar cell point of view, a module is a convenient means of packaging solar cells so that they can be used by a variety of users. The requirements on the module from this point of view include providing an easily manufactured modular package of cells with broad appeal, adaptable to a variety of applications, sites, environments and array designs. In reality, both sets of requirements must be met.

In the following paragraphs an attempt is made to summarize the total integrated set of requirements of the module and to note design analysis and test methods and design approaches that have been found useful.

Module Structural Design

The primary structural requirement on the module is to support the solar cells in the field and to limit breakage of cells and other module components to an acceptable level. An important consideration is the fact that both the expected loads (wind, snow, hail, earthquakes) and the strength of the major module components (cells, glass, interconnects, encapsulants) are probabilistic in nature. In other words, an absolute value is not definable; only the probability of achieving a particular value is definable. Because of this, a variety of specialized probabilistic design methods have been generated. ANSI, in American National Standard A58.1-1972, provides standard probability data on wind, snow and earthquake loads (12) and Gonzalez provides data on hail (13).

Because glass fracture is dependent on the coincidence of a flaw and a high stress, glass strength varies widely from sheet to sheet and from location to location within a sheet. Based on a combination of non-linear stress analysis and empirical fracture data, Moore provides a convenient tool for sizing glass for a given probability of failure due to uniform pressure loads such as wind and snow (14). In a second document, he also describes a useful cyclic loading test technique (15). For design purposes, a uniform loading of 50 lb/ft^2 is commonly used because it provides a low probability of being exceeded and has a minimal impact on module price.

Design and test techniques for hail-impact loading have also been developed in response to high levels of field failures due to hail impact (16, 17). Field experience indicates that resistance to 1-in.-dia hail is required, even in low-hail-incidence regions of the country. This large size reflects the design margin required to protect the one-out-of-a-thousand weakest cell, or largest glass flaw.

Minimizing life-cycle cost has been found to be the most effective means of selecting the appropriate failure probability levels and the associated module design parameters (5, 6).

Module Thermal Design

Solar cell power output decreases at a rate of approximately 0.005 watts per watt per ^oC increase in temperature and makes incorporation of passive temperature-control techniques economically important. For example, a 10^oC increase in cell temperature has the same economic impact as a 5% increase in cost of the total installed array subsystem. In general, simple passive temperature-control techniques have been found to be economically preferable to techniques such as active cooling or fins (18, 19). Because radiation and convection cooling are about equal in importance, maintaining high-emittance external surfaces and providing for heat rejection from both the front and rear of the module are important. Air gaps or low-conductivity paths between the solar cell and front or rear surfaces should be avoided.

The concept of a Nominal Operating Cell Temperature (NOCT) has been developed to provide a convenient means of quantifying a module's thermal design and providing a meaningful reference temperature for rating power output (17, 18, 19, 20). A module's NOCT is the temperature the cells attain in an external environment of 80 mW/cm^2 irradiance, 20^oC air temperature, and 1 m/s wind velocity. This environment has been chosen so that the annual energy produced by a module is well approximated by its efficiency at NOCT times the number of kWh/year of irradiance incident on the module at the site of interest. Table 1 presents typical values of NOCT for a variety of module construction features.

Module Safety Design

To meet the requirements of safety at the subsystem level, the module itself must incorporate

MODULE CONSTRUCTION	NOCT (°C)
FINNED ALUMINUM SUBSTRATE	40
CLEAR GLASS SUBSTRATE	41
ALUMINUM SUBSTRATE (NO FINS)	43
FIBERGLASS/PLASTIC SUBSTRATE	47
DOUBLE PANE WITH AIR GAP	60

$$T_{CELL} = T_{AIR} + \frac{(NOCT-20)}{80} S, °C$$

S = INSOLATION, $^{mW}/cm^2$

Table 1. Typical Nominal Operating Cell Temperatures. (NOCT).

a variety of safety construction features. These include:

(1) Grounding all external conductive surfaces.

(2) Maintaining low leakage currents to ground so as not to interfere with ground fault sensors.

(3) Insulating all live electrical circuit elements sufficient for the highest expected array voltage above ground.

(4) Providing high reliability and long life in all safety elements.

(5) Providing circuit redundancy (by-pass diodes and/or multiple interconnects) to prevent in-circuit arcs due to open circuits.

In addition to the above general requirements, Underwriters Laboratories has developed a detailed compilation of standard safety construction practices applicable to photovoltaic modules (21). Many of the requirements in this interim standard for safety are expected to be applicable to obtaining UL listing of photovoltaic modules in the future. The document also covers other safety hazards such as flammability, sharp edges and high-temperature surfaces.

An important design problem in achieving safe modules is reliably isolating the cell string from the module frame and external surfaces. Because of the large areas involved, this too is a flaw-sensitive design problem and requires statistical characterization of the insulation materials and processes. Mon provides useful design techniques and empirical data for the design of module electrical insulation systems in a companion paper (22).

Module Circuit Reliability

As indicated earlier, the large number of series cells in a high-voltage (above 100-volt) array makes the array very sensitive to cell failures. Achieving high reliability requires both that piece-part failures be held to low levels and that fault-tolerant circuit redundancy be utilized. Incorporation of these solutions logically falls at the module level.

Of the cell-failure mechanisms presently seen in the field, cell cracking is by far the most prevalent, and is occurring at a rate of about one cell per hundred per year. However, only 2 to 10 percent of these cracked cells have been classified as failed cells due to open-circuiting or substantial power degradation.

The three primary causes of cell cracking appear to be differential expansion between the cell and its support, impact loading by hailstones, and reduced strength due to cell damage occurring during cell processing and module assembly. Although qualitative design techniques exist that address differential expansion and hail stresses (23, 16), quantitative design for low failure rates is made difficult by the broad statistical distribution of cell strength due to processing-induced flaws (24). This lack of quantitative techniques for designing for the one-out-of-a-thousand worst-case cell places a high reliance on iterative design and test techniques using thermal-cycling, humidity-freezing, mechanical loading and hail-impact tests (17).

One important means of reducing the degradation associated with a cell that has cracked or otherwise degraded in a local area is the use of multiple electrical interconnects that attach to the cell at two or more locations. Statistical design techniques for assessing the level of improvement are described in (3). The use of multiple interconnects is also useful in preventing open circuits due to failure of the interconnects themselves, or their attachment to the cells.

Interconnect failure due to mechanical fatigue is a classic photovoltaic array failure mode and, like cell cracking, must be treated statistically. Excellent prediction of interconnect failure probability has been achieved recently by Mon and Moore (25), using the work of Manson (26) together with finite-element stress analysis of the interconnect and emperical failure distribution data. A sample of their data (Figure 5) indicates that, even with carefully controlled manufacture and installation, the endurance of interconnects from the same lot can be expected to vary by as much as a factor of 100.

Because of the difficulty and expense of attempting to eliminate the extreme-low-endurance cells and interconnects, the preferred approach to achieving high reliability involves maintaining piece-part failures at low but finite levels, and then introducing redundancy features to control array degradation. Analyses by this author indicate that if cell open-circuit failures are maintained at about 0.0001 per year or lower, then the effect of these failures on system power degradation can be reduced to negligible levels through the use of fault-tolerant series-paralleling and bypass diodes (5). Use of these circuit-redundancy techniques is also effective in improving module

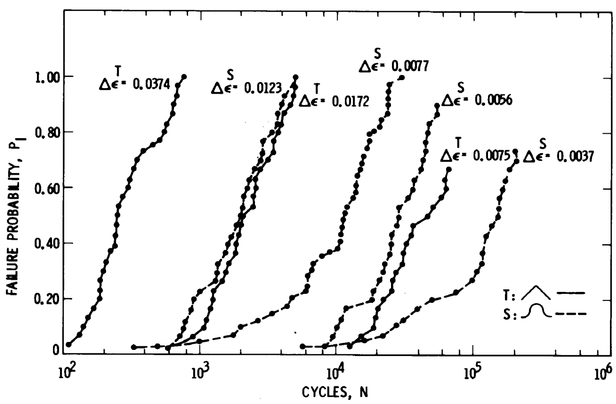

Figure 5. Cyclic mechanical fatigue test data for two copper interconnect shapes (T, S) and peak-to-peak strains ( ).

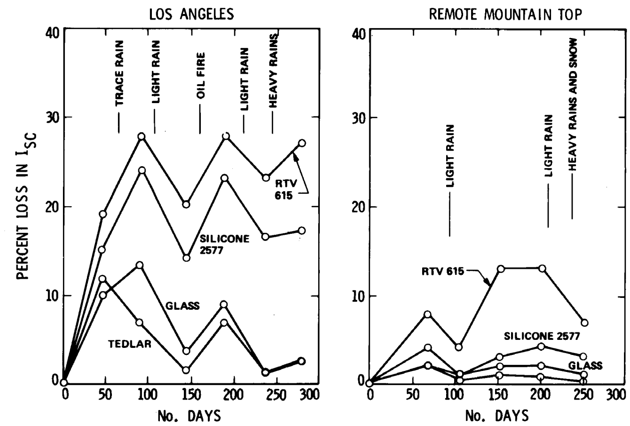

Figure 6. Loss in module short-circuit current (I_{SC}) due to soiling vs days of field exposure.

yield (3, 4) and controlling hot-spot cell heating (27). Design techniques for selecting appropriate series-paralleling and bypass diode configurations are described in detail (3, 5 and 27). An overview of these techniques is provided in a companion paper (4).

Module Environmental Endurance

In addition to failures that are best treated as a reliability problem, many failures are more appropriately considered in terms of environmental endurance. General deterioration or failure of the module encapsulant system is a primary example. The same temperature and humidity cycling stresses that cause many cell and interconnect failures also stress the encapsulant system severely. Ultraviolet irradiation, corrosion, and optical surface soiling also lead to degradation of module materials and optical performance.

A substantial effort within JPL activities has been directed at developing encapsulant materials and processes and understanding potential life-limiting failure mechanisms. A detailed overview of present encapsulant system materials and design techniques is found in (28) and useful environmental qualification tests for assessing the relative performance of candidate systems are found in (17). Useful data on the relative soiling of various module-surface encapsulant materials is presented in (29) and Figure 6.

SUMMARY

Many design requirements, design analysis and test methods, and design approaches have been identified and developed for flat-plate photovoltaic arrays and modules. This has defined ways of reducing the cost and of improving the utility and reliability of photovoltaic arrays and modules for a broad range of terrestrial applications. Many of these developments have been given detailed documentation.

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