RELIABILITY RESEARCH ON THIN-FILM AMORPHOUS-SI PHOTOVOLTAIC MODULES*

Ronald G. Ross., Jr.**

Jet Propulsion Laboratory
Pasadena, CA, USA

ABSTRACT

As part of the U.S. Department of Energy National Photovoltaics Program, mechanism-specific reliability goals are proposed for amorphous-silicon photovoltaic modules targeted for use in large-scale energy-generation applications. These goals are compared with reliability test results recently obtained at JPL on first-generation large-scale a-Si modules to highlight priorities for reliability research. Key research priorities include light induced effects, cell corrosion, glass breaking strength, and protective encapsulants specifically designed for thin-film modules.

INTRODUCTION

During the past 10 years the Jet Propulsion Laboratory Flat-Plate Solar Array Project has been the lead agency in the United States studying the engineering design and reliability of flat-plate photovoltaic modules. Although most of this research has centered on the use of crystalline-silicon solar cells, research has recently shifted to emphasizing the reliability of modules incorporating newly developed thin-film solar cells. This paper reviews the results of ongoing JPL research examining the durability of amorphous silicon cells and modules.

RELIABILITY GOALS FOR a-SI MODULES

Amorphous-silicon solar cells and modules are presently being used in a great diversity of applications ranging from small consumer products to prototype utility-scale electrical energy generation plants. Each of these applications has a unique requirement for performance stability and reliability that depends on the nature of the application.

Many consumer products, for example, are designed for full operation over a wide range of irradiances--from a dimly lit interior room to bright sunshine. To meet the power and voltage demands at the lowest irradiance level, the array for such an application is often oversized at the highest irradiance level by a factor of 1000. Modest (e.g., 50%) degradation of the power performance of such an array only shows up at the lowest irradiance levels and is generally inconsequential to the application.

In contrast, energy-generation applications are sized for the highest prevailing irradiance levels and have little tolerance for array performance degradation. Based on this economic sensitivity to degradation, the national photovoltaics program of the U.S. Department of Energy has chosen a 30-year-life as a target goal for PV modules.

The remainder of this paper examines the reliability of amorphous-silicon PV modules in the context of commercial energy-generation applications with system operating voltages above 100 volts. The high operating voltage of such applications impacts a large number of reliability parameters including voltage isolation and grounding requirements, electrochemical corrosion, hot-spot heating, bypass diodes, and the number of series cells in an array source circuit; the number of series cells in an array is particularly important because it affects the array's tolerance to open-circuit failures of cell and module interconnects.

Mechanism-Specific Reliability Goals--A key step in achieving 30-year-life thin-film modules is establishing mechanism-specific reliability goals. This requires that all failure mechanisms be determined, and that the economic importance at the system level be quantified for each failure or degradation occurrence.

Table 1 lists 13 failure mechanisms likely to be associated with thin-film a-Si cells monolithically deposited on a glass superstrate. 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 denote a constant percentage of components failing each year. For components that fail with increas-

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** Reliability and Engineering Sciences Manager, Flat-Plate Solar Array Project, and Supervisor, Photovoltaic Engineering Group, System Integration Section.

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Table 1. System Life-Cycle Energy Cost Impact and Allowable Degradation Levels for 13 Principal Thin-Film Module Failure Mechanisms

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 between cells	%/yr	0.08	0.13	0.02	Energy
	Short-circuit cells	%/yr	0.24	0.40	0.05	Energy
Power degradation	Light induced effects	%	10	10	5	Energy
	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.02	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

ing rapidity ($\%/y^2$) is the unit used to indicate linearly increasing failure rate. 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 a strawman allocation of allowable degradation among the 13 mechanisms to achieve a specific total reliability performance. The reliability allocation is consistent with a 20% increase in the cost of energy over that from a perfect, failure-free system with a 30-year life.

In contrast to Table 1, previous work (1) provides similar data generated for 13 principal failure mechanisms associated with modules made with crystalline-silicon solar cells. Although different degradation allocations could have been chosen in Table 1 the important point is that this allocation allows the significance of observed failures to be measured, and goals to be developed to guide mechanism-specific research activities.

RELIABILITY TESTING OF AMORPHOUS-SI MODULES

An extensive test program is presently underway at JPL to assess the reliability attributes of present-day a-Si cells and modules and to define priorities for reliability research. The overall research methodology follows that described earlier for crystalline-Si modules (2) and includes qualification testing, field testing and mechanism-specific laboratory accelerated testing.

A critical first step in the investigation of the reliability of a-Si cells and modules was modifying JPL's Large Area Pulsed Solar Simulator (LAPSS) to insure consistent, high-accuracy measurements of a-Si current-voltage performance under internationally recognized reference conditions. To this end the LAPSS was filtered to provide a close-tolerance 100 mW/cm^2, Air Mass 1.5 Global spectrum, and primary reference cells were developed using high-efficiency crystalline-Si cells with their spectral response filtered to closely match that of typical a-Si cells. In combination, the LAPSS filtering and generic a-Si reference cells provide excellent (1% long-term repeatability) measurements of a-Si cells and modules (3).

Test Results

To provide an assessment of the reliability research priorities for a-Si modules a number of first-generation modules were acquired from leading a-Si module manufacturers and subjected to an extensive series of tests. These included 1) testing to the standard JPL Block V qualification test sequence (4) developed for crystalline-Si modules, 2) outdoor weathering at both ambient conditions and at fixed elevated temperatures of 85°C and 100°C, 3) long-term temperature-humidity testing at 85°C 5% RH and 85°C 85% RH conditions and various bias voltages, and 4) specialized laboratory hot-spot and corrosion testing. The findings are detailed below according to the 13 failure-mechanism categories defined in Table 1.

Open-circuit between cells--Unlike crystalline-Si cells, which are generally interconnected by metallic ribbon leads, cells in a-Si modules are often interconnected by careful overlapping and scribing of adjacent cell layers during module processing. One module type with typical monolithic cell interconnects exhibited open-circuit cell failures in both field testing and qualification testing. Because the problem manifests itself during humidity testing and not during thermal cycling, it is expected to be associated with corrosion of the aluminum back metal in the region of the interconnects.

The extreme sensitivity of a high voltage power system to open-circuit cells (Table 1, column 4) requires that the reliability of the cell interconnects be thoroughly addressed. In addition bypass diodes should be incorporated into the array to serve as redundant circuit elements.

Short-circuit Cells--Although short circuiting is a classical failure mode for thin-film cells it did not surface as a key failure mechanism in this series of module tests.

Light induced effects--Light induced effects were prominent in nearly all field-tested modules. As shown in Fig. 1, the degradation was typified by modest short-circuit current loss accompanied with a shunt-like loss in fill factor. However, the initial rapid rate of degradation slowed to a stable asymptotic level after a few months of field exposure. As shown, the electrical operating point of the module was found to have a significant influence on the level and rate of degradation. Although open-circuit modules generally degraded the most quickly, followed by those loaded at their peak-power point, one manufacturer's modules behaved just the opposite. Because most power modules will be used with peak-power loading, this loading condition seems the most appropriate.

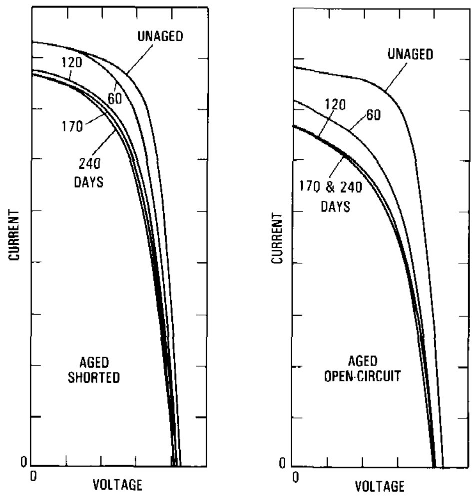

Fig. 1. I-V Performance Degradation Due to Light Induced Effects Versus Outdoor Aging Period (Ambient Operating Temperature)

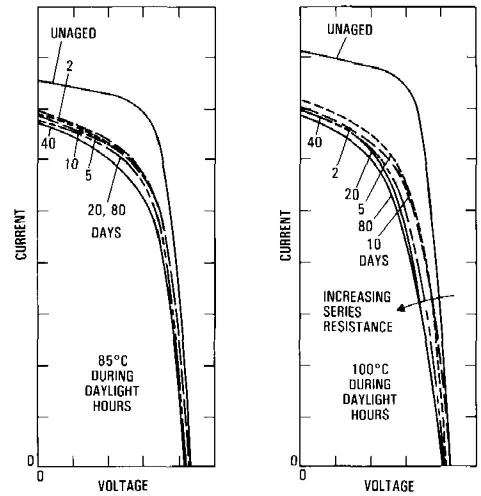

Fig. 2. I-V Performance Degradation Due to Light Induced Effects for a-Si Modules Aged Outdoors at Elevated Temperatures

In studies to determine the dependency of the degradation on stress parameters, modules were also field tested under a variety of thermal conditions. Modules operated in the field at fixed elevated temperatures of 85°C and 100°C degraded very rapidly (Fig. 2), but stabilized at the same modest level of degradation as the unheated samples.

One difficulty in studying light induced effects is the absence of readily available laboratory tests for accelerating the effects observed in the field. For example, the Block V qualification test sequence (4) does not test for light induced effects and does not trigger the degradation. In an attempt to identify a relatively inexpensive procedure to test for light induced effects, a-Si modules were aged in the dark in 85°C 5% RH and 85°C 85% RH environments both shorted and forward-voltage (reverse current) biased to their typical field operating voltage level. The modules with forward voltage bias were found to behave in a manner quite similar to the field-tested modules. Although more data is required before a definitive assessment can be made, this forward-voltage-bias test holds promise as a useful inexpensive test procedure. Much work is needed to correlate the rates of degradation in chamber tests with those expected in the field. A major complication is the complex and variable dependency of the light induced effect on temperature and applied voltage.

Cell Gradual Power Loss--In contrast to the light induced effect, which rapidly reaches a quasi-equilibrium level, other degradation mechanisms may exhibit a uniform degradation rate of increasing power losses. Such losses were noticed with most a-Si modules in the form of gradually increasing series resistance. As shown in Fig. 2 this series-resistance increase is accelerated at higher temperatures. Preliminary activation-energy data suggest a typical Arrhenius relationship to temperature with a degradation rate doubling with approximately every 10°C increase in module temperature. With an activation energy of this magnitude, 2400 hours of continuous 100°C testing corresponds to about 20 years of field exposure in a warm climate such as Los Angeles, California (5). Scaling the series resistance effects in Fig. 2 to field conditions suggests that the gradual power loss of this module due to increased series resistance is approximately 5% per year. This is substantially above the target amount in Table 1 (0.2% per year) and indicates that reducing long-term series-resistance degradation should be an important research priority.

Module Optical Degradation--Optical degradation, when it exists in crystalline-Si modules, generally results from photothermal yellowing of the front-surface encapsulant or degradation of cell or glass anti-reflection coatings. Although no such degradation mechanisms were observable with the a-Si cells on glass superstrates, module designs using encapsulated stainless steel backed solar cells need to be assessed.

Front-Surface Soiling--Soiling of modules with glass or Tedlar front surfaces is generally not a problem (1). Amorphous-Si modules behave similar to crystalline-Si modules with average soiling levels on the order of 3%.

Module Glass Breakage--Crystalline-Si modules have almost universally adopted 3 mm (0.125 inch) tempered glass superstrates to provide reliable protection against thermal stress and hail loads. When amorphous-Si cells are deposited on the rear of the module superstrate, the high-temperature tin-oxide coating process anneals the glass and generally requires that the glass be either structurally backed up or partially tempered following the coating process. Large a-Si (30 cm x 30 cm) modules making use of 3 mm (0.125 inch) annealed glass have difficulty passing the JPL Block V hail test; on the other hand both structurally supported and partially-tempered a-Si glass modules meet the requirement. The data indicate that glass strength is an important consideration with present-day modules and will become even more important as module sizes increase in the future.

Module Open Circuits--This category refers to open-circuit failures associated with electrical busses and module connections. One module type displayed a problem with attachment of leads to the end solar cells of its monolithic assembly of series-connected cells and failed open circuit after temperature and humidity cycling. Care is required in this area.

Module Hot-spot Failures--A substantial program of hot-spot testing of a-Si cells and modules has been conducted at JPL over the past 2 years (6). The test data indicate that amorphous-Si cells display hot-spot heating effects quite similar to crystalline-Si cells, but are in some cases more tolerant than crystalline cells. Bypass diodes provide the necessary protection for sensitive high-current designs.

Bypass diode Failures--Whenever bypass diodes are incorporated into the module design, they provide a potential source of failure. Only one amorphous module tested contained integral bypass diodes. Detailed design requirements and test procedures are now available for bypass diodes (7).

Module Shorts to Ground--When modules are intended for use in high-voltage (>50 volt) applications, the cell circuit must be reliably isolated from the module frame and external surfaces. The general requirement is that the module leakage current from cell string to external surfaces must be less than 50 μA when the applied voltage (cell to module exterior) is set to twice the worst-case system voltage plus 1000 volts. For most multi-kilowatt-size applications this (hi-pot) test voltage is in the range of 1500 to 3000 volts. Meeting this requirement demands great care in the design of the module electrical insulation system for any module, whether using crystalline-Si or amorphous-Si cells. Amorphous-Si modules using monolithically deposited cells on glass must additionally contend with the fact that the tin-oxide transparent conductor often causes the front surface and edges of the glass to be electrically connected to the cell string. This tin-oxide conductive path to the module exterior must be reliably interrupted and augmented with a high quality weather-resistant insulation system.

In addition to posing a safety hazard, module leakage currents also result in electrochemical corrosion of the solar cells. Extensive research at JPL over the past two years has clarified the importance of this degradation mechanism and led to a much improved understanding of the governing design parameters (8).

Module Delamination--Delamination (debonding) of the encapsulant system is a historical failure mechanism for all photovoltaic modules. Although no unique problems were noted with the amorphous-Si modules tested in this activity, this is an element of module design that must be carefully addressed.

SUMMARY

A key step in achieving 30-year-life thin-film modules is establishing mechanism-specific reliability goals and conducting a systematic research effort addressed to meeting the goals. The strawman reliability allocations presented in Table 1 have been contrasted with the reliability attributes of a number of first-generation large-scale a-Si modules as a means of defining reliability research priorities. Key research priorities highlighted in this study include light induced effects, cell corrosion leading to increased series resistance, glass breaking strength for large modules, and the development of protective encapsulants that meet the outdoor weathering and voltage isolation required for long-life modules. Research on these subjects is actively underway.

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