RELIABILITY RESEARCH TOWARD 30-YEAR-LIFE PHOTOVOLTAIC MODULES *

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As part of the United States National Photovoltaics Program, the Jet Propulsion Laboratory's Flat-Plate Solar Array (FSA) Project has maintained a comprehensive reliability and engineering sciences activity addressed toward understanding the reliability attributes of terrestrial flat-plate photovoltaic arrays and to deriving the analysis and design tools necessary to achieve module designs with a 30-year useful life. This paper provides an overview of the reliability research approach being used and highlights significant results to date.

1. Introduction

Over the past decade, research directed at improving the reliability of terrestrial photovoltaic (PV) modules has made substantial progress. During the 1970s significant advances were first made through the systematic identification of failure mechanisms in field application experiments and through the development and use of qualification tests directed at these mechanisms. The test levels were carefully selected and revised with time so as to fail past module designs with a known history of field problems and to pass modules with good field performance.

After the early degradation mechanisms such as encapsulant delamination and interconnect fatigue were solved to the point of passing the qualification tests, research at JPL has been increasingly focused on the problem of achieving truly long-life (20- to 30-year) performance. This pursuit has led to the evolution of a reliability methodology that is the subject of this paper.

2. A Reliability Methodology for Photovoltaics

Achieving 20- to 30-year life represents a formidable challenge to the module developer because of the general lack of technology enabling prediction of the results of the complex chemical and physical reactions involved in long-term aging. Without an accurate means of prediction, selection of design alternatives and problem solutions must rely upon historical trends and qualitative assessments such as qualification tests. This problem is obviously not unique to the photovoltaics industry; in fact, the difficulty is far greater with more complex systems. Photovoltaics has an important advantage over more complex alternative technologies; the very limited number of different types of components involved in a PV system allows a greater level of reliability research and testing per mechanism. On the other hand, if a component of a photovoltaic module has a generic problem, a large fraction of the PV system may be at risk--a classic case of having all of your eggs in one basket.

The general nature of photovoltaics, with its limited number of failure mechanisms, both allows and demands a somewhat different approach to achieving long life than may be appropriate, or possible, with alternate technologies.

During the past few years, JPL research directed at achieving 20- to 30-year module life has evolved into a general methodology with six major elements:

1) Identification of key degradation mechanisms
2) Establishment of mechanism-specific reliability goals
3) Quantification of mechanism parameter dependencies
4) Development of degradation prediction methods
5) Identification of cost-effective solutions
6) Testing and failure analysis of trial solutions.

Although a substantial degree of synergism exists among these elements, it is useful to address each separately.

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2.1 Identification of Key Degradation Mechanisms

At the root of achieving long-life modules is ensuring that all the important problems are identified, and that excessive resources are not expended on "non-problems". This is easier said than done. Experience to date indicates that the most convincing evidence of a problem is well documented field failures. This requires careful monitoring of field applications with statistically significant numbers of modules, and an active problem-failure reporting system. Detailed failure analysis to identify the fundamental failure mechanism is a critical step.

Failures observed during qualification testing are also generally indicative of a problem, but are much less convincing due to the small number of samples in test and the lack of quantitative correlation to field performance. Similarly, good performance in non-operating field test racks, as contrasted to performance in operating photovoltaic systems, has been found to be a necessary, but not sufficient, condition for long life. In effect, the system interface stresses such as applied voltages and currents have been found to play a significant role in photovoltaic failure mechanisms. Hot-spot heating failures, shorts to ground, and in-circuit arcs are important examples of failures that required operating systems for quantification.

Unfortunately, none of the failure-identification techniques discussed above is effective in identifying failure mechanisms that only show up after prolonged field exposure. For this we must rely on intermediate length (6-month to 2-year) tests that include the relevant stresses and achieve acceleration levels of 10 to 50.

Our experience has shown that the most reliable accelerator for a variety of mechanisms is increased temperature. However, increased humidity, applied voltage, and accentuated stress cycling are also useful accelerators for certain mechanisms. The cell testing at Clemson University, module testing at Wyle Laboratories, and encapsulant testing at Springborn Laboratories are examples of key research activities addressed to identifying important long-term failure mechanisms (1, 2, 3).

An additional element of these test programs is the inclusion of a variety to test articles from various manufacturers. This allows separation of generic problems from manufacturer-specific or process-specific problems.

2.2 Establishment of Mechanism-Specific Reliability Goals

Once the key mechanisms have been identified, target degradation allocations must be established for each, consistent with the desired economic life. A critical step in this process is quantifying the economic importance at the system level of each failure or degradation occurrence. For some mechanisms such as encapsulant soiling, the economic impact is directly proportional to the degradation level and is easily calculated. For others, such as open-circuit or short-circuit failures of individual solar cells, elaborate statistical-economic analyses that include the effects of circuit redundancy, maintenance practices, and life-cycle costing are required (4, 5). Without such analyses, failure levels cannot be interpreted with meaning.

Table 1. System Life-Cycle Energy Cost Impact and Allowable Degradation Levels for Flat-Plate Crystalline Silicon Modules.

Type of Degradation	Failure Mechanism	Units of Degrad.	Level for 10% Energy Cost Increase*		Allocation for 30-Year-Life Module	Economic Penalty
			k = 0	k = 10		
Component failures	Open-circuit cracked cells	%/yr	0.08	0.13	0.005	Energy
	Short-circuit cells	%/yr	0.24	0.40	0.050	Energy
	Interconnect open circuits	%/yr^2	0.05	0.25	0.001	Energy
Power degradation	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.20	Energy
	Front surface soiling	%	10	10	3	Energy
Module failures	Module glass breakage	%/yr	0.33	1.18	0.1	O&M
	Module open circuits	%/yr	0.33	1.18	0.1	O&M
	Module hot-spot failures	%/yr	0.33	1.18	0.1	O&M
	Bypass diode failures	%/yr	0.70	2.40	0.05	O&M
	Module shorts to ground	%/yr^2	0.022	0.122	0.01	O&M
	Module delamination	%/yr^2	0.022	0.122	0.01	O&M
Life-limiting wearout	Encapsulant failure due to loss of stabilizers	Years of life	27	20	35	End of life

*k = Discount rate

Table 1 lists 13 principal failure mechanisms for flat-plate crystalline-silicon photovoltaic modules, together with their economic significances and target allocation levels (5). The units of degradation listed in the third column provide a convenient means of quantifying the failure levels of the individual mechanisms according to their approximate time dependence. For example, units of %/yr in the context of component or module failures reflect a constant percentage of components failing each year. For components that fail with increasing rapidity, percent per year per year (%/y^2) is the unit used to indicate linearly increasing failure rate. This failure trend is most easily interpreted by noting that the failure rate after (A) years is (A) times the %/y^2 value. For those mechanisms classified under power degradation, the %/yr units refer to the percentage of power reduction each year.

Using the units described above, columns 4 and 5 of Table 1 indicate the level of degradation for each mechanism that will result in a 10% increase in the cost of delivered energy from a large PV system. Because the mechanisms will generally occur concurrently, the total cost impact is the sum of the 13 cost contributions. Column 6 lists the strawman allocation of allowable degradation among the 13 mechanisms to achieve a total reliability performance consistent with expectations of a 30-year life. The total effect of the allowable levels is a 20% increase in the cost of energy over that from a perfect, failure-free system. The distribution among the mechanisms reflects this author's best judgment in light of likely achievable levels.

2.3 Quantification of Mechanism Parameter Dependencies

Once the key failure mechanisms have been identified and quantitative goals established for field-failure levels, the challenge is to achieve the levels and know that they have been achieved. This very difficult phase is divided into three research elements: quantification of parameter dependencies, development of degradation prediction methods, and identification of cost-effective solutions.

The major obstacle to predicting field life for any specific mechanism is the complex dependency of the degradation or failure rate on the large number of field-stress parameters, system-operating parameters, component-design parameters, and manufacturing-processing parameters. Without a quantitative understanding of the principal parameter dependencies, it is virtually impossible to make sense out of accelerated or field test data.

Ideally, the most effective means of quantifying the mechanism parameter dependencies is to thoroughly understand the chemical and physical processes involved in the degradation. Unfortunately, this level of understanding is never achieved; instead one must settle for a qualitative insight into the mechanism physics. Such insight is invaluable in identifying the principal degradation parameters and qualitatively understanding their influence.

In the case of interconnect fatigue, for example, it is well known that the level of fatigue is almost solely dependent upon the level of peak mechanical strain in the interconnect material and on the number of cycles of strain application. Based on this knowledge, one can use physical principles to derive the dependency of fatigue level on interconnect geometry, material coefficients of expansion, and module temperature and humidity variations (6).

The problem that remains is quantifying the failure statistics of an interconnect material as a function of peak strain and number of cycles. Figure 1 represents such a determination based on least squares fitting a general mathematical function through a large quantity of empirical test data gathered at parametric strain levels (6). This latter technique of using carefully selected mathematical functions to unify and interpolate among parametric test data has been found to be an excellent way to quantify mechanism parameter dependencies (2, 6, 7). Knowledge of the mechanism physics plays a key role in selecting the experimental parameters to be measured and in choosing the form of the mathematical functions to be fit to the data.

2.4 Development of Degradation Prediction Methods

Once the parameter dependencies are defined, the problem of degradation prediction is essentially reduced to determining the time history of applied stresses associated with the subject exposure, be it 30 years of field weathering, or 6 months in an accelerated test environment. Although the mathematical description is easy, neither fully characterizing the parameter dependencies nor accurately modeling the environment is accomplishable with finite resources and time. Engineering skill is involved in achieving an adequately accurate prediction with available resources.

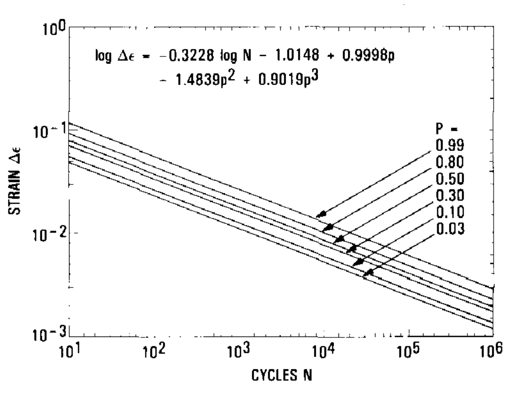

Fig. 1. Fatigue curves for OFHC 1/4-hard copper versus failure probability (p).

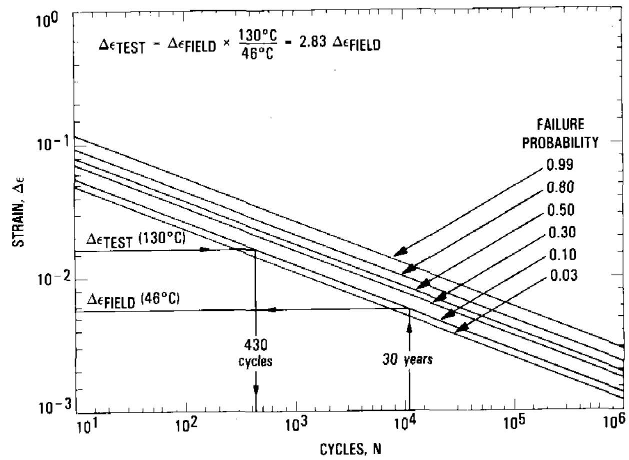

Fig.2. Interconnect fatigue life prediction from -40°C to +90°C thermal cycle test (OFHC 1/4-hard copper).

For the previously mentioned interconnect fatigue example, field experience indicates that the primary fatigue cycling strain for rack-mounted modules is caused by the approximately 46°C diurnal temperature swing experienced. This simplified characterization of the applied environmental stress, coupled with knowledge of the module's thermal expansion characteristics and fatigue characteristics (Fig. 1), allows a surprisingly accurate prediction of field life, or of the acceleration factor of a thermal-cycling test (Fig. 2) (6).

In recent years a variety of environmental stress characterizations have been developed at JPL. These include models of hail impact probability, wind loading pressures, and array voltage and current durations (5). In addition SOLMET weather data tapes have been used extensively to model module ultraviolet, temperature, and humidity exposure levels (2). These models are combined with complex electrochemical corrosion and photothermal degradation parameter dependencies in an attempt to achieve useful life predictions for these mechanisms (7).

2.5 Identification of Cost-Effective Solutions

Although convincing life-predictions are of great assistance in developing reliable modules, they play an even more important role in developing cost-effective modules. Cost effectiveness requires trade-offs of degradation rates, failure rates, and life against initial-manufacturing costs, field-maintenance costs, and lost energy revenues.

The art of estimating manufacturing costs is modestly well developed, as are techniques for estimating maintenance costs and lost energy revenues for a predicted level of field failures. Life-cycle costing serves as an excellent mathematical tool for integrating these disparate economic terms and allows cost-effectiveness to be quantified and trade-offs to be made (4, 6). Models for predicting the system economic impact of individual failures are required here, as they were also in establishing the quantitative reliability goals described earlier. A necessary part of defining cost-effective solutions is reconciling and iterating the initial goals with the realities of available technologies used in the most cost-optimum manner. If the available technologies fall short, either technology advances are required, or cost targets must be raised.

As an exemplary identification of cost-effective solutions, Fig. 3 presents the life-cycle energy cost (as a percentage of total PV system cost) for a variety of solar cell interconnect materials as a function of the interconnect thickness (6). The plotted costs include manufacturing costs, efficiency losses due to solar cell shading and I^2R losses, and power degradation due to interconnect fatigue failures. The latter are responsible for the rapidly rising trend on the right side of each cost curve. Such an analysis allows quantitative judgments to be made and cost-effective levels of reliability to be selected.

An important consideration in the identification of cost-effective solutions is minimizing sensitivities to processing variations and design uncertainties. In Fig. 3 this implies avoiding interconnect configurations associated with points on or near rapidly rising portions of the curves. The copper clad materials, with their broad flat minimums, are found to have a clear advantage in this respect.

2.6 Testing and Failure Analysis of Trial Solutions

The first and last critical step in any reliability program is extensive type-approval testing of the complete product. Such testing cuts across the entire reliability development effort from beginning to end. It plays a key role in the identification of failure mechanisms, in the illumination of parameter dependencies, in the selection of cost-effective solutions, and in the verification of final designs. By the end of the reliability effort, tests with quantitative correlation to field application should be available, based on the parameter dependencies determined and the prediction algorithms developed. A key element of complete-product testing is inclusion of the synergistic reactions between all of the components, including likely interfacing components on the user's side of the interface. This latter consideration is one of the reasons field-application data are more convincing than laboratory test data--they include interaction with the user.

3. Summary Remarks

Achieving 30-year-life flat-plate PV modules requires a systematic approach to the identification of failure mechanisms, to the establishment of allowable failure levels, to the development of failure-rate predictions, and to the development of cost-effective solutions. In addition, quality control practices must be introduced to maintain the designed-in quality during the production phase. Based on this methodology, the reliability of flat-plate crystalline-silicon photovoltaic modules has steadily increased over the past 10 years. From 5-year-life modules of the early 1970s have come the 10- to 20-year-life modules of today and anticipation of 30-year-life modules in the future.

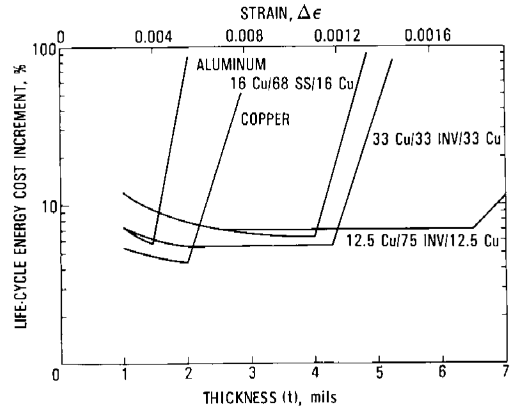

Fig.3. Life-cycle cost contribution of doubly redundant interconnects as a function of material thickness (1 mil = 0.0254 mm).

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