FLAT-PLATE PHOTOVOLTAIC MODULE AND ARRAY ENGINEERING*

R.G. Ross, Jr.**
Jet Propulsion Laboratory
Pasadena, CA 91109

ABSTRACT

As part of the U.S. Department of Energy's National Photovoltaics Program, numerous design requirements, design analysis and test methods, and advanced design concepts have been developed for flat-plate photovoltaic arrays and modules. This paper provides an overview of the key research results to date and provides 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.

1. INTRODUCTION

Since 1975 the Jet Propulsion Laboratory's Flat-Plate Solar Array Project has managed a comprehensive research and development activity addressed to lowering the cost and improving the utility and reliability of flat-plate photovoltaic modules and arrays for the broad spectrum of future large-scale terrestrial applications. An important part of this activity has focused on the engineering sciences associated with the disciplines of structural design, series/parallel circuit design, thermal design, electrical isolation and safety, and environmental protection. This paper addresses the need to summarize the results from these various studies by first describing the key 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 numerous references to available analytical tools and test methods that have been found useful in designing array elements. Emphasis is placed on identifying techniques that work and where a lack of techniques exists. 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.

2. ARRAY SUBSYSTEM DESIGN

The term "array subsystem" is used to refer to the entire photovoltaic array that provides dc power to the power conditioner or load, and 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 optimally among the subassemblies and components.

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

(1) Energy performance requirements
(2) Array-load interface requirements
(3) Reliability requirements
(4) Safety requirements
(5) Aesthetics requirements
(6) Costs

2.1 Energy Performance 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

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** Engineering Sciences Manager, Flat-Plate Solar Array Project, and Supervisor, Photovoltaic Engineering Group, Energy Technology Engineering Section.

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array and on the preferred tracking or fixed tilt angle. Although the tilt angle of a fixed-tilt array has only a small 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 United States (1,2).

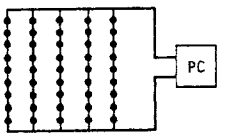
2.2 Array-load Interface Requirements

To control I^2R power losses in the power conversion equipment, or to otherwise satisfy the load, the array is generally required to provide maximum power at a specified voltage level. Small systems (up to a few hundred watts) generally require 12 to 24 volts; residential and 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.

An important consideration in the design of the array-load interface is the fact that the array current is proportional to the instantaneous irradiance level, and the array voltage decreases about 0.5% per 1°C of increasing solar-cell temperature. The array load must therefore accommodate substantial current and voltage variations caused by changing ambient conditions while continuously maximizing the power received from the array. Gonzalez et al provide a detailed treatment of array-load interface design considerations including the pros and cons of various load-control strategies and estimates of maximum expected array voltage and current levels (3, 4). The results are presented parametrically in a manner useful for any array size, voltage level or geographic location.

2.3 Subsystem Reliability Requirements

A third important subsystem requirement is that of achieving a cost-effective level of reliability and durability over the design-life of the system. Because of their modular nature, photovoltaic arrays have a higher-than-normal sensitivity to common-mode failures, but at the same time offer a wealth of redundancy options to increase reliability. An important consideration in this respect is the high sensitivity to



ARRAY VOLTAGE	SERIES CELLS (S)	POWER LOSS AT 5 YEARS
15	36	1.8%
150	360	16.5%
1500	3600	83.5%

POWER LOSS = $1 - [1 - (\text{YEARS} \times R)]^S$

Fig. 1. Array Degradation versus Number of Series Cells for a Cell Failure Rate (R) of 0.01% per Year

individual open-circuit cell failures that results when large numbers of cells are interconnected in series. Fig. 1 illustrates the sensitivity of systems not incorporating circuit redundancy to a cell failure rate of only 0.01% per year.

To ensure meeting system or application requirements, it is necessary first to address reliability at the subsystem level. requirements at this level are most usefully stated in terms of desired life-cycle energy cost, so that appropriate tradeoffs can be made among initial costs, long-term maintenance and replacement costs, and long-term energy loss due to accepted performance degradation over time. Means of performing these tradeoffs have been developed and demonstrated (5,6,7). The results of such an analysis define the preferred maintenance and replacement strategy, the overall circuit and mechanical redundancy, and reliability allocations (failure rate and cost) for the major array assemblies and components. Example allocations for modules are provided in (8).

2.4 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 on 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 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 (Fig. 2). Once started, such arcs have been known to burn for periods of hours. The only known solution to the problem of in-circuit arcs in high-voltage arrays is the incorporation of redundant circuitry to prevent a complete open-circuiting of the source circuit.

2.5 Aesthetics Requirements

Although aesthetics are highly subjective, they can be an important consideration 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.

2.6 Subsystem Cost Requirements

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

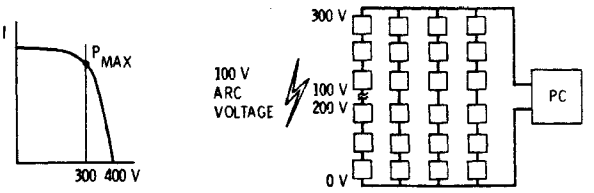


Fig. 2. Voltage Conditions that Provide the Potential for In-Circuit Arcing

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 that 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.
(2) Maintaining high solar-cell and module electrical efficiency to control costs of area-related items such as support structures and module materials. Fig. 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.

3. 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

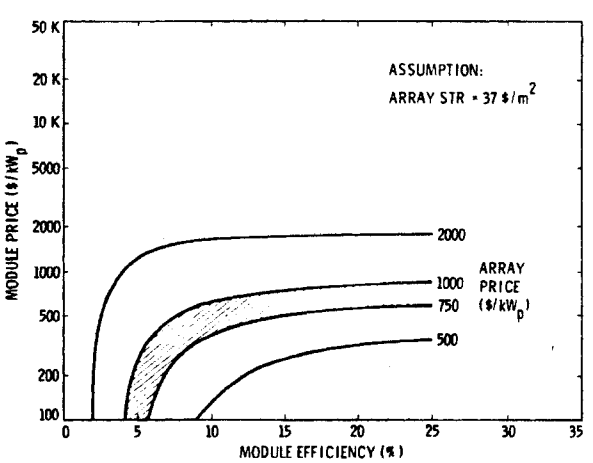


Fig. 3. Module Cost/Efficiency Tradeoff for Equal Array Cost and Area Related Costs of 37$/m²

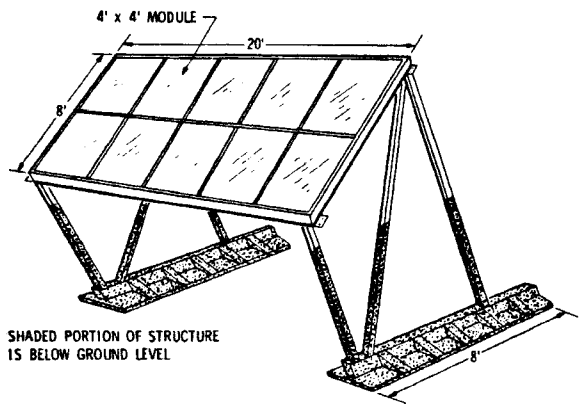


Fig. 4. Low-Cost Support Structure Using Buried Wooden End-Trusses

module frames (if used) to ground potential. The cost of mass-produced structures such as the concept shown in Fig. 4 is estimated to lie between 25 $\$/m^2$ and 50 $\$/m^2$ depending on the size of the application (9). 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 Fig. 4 achieves major cost savings by utilizing lightweight galvanized sheet-steel beams and treated-wood end trusses, which are buried to eliminate the need for concrete foundations. References describe additional low-cost ground-mounted support structure concepts (10,11,12).

Because wind-loading level is a cost driver for many support-structure designs, a major effort has also been addressed to refining estimates of maximum aerodynamic wind-loading levels to be expected in various field conditions. Results of an extensive wind 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 (13). However, dynamic interaction with the array's natural vibration frequencies has been shown to increase loads when frequencies fall below about 7 Hz (13).

4. 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 on 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 on the module and to note key design analysis and test methods and design concepts that have been found useful.

4.1 Module Structural Design

The primary structural requirement of 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 key module components (cells, glass, interconnects, encapsulants) are probabalistic 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 its American National Standard A58.1-1972 provides standard probability data on wind, snow and earthquake loads (14) and Gonzalez provides data on hail (15).

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 (16). In a second document he also describes a useful cyclic loading test technique (17). 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 (18, 19). 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 failure-probability levels and the associated module design parameters (5,6).

4.2 Module Thermal Design

Solar cell power output decreases at a rate of approximately 0.5% per 1°C increase in temperature and makes incorporation of passive temperature control techniques economically important. For example, a 10°C 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 (20, 21). 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 either front or rear surfaces should be avoided. Fig. 5 illustrates the typical linear effect of incident irradiance level on the cell temperature rise above ambient.

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 (19, 20, 21, 22). A module's NOCT is the temperature the cells attain in an external environment of 80 mW/cm^2 irradiance, 20°C 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. Typical values of NOCT range from around 45°C for ground-mounted arrays to 60°C for roof-mounted arrays with insulated rear surfaces. Based on the functional dependence suggested in Fig. 5, cell temperature is

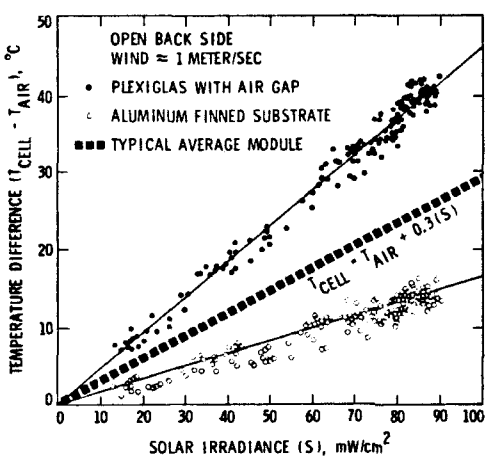


Fig. 5. Cell Temperature Dependence on Ambient Air Temperature and Irradiance Level

well characterized by the simple expression:

$$T_{cell}(^{o}C) = T_{air}(^{o}C)\left(\frac{NOCT-20}{80}\right) S\left(\frac{mW}{cm^2}\right)$$

4.3 Module Safety Design

To meet the requirements of safety at the subsystem level, the module itself must encorporate 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 sufficiently for the highest expected array voltage above ground.
(4) Providing high reliability and long life in all safety elements.
(5) Providing circuit redundancy (bypass 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 expected to be applicable to obtaining UL listing of photovoltaic modules in the future (23). 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 (24).

4.4 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 currently 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 % 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 (25, 18), quantitative design for low failure rates is made difficult by the broad statistical distribution of cell strength due to processing-induced flaws (26). 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, such as those defined in (19).

One important means of reducing the loss 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 (7). The use of multiple interconnects is also useful in preventing open circuits due to failure of the interconnects themselves, or their attachments 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 recently achieved by Mon et al (27) using finite-element stress analysis of the interconnect together with empirical fatigue curves that treat probability of failure as a parameter (Fig. 6). His data indicate 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 conducted 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 yield (4,7) and controlling hot-spot cell heating

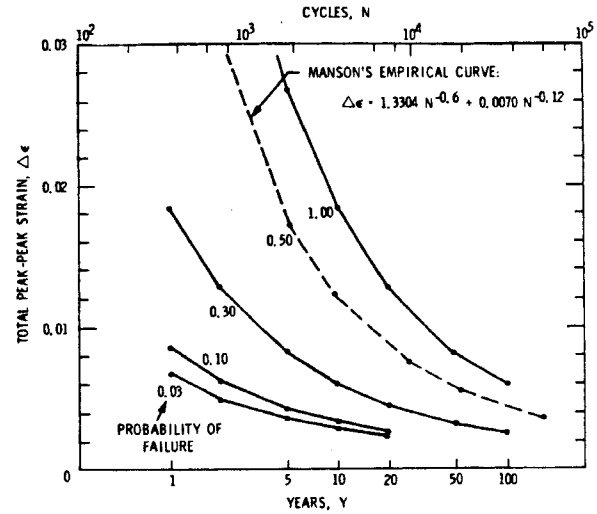


Fig. 6. Fatigue Curve for Copper Cell Interconnects with Probability of Failure as a Parameter

(28). Design techniques for selecting appropriate series/paralleling and bypass diode configurations are described in detail (5,7,28). An overview of these techniques is provided in (29).

4.5 Module Environmental Endurance

In addition to failures which are best treated in terms of reliability statistics, there are a number of failures that 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 which cause many cell and interconnect failures also severely stress the encapsulant system. Ultraviolet irradiation, corrosion, and optical-surface soiling also lead to degradation of module materials and optical performance.

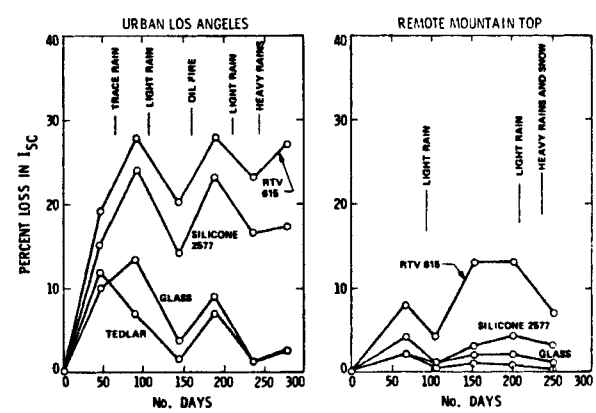


Fig. 7. Loss in Array Short-Circuit Current (I_{SC}) Due to Soiling Versus Days of Field Exposure

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 (30) and useful environmental qualification tests for assessing the relative performance of candidate systems are included in (19). Useful data on the relative soiling of various module-surface materials is presented in (31) and in Fig. 7.

5. SUMMARY

Many 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 has provided an overview of a large number of these engineering developments and provides a convenient reference to more detailed documentation in the literature.

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