THIN-FILM MODULE RELIABILITY RESEARCH
Annual Report

December 1987

Prepared for
U. S. Department of Energy

Through an Agreement with
National Aeronautics and Space Administration

by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
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ABSTRACT

During calendar year 1987 the Jet Propulsion Laboratory carried out a research Task addressed to understanding and resolving key critical-path reliability issues associated with module-level failure and degradation mechanisms in thin-film amorphous-silicon modules.

Specific subtasks were carried out in the areas of corrosion of cell monolithic interconnects, electrochemical corrosion between cells and module frame, hot-spot heating, and photodegradation of polymer encapsulants and frame members. This annual report provides a brief overview of the research findings and includes references to ten technical papers and reports written during the year that document the work in more detail. Six of the most important of these papers are included as Appendix A.
ACKNOWLEDGMENT

This report presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy and the Solar Energy Research Institute, through an agreement with the National Aeronautics and Space Administration.

Key research personnel supporting this effort included:

- R.G. Ross Jr.  Task Manager
- C.C. Gonzalez  Photodegradation and Hot-Spot Research
- G.R. Mon      Corrosion & Moisture Sorption Research
- R.S. Sugimura Field Testing and Administrative Support
- L.C. Wen      Corrosion and Moisture Sorption Research

Many thanks are due to E. Jetter, who carried out much of the data acquisition, reduction, and graphics; J. Meyer, who managed the computerized acquisition of corrosion and moisture sorption data; S. Leland and O. Witte, who fabricated the specimens and instrumentation, and maintained the lab facilities; J. Kiehl who typed the many manuscripts and monthly reports, and R. Phen and L. Knudsen, who managed the contractual interfaces. Thanks are also due our sponsors R. DeBlasio and L. Kazmerski of the Solar Energy Research Institute and M. Prince at the U.S. Department of Energy for their support and collaboration.

The test samples and close corroboration provided by the members of the U.S. Photovoltaics industry, in particular, ARCO Solar, Chronar, and Solarex Thin Film Div., were key to the success of this task. Their encouragement and support are gratefully acknowledged.


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INTRODUCTION

A critical first step toward achieving high-reliability thin-film modules is identifying the strengths and weaknesses of the available technologies. To this end a variety of investigators including the Jet Propulsion Laboratory (JPL), have been conducting field aging studies, accelerated testing programs, and application experiments using a broad variety of first-generation amorphous-silicon (a-Si) modules. These studies were summarized at the 19th IEEE Photovoltaic Specialists Conference in May 1987, as part of this tasks effort [1]. Other additional investigators are examining the reliability attributes of a-Si technology at the cell and materials level. In combination, the studies have led to a modestly complete definition of the research priorities for achieving reliable amorphous silicon modules and have led to a broad variety of ongoing solution-oriented research thrusts.

During 1987, JPL, under the sponsorship of the U.S. Department of Energy and the Solar Energy Research Institute, has conducted a systematic study of the fundamentals underlying four of the most important degradation mechanisms that involve materials and processes at the module level. These include:

- Corrosion of cell interconnect regions
- Electrochemical corrosion between cell string and module frame
- Hot-spot cell heating
- Ultraviolet photodegradation of module polymer encapsulants and frame materials

The overall research approach in each mechanism area involves the following common thrusts:

1. Developing a generic understanding of the fundamental mechanism physics with particular emphasis on quantifying the important reaction rate dependencies on material, processing, and environmental stress parameters.

2. Developing accelerated testing techniques and life-simulation modeling techniques as required to accurately assess the adequacy of thin-film module and device designs, and to develop improvements.

3. Developing reliability enhancement technologies as required to achieve failure and degradation levels consistent with mechanism-specific requirements associated with the DOE cost-effectiveness goals.

The findings of the subtasks are summarized in the following paragraphs and detailed in the referenced papers included in Appendix A.
Increased series resistance and module open-circuiting due to corrosion of the monolithic cell interconnect is perhaps second only to light-induced effects in its importance to a-Si module reliability. Because light-induced degradation reaches an acceptable equilibrium, corrosion may be more important in the long run.

The sensitive area of the module is the region shown in Figure 1, where adjacent cells are electrically interconnected by selectively overlapping the thin-film layers such that the back metallization on one cell has a low-resistance ohmic conduction path to the front-surface transparent conductive oxide (TCO) of its neighboring cell. This conduction path can be implemented by scribing away the a-Si layer, thus allowing the deposited rear metallization to directly contact the transparent front conductor, or by using a third metal to bridge the gap between the rear metallization and the front conductor. Both techniques are used in commercial modules, and both have failure mechanisms associated with them. The key problems relate to sharp discontinuities and stresses in the rear metallization where it passes over the cliff-like edges of the laser scribe, and to galvanic couples between the dissimilar metals, when a bridging conductor is used. An important contribution of this year's research effort was the observation, for the first time, of the actual region of open circuiting. The lower half of the back-lite photo shown in Figure 2 displays two white lines along each edge of the front-contact scribe indicating open circuiting along each edge of the dissimilar metal used as the bridging conductor in this design. Similar open circuiting has been observed along the cliff-like edges of the scribe when the bridging conductor is not used.

A significant part of the CY 1987 research was directed at understanding the rate at which corrosion attacks these sensitive regions, and to developing means of minimizing the problem [2, 3]. Because an important element of the solution is controlling the ingress of moisture into the sensitive interconnect region, quantifying the rate of moisture ingress into various

Figure 1. Cross-section of typical monolithic interconnection of a-Si cells on glass superstrate
Figure 2. Light dots in lower photo are metal voids (open circuiting) along bridging-conductor region of a-Si cell interconnect shown in upper photo.

Figure 3. Picture frame of moisture ingress on one-square-foot glass-glass module after 2000 hours of 85°C 85%RH testing.
encapsulant systems was a key research focus. Particular emphasis was placed on module designs where the cells reside between two layers of glass that are bonded together using a polymer adhesive such as Ethylene Vinyl Acetate (EVA). However, other testing was accomplished on a variety of encapsulant systems involving glass on one side, and a combination of films and foils on the other.

Figure 3 displays the results obtained after nearly 2000 hours of testing a glass-glass system in a constant 85°C 85%RH chamber environment [2]. The picture frame of moisture ingress is clearly visible and suggests a long time constant, approaching thousands of hours, for moisture to significantly affect the central module area. This result, however, is contradicted by the fact that the module corrosion-induced series resistance increases in a much shorter time period.

To better quantify the time constants for moisture ingress, a variety of special instrumentation was developed and special tests were conducted. Figure 4 displays 3 types of instrumentation that were used during the year and found useful:

Figure 4(a) displays sensors developed to measure the rate of moisture ingress by noting the moisture-dependent change in ionic conductivity between the inner and outer electrode of each electrode pattern. By placing the patterns at various distances in from the module periphery, the time dependence of moisture diffusion was determined. The difficulty with this type of instrumentation is ensuring that no moisture can reach the sensors through the electrical leads that attach to the sensors via holes drilled in the glass.

Figure 4(b) shows a second instrumentation technique based on laminating cobaltous chloride (color change) humidity sensors into the module. This approach eliminated the extraneous moisture leakage paths, but resulted in a modest void volume internal to the module; this complicated quantitative interpretation of the results.

Figure 4(c) shows a third instrumentation technique based on an integrated-circuit humidity sensor wire bonded out to vacuum deposited printed-circuit wiring. Except for difficulty in surviving the lamination procedure, this instrumentation led to excellent quantitative results such as those shown in Figure 5. All of the results confirmed that the time constant for moisture ingress is on the order of thousands of hours with a glass-glass module.

Because these long time constants are in substantial disagreement with the 10 to 40 day time previously determined to be required to achieve significant series-resistance increase in 85°C 85%RH exposure tests [4], research was expanded to examine the possible role of laser scribe lines and bridging conductors in providing preferential moisture diffusion paths. Figure 6 is a photograph of the wicking action confirmed recently for one style of bridging conductor; the white bars represent the distance moisture wicked up from the lower edge of the module as measured using a special dye penetrant and photographed with ultraviolet light. These data suggest that it is important to ensure that preferential diffusion paths, such as a
(a) Ionic-conductivity humidity sensors

(b) Cobaltous chloride color-change humidity sensors

(c) Integrated-circuit humidity sensor

Figure 4. Instrumentation for measuring moisture ingress in modules
Figure 5. Measured rate of moisture increase in glass-EVA-glass module, 3 inches inboard from module periphery

Figure 6. Extent of moisture wicking up silver-frit bridging conductors made visible by dye penetrant
bridging conductor, do not extend to the outer peripheries of the module, where they can serve as moisture conduits to the outside environment.

**ELECTROCHEMICAL CORROSION**

Electrochemical corrosion between cell string and module frame has been the subject of extensive research at JPL over the past four years. This mechanism is associated with corrosion and transport of metal ions between cell and frame under the influence of the large cell-frame voltage potential present in applications with high system voltages above or below ground potential. The mechanism is found in modules of any design (crystalline and thin-film) where the module electrical insulation allows excessive leakage currents.

Previous research at JPL has shown that the solution to electrochemical corrosion rests with achieving low leakage-current levels through the use of encapsulants with low ionic conductivities, and through control of the ionic conductivity of encapsulant free surfaces and interfaces [5, 6, 7].

An important contribution of this year's research activity was the accurate characterization of the moisture and temperature dependency of the ionic conductivity of encapsulant free-surfaces and interfaces [8]. Figure 7 illustrates the enormous (many-orders-of-magnitude) sensitivity of the surface conductivity of EVA and PVB to the presence of moisture. It is this extreme sensitivity of surface conductivity to moisture that is responsible for the majority of module electrical-breakdown field failures.

![Figure 7. Surface conductivity of PVB & EVA as a function of relative humidity and temperature](image-url)
A unique form of electrochemical corrosion of a-Si modules, referred to as bar-graph corrosion, was also first reported this year [1, 9]. In this mechanism, shown in Figure 8, electrochemical corrosion attacks the tin oxide-glass interface causing delamination of the tin oxide from the glass. A variety of experiments were conducted to understand the physics underlying this mechanism and to identify prevention techniques. Results of JPL lab testing (Figure 9), and surface analysis conducted at SERI, confirmed that the problem is caused by electrochemical attack of the TO-glass interface under conditions where the cells have a positive polarity relative to the frame, and excessive leakage currents exist.

Another instance of field failures caused by electrochemical corrosion was reported during the year for a large array using crystalline-silicon modules in the Marshall Islands. JPL supported the development of repair procedures for this installation by measuring the ionic conductivity of a variety of candidate caulking materials under consideration for arresting the excessive leakage currents.

A major contributor to excessive leakage currents with a-Si modules has been determined to be the tin-oxide transparent conductor; it often extends around the edge of the glass superstrate and onto the module front surface. This causes the front surface and edges of the glass to be electrically connected to the cell string.

Figure 8. Bar-graph delamination of a-Si cells from glass superstrate
Figure 9. Bar-graph corrosion visible in encapsulated a-Si test coupons stressed with applied potentials of ± 200 volts from cell string to external solution electrolyte.

Testing at JPL of modules with laser scribe interruption of the TO conductor determined that this technique is not sufficient as a high reliability insulation system. Numerous megohm-level resistance paths were found between the cell string and module exterior edges of most commercially available a-Si power modules. This tin-oxide conductive path to the module exterior must be reliably interrupted and augmented with a high quality weather-resistant insulation system. Work on the development of such systems is actively underway.

HOT-SPOT CELL HEATING

Hot-spot heating occurs in a photovoltaic module when the short circuit current of a cell becomes lower than the string operating current, causing the affected cell to go into reverse bias and absorb power equal to the product of the cell reverse-bias voltage and the string current. The reduced short-circuit current can be caused by local partial shadowing or soiling, or by other degradation mechanisms such as glass cracking, or the "bar graph" corrosion noted earlier. Figure 10 illustrates the cell erosion that occurs in a-Si cells under severe hot-spot heating conditions.

Significant research has been carried out at JPL over the past 3 years to understand the nature of hot-spot heating in a-Si modules, to devise test methods, and to develop recommendations to improve module endurance [10]. The objective is to achieve modules that will safely endure commonly encountered levels of reverse biasing without suffering permanent hot-spot heating damage.

Research during this reporting period focused on understanding the hot-spot endurance of the new large-area (1' x 4') a-Si modules that contain solar
Figure 10. Typical erosion of a-Si cells caused by severe hot-spot heating

Figure 11. Hot-spot testing of prototype ARCO Solar G-4000 large-area a-Si module
cells with currents as high as 2.5 amps. This high current level worsens the hot-spot severity, and requires special consideration in the design process. Large-area modules from ARCO Solar (Figure 11), Solarex Thin-film Div., and Chronar were tested and evaluated, and recommendations were made relative to means of controlling hot-spot heating levels in these modules [11].

Since the degree of hot-spot heating is a function of the series-parallel configuration of the circuit in which the cell is located, there are circuit-design techniques that can be used, both in a module and in an array, to ameliorate the effects of the heating. For crystalline-silicon modules the primary technique is to limit the reverse bias voltage through the use of bypass diodes.

Although bypass diodes are also applicable to a-Si modules, the research results on large-area a-Si modules suggest that an important technique for these modules is that of limiting current by scribing a module into two or more parallel strings of smaller cells. Plots such as Figure 12 were developed as guidelines for determining maximum cell size to limit hot-spot temperature to a given level [11].

![Figure 12. Hot-spot temperature rise above operating temperature in large-area a-Si cells versus back-bias current](image-url)
ULTRAVIOLET PHOTODEGRADATION OF ENCAPSULANTS

A final element of the JPL research activity during 1987 was focused on continued study of the effects of ultraviolet exposure on polymer encapsulants and frame materials. Previous study at JPL has extensively examined the photostability of encapsulant materials such as EVA as a function of both temperature and irradiance level [12, 13]. One limitation of the previous work was the inability to examine the effect of humidity level on the photodegradation process. This has been overcome through the development of a special aging chamber (Figure 13) capable of accurately controlling sample temperature and humidity, while simultaneously providing a 1-sun ultraviolet irradiance level; the 1-sun UV level avoids the problems of determining the non-linear acceleration factor associated with other UV flux levels. As a result, the chamber acceleration factor is dependent on the more easily established correlation associated with 24-hour-a-day exposure and increased temperature. In previous research at low humidity (1-sun UV, 85°C 5%RH), the acceleration factor of the chamber was determined to be from 7 to 70 depending on the normal operating temperature of the material in its intended application. This was done by comparing the known field performance of selected materials with the measured performance of the same materials in the chamber environment.

During 1987, research centered on evaluating the effects high humidity on the photostability of a wide variety of transparent Tedlar film materials, and on a limited number of plastic frame materials. Samples of these same materials were exposed previously to the 1-sun UV, 85°C test condition, with less than 5% humidity.

Results of the high humidity exposure determined that humidity has only a small synergism with the photodegradation process of these materials. Times to failure, such as the cracking displayed in Figure 14 were within 10 to 20 percent of the times determined with the absence of humidity. However, the level of degradation suggested that none of the tested materials is consistent with 30-year-life exposure as a front cover material.

SUMMARY

During CY 1987 substantial progress was made in understanding and resolving four key reliability issues associated with first-generation a-Si power modules. These issues included:

- Corrosion of cell interconnect regions
- Electrochemical corrosion between cell string and module frame
- Hot-spot cell heating
- Ultraviolet photodegradation of module polymer encapsulants and frame materials
Figure 13. Temperature-humidity-ultraviolet combined environment test chamber

Figure 14. UV degradation of candidate vinyl backing films for thin-film modules
Detailed results of the research were documented in six technical papers included in Appendix A, and two summary papers presented at Solar Energy Research Institute annual program review meetings [14,15].

In addition to the documentation of CY'87 activities, two technical reports were issued providing final documentation of crystalline-Si reliability research conducted under in support of the DOE sponsored Flat Plate Solar Array Project [16,17].

REFERENCES


Appendix A
THIN-FILM MODULE RELIABILITY RESEARCH
SELECTED 1987 DOCUMENTATION


RECENT ACHIEVEMENTS IN MODULE RELIABILITY RESEARCH*

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ABSTRACT

After 10 years of extensive research on crystalline-silicon flat-plate photovoltaic modules, the emphasis of recent reliability research has shifted to the emerging first-generation thin-film amorphous-silicon modules. These new modules share much in common with their crystalline precursors, but also include many new materials and processes that demand the development of new reliability technologies. Key research thrusts include light-induced effects, cell corrosion, thermal diffusion, hot-spot heating, and electrical isolation of the cells from the module exterior. Research goals and recent achievements are described in each of these areas.

INTRODUCTION

Amorphous-silicon (a-Si) 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. 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.

It is this stringent 30-year-life goal that is the principal focus of the detailed reliability studies described here.

RELIABILITY TESTING OF a-SI MODULES

A critical first step toward achieving high-reliability modules is identifying the strengths and weaknesses of the available technologies. To this end a variety of investigators have and are conducting field aging studies, accelerated testing programs, and application experiments using a broad variety of first-generation a-Si modules. Many additional investigators are examining the reliability attributes of this technology at the cell and materials level. In combination, these studies have led to a modestly complete definition of the research priorities for achieving reliable amorphous silicon modules and have led to a broad variety of ongoing solution-oriented research thrusts.

As a precursor to examining the mechanism-specific research activities, it is useful to review the general findings of the module-level tests. Although the majority of the results presented are drawn from our JPL test program, they are thought to be representative of the findings of the broader community; they also represent generic findings that are more or less applicable to most of the first generation and prototype a-Si power modules. The tested modules were all one square foot or larger in area and were from four manufacturers in the United States: ARCO Solar, Chronar, Solarex Thin-Film Division, and Sovonics.

Block V Qualification Testing Results

To assess the reliability attributes of the first-generation a-Si modules and to define priorities for required reliability research, a representative sample of a-Si modules was acquired from the four U.S. manufacturers and subjected to the standard

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* This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy and the Solar Energy Research Institute through an agreement with the National Aeronautics and Space Administration.

** Supervisor, Photovoltaic Engineering Group, System Integration Section.
Global spectrum, and by developing primary combination, the LAPSS filtering and generic a-Si cells with their spectral response filtered to crystalline-Si module designs. Such designs rarely closely match that of typical a-Si cells. In Table I, the test sequence is accomplished by filtering the LAPSS to modules under test (2). This was validated by the suitability of crystalline-Si modules for field service and for identifying areas of design weakness.

Table 1. JPL Block V Module Qualification Tests

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<th>Test</th>
<th>Level and Duration</th>
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<tr>
<td>Temperature cycling</td>
<td>200 cycles: each cycle: 4 h, -40°C to 90°C</td>
</tr>
<tr>
<td>Humidity-freeze</td>
<td>10 cycles: each cycle: 20 h at 85°C, 85% RH followed by 4 h excursion to -40°C</td>
</tr>
<tr>
<td>Cyclic pressure loading</td>
<td>10,000 cycles, ± 2400 Pa (= 50 lb/ft²)</td>
</tr>
<tr>
<td>Wind resistance (single)</td>
<td>Underwriters Lab Standard UL 997</td>
</tr>
<tr>
<td>Hall impact</td>
<td>10 impacts at most sensitive locations using 29.4 mm (1 in.) (crab at 23.2 m/sec 52 mph)</td>
</tr>
<tr>
<td>Electrical isolation</td>
<td>Leakage current &lt;500 µA at twice worst-case system open circuit voltage plus 1000 V</td>
</tr>
<tr>
<td>Hot-spot endurance</td>
<td>3 cells back-biased to maximum bypass-diode voltage and cell-string current for 100 h of time</td>
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JPL Block V qualification test sequence outlined in Table I (1). This test sequence is in use for validating the suitability of crystalline-Si modules for field service and for identifying areas of design weakness.

A critical first step in the investigation was modifying JPL's Large Area Pulsed Solar Simulator (LAPSS) to ensure consistent, high-accuracy measurements of a-Si current-voltage performance under internationally recognized reference conditions. This was accomplished by filtering the LAPPS to provide a close-tolerance 100 mV/cm² Air Mass 1.5 Global spectrum, and by developing primary reference cells with 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 without the need for detailed characterization of the spectral response of the cells and modules under test (2).

In general, the first-generation a-Si modules performed well in the Block V test sequence—comparable to the performance of first-generation crystalline-Si module designs. Such designs rarely pass the test completely, because of minor design deficiencies, but degradation levels are modest (on the order of 10%); a degradation of less than 5% is required to pass the Block V test.

It is useful to examine the detailed performance of the a-Si modules on a test-by-test basis to identify specific strengths and weaknesses.

Mechanical Loading Performance—Nearly all of the modules performed well in the mechanical loading tests, which include cyclic pressure loading, mechanical twist, and impact by 1 inch (22 cm) diameter hailstones. The one sensitive area was in the resistance to hail impact. 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. Large a-Si (30 cm x 30 cm) modules making use of 3 mm (0.125 inch) annealed glass were found to have difficulty passing the JPL Block V hail test; on the other hand, both structurally supported and partially-tempered a-Si glass modules met the requirement. The data indicate that glass strength is an important consideration with present-day modules, but is amenable to straightforward solutions.

Temperature-Humidity Endurance—This is the area where most of the modules exhibited minor problems involving softening and warping of plastic parts, some delamination of non-EVA systems, and power degradation due to increased series resistance. In one case, the series-resistance increase progressed all the way to module open circuiting. Because of the system sensitivity to power reduction and open-circuiting, the series-resistance increase was identified as a critical area requiring improvement.

Hot-Spot Endurance—During exploratory hot-spot testing, a-Si modules were found to have hot-spot heating characteristics quite similar to those of crystalline-Si modules, but were in some cases more tolerant than their crystalline counterparts (3). No problems were found with cells with maximum currents below about 400 mA, above this current high levels of hot-spot heating were encountered. Bypass diodes and other circuit changes provide readily available solutions for the sensitive high-current module designs.

Field Testing of Amorphous-Si Modules

Because the Block V test sequence was developed and refined specifically for crystalline-Si modules, another important first step was testing the applicability of the test procedure to amorphous-Si modules. This required careful comparison of real-time and accelerated field-aging results with those obtained in the Block V test sequence. Of specific concern was light-induced degradation, which is known to be important in a-Si modules, and which is not tested for in the Block V tests.

To obtain high quality field data, a representative sample of first-generation and prototype a-Si modules was placed in the field at JPL's main test site as shown in Fig. 1. Performance degradation was carefully monitored by periodically removing the modules and making precision I-V measurements using JPL's LAPSS measuring system. Control modules, stored in the dark at room ambient, validated the long-term 1% repeatability of the measuring system.

When mounted in the field, each module was electrically loaded to a specific electrical operating point on its I-V curve; some modules were loaded open-circuit, some short circuit, and the majority were loaded at their maximum power point via a constant-voltage (zener diode) load. Light induced effects were prominent in nearly all field-tested modules. As shown in Fig. 2, the degradation is typified by modest short-circuit...
current loss accompanied with a shunt-like loss in fill factor. However, the initial rapid rate of degradation slows to a stable asymptotic level after a month or so of field exposure. Consistent with device testing experience, the electrical operating point of the module is also found to have a significant influence on the level and rate of degradation (Fig. 2). Although open-circuit modules generally degrade the most quickly, followed by those loaded at their peak-power point, some manufacturer's modules behave just the opposite. Because most power modules will be used with peak-power loading, this loading condition seems the most appropriate for field aging studies.

Theoretically, the rate of light-induced degradation should be minimal at elevated temperatures (above 90°C) due to increased thermal annealing of the degradation centers. This implies that aging studies conducted at elevated temperatures should be able to easily separate thermally activated degradation mechanisms, such as corrosion, from the thermally deactivated, light-induced degradation.

To examine the usefulness of high-temperature aging, modules were also aged in the field at JPL equipped with rear-side heaters to control the operating temperature. These modules were operated at peak-power loading at fixed elevated temperatures of 70°C, 85°C, and 100°C. For some of the modules the elevated temperature was imposed 24 hours each day; for the others the elevated temperature was only maintained during daylight hours. Unexpectedly, modules operated in the field at fixed elevated temperatures of 85°C and 100°C for daylight periods of 9 hours per day degraded very rapidly (Fig. 3), but stabilized at the same modest level of degradation as the unheated samples. However, at longer test durations corrosion mechanisms, suggested by the increased series resistance in Fig. 3, began to appear. After completing 160 days of testing, current-voltage (I-V) curve comparisons showed progressive series-resistance increases leading to total power losses as high as 62% for the 100°C samples.

For the 100°C samples that were heated continuously, the degradation was even further accelerated; degradation levels reached 98% after 40 days, and complete failure occurred after 80 days. Additional continuous-heating tests at 70°C revealed identical trends at the 60-day inspection period to those observed for the continuous 100°C heated modules. After that time, the degradation rate slowed (levelled off) compared to the rapid degradation observed from day 0 through day 40.

These elevated-temperature field-aging results do not agree with typical device-level laboratory experiments.
testing and suggest that much is unknown relative to the parameters controlling light-induced degradation. As a check on the validity of the data the experiments were repeated elsewhere with similar results (4).

Accelerated Laboratory Aging Tests

In combination, the Block V qualification testing and the field aging reveal a number of degradation mechanisms important to a-Si modules and highlight the inadequacy of the Block V test procedure to predict the light-induced degradation observed in the field. To further understand the stress parameters influencing these mechanisms and to separate the interrelated effects of light-induced effects and cell corrosion, a number of a-Si modules were subjected to long-term testing in 85°C 5%RH and 85°C 85%RH dark-chamber environments. During the test a forward-voltage, reverse-current electrical bias was applied to 50% of the modules to stimulate the light-induced degradation mechanism. This current-induced degradation is considered to be indistinguishable from light-induced degradation, except that the rates of degradation are not easily comparable (5).

The following observations can be noted from the matrix of test results presented in Fig. 4.

1) No module degradation is noted under high-temperature low-humidity aging with no electrical bias.

2) The electrical bias causes a decrease in short-circuit current and fill factor similar to that associated with light-induced degradation in the field; however, the level of degradation is considerably less than that observed in field-aged modules.

3) High humidity causes rapid increases in module series resistance in a mechanism (corrosion of the cell interconnects) that is quite distinct from the light-induced degradation. This series-resistance increase is seen in the Block V humidity testing and is the same as that observed in the modules field-aged at elevated temperatures (without added humidity).

Application Experience with a-Si Modules

Although JPL has not been a direct participant in any field applications of a-Si modules, several large-scale testing applications have been fielded by Chronar, Solarex Thin Film Division, and others, in collaboration with some of the electrical utilities in the U.S. These applications are an important complement to the laboratory and field-test aging experiments because they include additional user-interface stresses such as handling and installation loads, and additional system-interface stresses such as high cell-string-to-frame operating voltages; the large number of modules in these installations also greatly improves the statistical quantification of module reliability.

In discussions with these manufacturers it appears the application experiments are more or less collaborating the field-test results noted above, but are additionally emphasizing the importance and need for good electrical isolation between the monolithic cell string and the module/array frame.

Achieving good isolation between cell string and frame is particularly difficult with many amorphous-Si modules because of the presence of the conductive tin-oxide layer that effectively couples the cell string to the edges and exterior surfaces of the module glass superstrate. The environmental durability and long-term reliability of the often used laser-scribe interruption of the tin oxide film has been brought into serious question. Underwriters Laboratories describes detailed requirements in this area in their document Standard for Safety Flat-Plate Photovoltaic Modules and Panels (6).

In addition to the generic electrical isolation issue associated with ensuring electrical safety and preventing ground-fault arcing, achieving very low cell-frame leakage currents is also being found to be critically important to preventing electrochemical corrosion of the cells. Recently, Solarex has observed significant numbers of a-Si modules with “bar-graph” delamination of the thin-film tin-oxide/cell stack from the glass superstrate (7). Pictured in Fig. 5, the delamination occurred in only the portion of their high-voltage array with a particular voltage relationship to ground. When another portion of the array was substituted for the degrading one, it soon began to develop the same “bar-graph” delamination. Because of the tie to the arrays voltage polarity, the mechanism is expected to be electrochemical in nature.
MECHANISM-SPECIFIC RESEARCH THRUSTS

The module-level testing and analysis described above has led to the identification of important degradation mechanisms in amorphous-Si modules that are actively being researched so that 30-year-life modules can become a reality. These include:

- Light-induced degradation
- Corrosion of the cell interconnection regions and back metal
- Electrochemical corrosion between cell string and module frame including "bar graph" delamination of the tin oxide
- Electrical breakdown and leakage currents between the cell string and module frame
- Degradation of large-area a-Si cells due to hot-spot heating
- Interdiffusion of dopants and chemical elements between the cell thin-film layers

Many of the recent achievements in enhanced module reliability are the result of numerous mechanism-specific research thrusts focused in these areas. Although it is beyond the scope of this paper to review all of these achievements in depth, it is useful to highlight some of the areas of research and progress.

Light-Induced Effects

Light-induced effects are responsible for module degradation levels ranging from 15 to 50% during the first few months of field exposure. However, after this time the degradation slows significantly, appearing to stop at a stable equilibrium level (see Fig. 2). Many dozens of investigators are attempting to understand the fundamental physics of the mechanism, which has been found in all a-Si cells and modules independent of important differences in cell manufacturing processes. The evidence to date suggests that the degradation mechanism is intrinsically coupled to the fundamental silicon-silicon atomic bonds associated with the a-Si material. Carriers (electrons and holes), either photogenerated or injected via an applied forward-voltage bias, are found to trigger the formation of metastable atomic defects when they recombine within the a-Si intrinsic layer; these defects then serve as recombination centers and carrier traps that reduce the output current from the cell. Open-circuit voltage is only minimally affected.

If the cell is heated to an elevated temperature (such as 160°C for 1/2 hour), the metastable defects anneal out and the cell is found to return to its original efficiency. The long-term stable equilibrium level of degradation at operating temperatures is thought to be an equilibrium between the rate of degradation and the lowered rate of annealing at this temperature. The presence of illumination and the concentration of hydrogen within the cell are additional factors that have been found to affect the rate of annealing.

Once the metastable defects are formed, the reduction in cell current output is dependent on the transit time required for a photo-generated carrier to pass from the intrinsic layer to the cell collectors; the current reduction is therefore dependent on the thickness of the i-layer and the level of the accelerating electric field internal to the cell. Because the internal electric field falls as the cell approaches open-circuit voltage, the current loss depends on the cell operating voltage and is manifested as the reduced fill factor noted in Fig. 2.

One means of reducing the light-induced current loss is to reduce the thickness of the cell i-layer (8). The inherently lower cell thickness associated with multiple-junction (tandem) cells has generally been responsible for lower levels of light-induced degradation in these devices.

Sabisky (9) presents an extensive summary of recent research on light-induced effects. Much of the latest research was reported on at the Conference on Stability of Amorphous Silicon Alloy Materials and Devices held in Palo Alto, California on January 28-30, 1987. The proceedings of the conference are due to be published by the American Institute of Physics.

Corrosion of Cell Interconnect Regions

Increased series resistance and module open-circuiting due to corrosion of the monolithic cell interconnect is perhaps second only to light-induced effects in its importance to a-Si module reliability. Given that it does not reach an acceptable equilibrium, it may be more important in the long run.

The sensitive area of the module is the region shown in Fig. 5, where adjacent cells are electrically interconnected by selectively overlapping the thin-film layers such that the back metallization on one cell has a low-resistance ohmic conduction path to the front-surface transparent conductive oxide (TCO) of its
neighboring cell. This conduction path can be implemented by scribing away the a-Si layer, thus allowing the deposited rear metallization to directly contact the transparent front conductor, or by using a third metal to bridge the gap between the rear metallization and the front conductor. Both techniques are used, and both have failure mechanisms associated with them. The key problems relate to sharp discontinuities and stresses in the rear metallization where it passes over the cliff-like edges of the laser scribe, and to galvanic couples between the dissimilar metals, when a bridging conductor is used. The back-emit photo shown in Fig. 7 displays two white lines along either edge of the front-contact scribe indicating open circuiting along each edge of the dissimilar metal used as the bridging conductor in this design. Similar open circuiting is found along the cliff-like edges of the scribe when the bridging conductor is not used.

Considerable research is underway to fully understand the rate at which corrosion attacks these sensitive regions and to develop means of minimizing the problem (10, 11). An important element of the solution is controlling the ingress of moisture into the sensitive interconnect region and using corrosion resistant metals and encapsulants.

**Electrochemical Corrosion**

Electrochemical corrosion between cell string and module frame has been the subject of extensive research at JPL over the past four years. This mechanism is associated with corrosion and transport of metal ions between cell and frame under the influence of the large cell-frame voltage potential present in applications with high system voltages above or below ground potential. The mechanism is found in modules of any design (crystalline and a-Si) where the module electrical insulation allows excessive leakage currents. Fig. 8 shows an example of electrochemical corrosion found in a recent crystalline-Si system in an equatorial climate, whereas Fig. 5 shows a unique form of electrochemical corrosion observed with a-Si modules.

The solution to electrochemical corrosion rests with achieving low leakage current levels through the use of encapsulants with low ionic conductivities, and through control of the ionic conductivity of encapsulant free surfaces and interfaces (12, 13, 14, 15).

**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

Fig. 8. Electrochemical Corrosion of Crystalline-Si Cells in High-voltage Equatorial Application
this (hi-pot) test voltage is in the range of 1500 to 3000 volts (6). Meeting this requirement requires great care in the design of the module electrical insulation system for any module, whether using crystalline-Si or a-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.

Initial testing at JPL of modules with laser scribe interruption of the TCO conductor indicates that this technique is not sufficient as a high reliability insulation system. Numerous megohm-level resistance paths were commonly found between the cell string and module exterior edges of most commercially available a-Si power modules. This tin-oxide conductive path to the module exterior must be reliably interrupted and augmented with a high quality weather-resistant insulation system. Work on the development of such systems is actively underway, but this author is unaware of any published work to date.

Hot-Spot Cell Heating

Hot-spot heating occurs in a photovoltaic module when the short circuit current of a cell becomes lower than the string operating current, causing the affected cell to go into reverse bias and absorb power equal to the product of the cell reverse-bias voltage and the string current. The reduced short-circuit current can be caused by local partial shadowing or soiling, or by other degradation mechanisms such as glass cracking, or the "bar graph" corrosion noted earlier. Fig. 9 illustrates the cell erosion that occurs in a-Si cells under severe hot-spot heating conditions.

Significant research has been carried out at JPL over the past 3 years to understand the nature of hot-spot heating in a-Si modules, to devise test methods, and to develop recommendations to improve module endurance (3, 16). The objective is to achieve modules that will safely endure commonly encountered levels of reverse biasing without suffering permanent hot-spot heating damage.

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**SUMMARY**

As an indication of the evolving nature and continuing growth of photovoltaic technology, thin-film a-Si power modules have made their commercial debut during the past 2 years. Because of the extensive interest in this technology, the majority of recent reliability research has focused on characterizing the reliability of the first-generation a-Si power modules, and on initiating the development of reliability enhancements required to achieve 30-year life. Extensive field testing and early application experience have
highlighted certain failure mechanisms as being the most important to long-term power generation. These include light-induced effects, corrosion of the cell monolithic interconnects, electrochemical corrosion between cells and module frame, electrical breakdown between cell string and frame, and diffusion of dopants and chemical elements between the thin-film cell layers. Research efforts in each of these areas are actively underway and are making important contributions to the reliability of this promising technology.

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ENCAPSULANT FREE-SURFACES AND INTERFACES:
CRITICAL PARAMETERS IN CONTROLLING CELL CORROSION

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ABSTRACT
We present some results of studying the interaction of moisture with photovoltaic (PV) modules and custom-built test coupons in both laboratory and outdoor ambient environments. We measured module cell-to-frame leakage currents, encapsulant bulk and surface currents, glass surface currents, and encapsulant/glass interface currents as functions of temperature and humidity. Using a computer model of inter-electrode conduction, we delineate preferential conduction paths in PVB- and EVA-encapsulated modules. In comparing the results of field and laboratory test environments on identical samples, we note and comment upon the greater severity of the outdoor environment. We conclude with a discussion of several aspects of water-module interaction, including design strategies and continuing research aims.

BACKGROUND
A particular performance degradation mode that has been extensively documented is electrochemical corrosion (1-4). Voltage differences between two electrified cells within a module, or between an electrified cell and a grounded frame, drive chemical oxidation and reduction reactions at the cell/encapsulant and the frame/encapsulant interfaces and cause ionic ("leakage") currents to flow between these electrified module parts. A schematic depiction of this process is shown in Fig. 1.

Leakage current, which is the rate of inter-electrode ionic charge transfer, is a measure of the electrochemical reaction rate and can be modelled as an Arrhenius temperature/rate process (log current inversely proportional to reciprocal absolute temperature) with a rate doubling for approximately every 100°C increase in temperature (5). Its level is determined by the impressed voltage, the geometric arrangement of the module components, and the effective ionic conductivity, which depends upon the environmentally sensitive dielectric and water sorption properties of the encapsulant.

The encapsulant plays a key role in module electrochemical processes; its selection affords the major opportunity for controlling ionic charge transfer rates in photovoltaic modules. It serves as the (solid state) electrolyte in electrode interactions and is the medium through and along which dissolved metallization ions are transported. The dielectric properties of the polymeric compound determine the ease with which metallization ions dissolve. Its conductivity properties and indigenous ionizable species concentrations determine the inter-electrode ion transfer magnitudes. The values of these fundamentally important encapsulant properties are strongly affected by the encapsulant temperature and moisture content. Hence module ionic charge transfer rates will depend, in a complex way, on the environmental temperature and water vapor partial pressure variations and on the water sorption and diffusion characteristics of the polymer.

The interplay of moisture with polymer materials--i.e., the module encapsulant--is more

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In this paper we present data that may serve as a basis for quantitative studies of the water/module interaction problem. We present sorption measurement data for the encapsulants PVB and EVA. We present Arrhenius activation energy constants for bulk conduction in these encapsulant materials, together with plots of bulk and surface conductivity of EVA and PVB, surface conductivity of a borosilicate and a soda-lime glass, and interface conductivities of these encapsulant/glass composites. These data were used in a computerized simulation of two-dimensional conduction to study ionic conduction characteristics of PVB- and EVA-encapsulated modules. Laboratory and field surface, bulk, and interface data on the same test coupons are compared; these data reveal that the "real world" environment is more severe than generally applied laboratory temperature/humidity environments. The consequences of these data will be discussed.

SORPTION

Sorption data were acquired utilizing a Cahn Balance having microgram resolution. From one arm of the beam balance the sample, typically a sheet of polymer, is suspended in a Blue M environmental chamber. The other arm sports counterweights suspended in an unchanging environment. The chamber environment can be controlled over the ranges 10% - 100% relative humidity (RH) and 20°C - 85°C.

Sorption equilibrium isotherms, based upon data collected at JPL from pristine PVB and EVA samples, are presented in Figure 2. The isotherms account for both surface and bulk water. It is seen that PVB is considerably more sorbant than EVA.

This sorption data was acquired on polymer sheets offering large areal exposure to the applied environment. The data may be applicable to unglazed modules but perhaps not to glass-polymer-glass modules which offer limited polymer exposure (generally along a gasketed lineal perimeter) to the environment.

IONIC CONDUCTION

Water within a polymer and on its surface that is available to participate in the ionic conduction process does so by providing a medium in which ionization can readily occur. The high involved (6,7) and hence less well understood than are temperature-rate relationships. Whereas all parts of a PV module are at approximately the same temperature (±3°C), the moisture level can vary by orders of magnitude from module surface to module interior. This greatly complicates the calculation of moisture effects because the moisture level must be specifically computed for the exact site of the governing reaction. Quantifying the reaction rates expected under varying field conditions (temperature, relative humidity, dew, rain, etc.) requires complex transient models of the modules' spatial governing reaction. Quantifying the reaction rates of the leakage current dependency on this moisture level and distribution.

Analytical Expressions

Semi-empirical equations having some theoretical basis (8,9) have been utilized to relate the dependency of ionic conduction upon temperature, sorbed moisture content, and material permittivities. We use these equations and further develop them to provide analytical expressions against which to compare experimental measurements and to serve as a basis for model analysis of overall PV module conduction processes:

\[ k = M_0 \exp\left(-\frac{E}{RT}\right), \quad \mu_0 = \frac{U_0}{2Z} \quad \ldots(1) \]

where

- \( k \) = ionic conductivity, \((\text{ohm-cm})^{-1}\)
- \( M_0 \) = scale constant, \((\text{ohm-cm})^{-1}\)
- \( R \) = gas constant, 1.987 \( \text{cal/mole-K} \)
- \( T \) = temperature, \( \text{K} \)
- \( E \) = activation energy, \( \text{cal/mole} \) (the energy required to ionize one mole of bound ion in a medium)
- \( U_0 \) = dissociation energy, \( \text{cal/mole} \) (the energy required to ionize one mole of bound ion in-vacuum)
- \( Z \) = relative permittivity of polymer medium

Bulk Conductivity. We model the bulk permittivity of a polymer/water composite as

\[ Z = Z_p (Z_w / Z_p)^c \quad \ldots(2) \]

where \( c \) is the volume fraction of water in the composite and the subscripts "p" and "w" refer to "polymer" and "water", respectively. This formula derives from an expression by Hartshorn (9) modified to apply to a polymer with specific gravity near unity and having a small water concentration.

When Eqn. 2 is substituted into Eqn. 1, we obtain

FIG. 2. Water Sorption Isotherms for PVB and EVA
where \( E_v = U_0/2Z_p \) is the activation energy for the dry state, \( C = 0 \). If a material suffers hygrothermal degradation, its sorption capacity will generally increase. To account for degradation, we replace \( C \) in Eqns. 2 and 3 with \( hC \). The degradation factor \( h \) multiplies the water concentration \( C \) over what it would be in the non-degraded material for equivalent exposure conditions.

Surface Conductivity. For water on a polymer surface, we adopt the expression

\[
Z = Z_p (V_p + V_w Z_p/Z_w)^{-1}
\]  

(4)

where \( V_p \) and \( V_w \) are the polymer and water volume ratios relative volume of the composite surface conduction layer. Substituting Eqn. 4 into Eqn. 1 gives

\[
k_s = M_s \exp\left[-\frac{(E_v/RT)(1-V_w(1-Z_p/Z_w))}{(1-V_w)}\right]
\]  

(5)

For surface conductivity we make the additional distinction that \( V_w = y \), where \( y \) is the fraction of the surface covered with moisture and \( r \) is the water volume ratio of the covered sites, assumed to be equal to the ambient relative humidity for steady state exposure conditions. For polymer surfaces, experimental conduction data can be fitted with \( y \)-values near 1, but for glass surfaces, a better fit is obtained with \( y \) about 0.1.

Interface Conductivity.

We invoke superposition to model the ionic conductivity of a polymer/glass interface:

\[
k_I = k_g + k_p
\]  

(6)

A superposition model may be valid if, for example, the two surfaces strongly interact or if adhesive binders or primers (10) are used to promote coupling.

Experimental Results: Laboratory

Activation Energies. Arrhenius plots for "dry" PVB and EVA are presented in Fig. 3. The data groupings reflect different sample design and fabrication processes, but despite considerable differences in sample exposure histories, the activation energies have remained relatively constant at \( E_v = 17.1 \text{ kcal/mole} \) for PVB and \( E_v \approx 13.6 \text{ kcal/mole} \) for EVA.

Bulk Conductivities. Bulk equilibrium ionic conductivity data for pristine PVB and EVA are presented in Fig. 4. The superposed curves are generated using Eqn. 3 with \( M_s = 15 \text{ (ohm cm)}^{-1} \) and \( h = 1 \) for the PVB data, and \( M_s = 0.000224 \text{ (ohm-cm)}^{-1} \) and \( h = 2.31 \). The degradation factor \( h \approx 2.31 \) giving the "best" fit for the EVA data may imply that the EVA used to obtain this data may have been more sorbant than that used to obtain the sorption data in Fig. 2. EVA exposed 45 days to an 85°C/85%RH environment exhibited sorption capacities more than twice those indicated in Fig. 2.

Surface Conductivities. The raw PVB and EVA surface and interface conductivity data contain bulk contributions. To permit division of this data into bulk, surface, and interfacial components, a multi-nodal network model (11), which outputs voltage at each node and current flow between adjacent nodes, was constructed to simulate the conduction paths in the measurement samples.

The PVB and EVA surface conductivity data, with bulk contributions excluded, are presented in Fig. 5. The superposed curves are generated using Eqn. 5 with \( M_s = 1.26E^{-7} \text{ ohm}^{-1} \text{ cm} \) and \( E_s = 12.45 \text{ kcal/mole} \), and \( y = 1 \) for PVB, and with \( M_s = 1.7E^{-12} \text{ ohm}^{-1} \text{ cm} \) and \( E_s = 6.83 \text{ kcal/mole} \), and \( y = 1 \) for EVA, respectively. Compared to bulk conductivity values, surface conductivity values are relatively insensitive to temperature variations but are very responsive to relative humidity variations.
The surface conductivities of borosilicate (Pyrex 7740) and soda-lime glass are presented in Fig. 6 (borosilicate glass: $M_s = 23.22$ ohm$^{-1}$, $E_s = 23.3$ kcal/mole, $y = 0.11$; soda-lime glass: $M_s = 0.02775$ ohm$^{-1}$, $E_s = 15.46$ kcal/mole, $y = 0.11$). The surface conductivity of borosilicate glass is considerably lower than that of soda-lime glass. The surface conductivity of both glasses is more sensitive to temperature variation than that of the two polymers.

**Interface Conductivities.** PVB/glass interface data are presented in Fig. 7 and EVA/glass interface data in Fig. 8. Evidently for PVB/glass, at low humidity the glass surface dominates, while at high humidity the PVB surface dominates, the interface conduction process. The glass surface dominates the EVA/glass interface conduction process at all humidity levels.

Additional borosilicate/polymer interface conductivity measurements were made with various polymers, including polyvinyl chlorides, fluorides, acrylics, and polyesters. The glass dominated the interface conduction process for all but the polyester/glass composite.

**Experimental Results: Field**

The same samples that were used to obtain the laboratory bulk, surface, and interface leakage current measurement data were then field mounted at a JPL outdoor test site. Raw data collected over four different days in March 1986 are presented as bulk, surface, and interface leakage currents in Figs. 9-11, respectively. Beneath the data for each day, the type of day is indicated by a typifying word and temperature. To the left of the field data, for the purpose of comparison, are the corresponding $85^oC$ laboratory measurement data for the same samples.

General observations are that in both laboratory and field environments, currents in PVB considerably exceeded those in EVA, interface currents exceeded surface currents, and large surface and interface current excursions occurred during periods of rain and dew.

The fact that these low temperature field data have associated with them current levels comparable to and exceeding those observed in what is considered to be a severe accelerated
environment—namely, 85°C/100%RH—underscores the major role liquid water plays in establishing field leakage current levels and hence in contributing to PV module electrochemical corrosion. Indeed, when doing life prediction simulation, it may suffice to consider only the leakage currents generated during periods of module exposure to liquid water.

One form of water damage actually observed at the test-stand was the formation of liquid water pockets at material interfaces of some test coupons. As temperature increased, this trapped water presumably vaporized, causing blistering and delaminations.

**Fig. 9. Lab/Field Bulk Leakage Current Data**

**Fig. 10. Lab/Field Surface Leakage Current Data**

**Fig. 11. Lab/Field Interface Leakage Current Data**

**LEAKAGE CURRENT PATHS**

We now focus on the interplay of bulk, surface, and interface conductivities in determining overall conduction path geometries in PV modules. Glass superstrate test coupons were constructed consisting of a single C-Si cell and aluminum bar (“frame”) encapsulated in PVB or EVA. Measurements were made at 500 volts cell-to-frame. A two-dimensional multi-nodal SINDA (11) conduction model of a typical test coupon, shown in Fig. 12, was employed to achieve a first cut understanding of leakage current division among possible paths. The ultimate parameter determining the leakage current is the total resistance \( R_T \) between cell and frame, as determined by the series/parallel network connecting the two. Fig. 13 shows how \( R_T \) varies with bulk, surface, and interface resistivities and the key geometric parameters defined in Fig. 12. In Fig. 13, \( \psi \) is the reciprocal sum of surface and interface conductivities.

The simulation results presented in Fig. 13 supercede those presented in Fig. 8, Reference (1), which fails to account for conduction at the encapsulant/glass interface.

**Fig. 12. Sample Model Used in Computer Conduction Simulation**

In Fig. 14, the resistivity ratio (abscissa in Fig. 13) is plotted vs. temperature and relative humidity for PVB and EVA. Thus the ionic conduction characteristics generated by the simulation model (Fig. 13) can be correlated with the ionic conduction characteristics of module encapsulants in equilibrium temperature/humidity environments (Fig. 14).

As an example of the usefulness of Figs. 13 and 14, note that for EVA/glass modules the surface-interface/bulk resistivity ratio is small \( (\psi / \rho_V < 0.3) \); the dominant cell-to-frame conduction paths are via the surface and interface. Under these conditions the leakage current level is inversely proportional to the encapsulant thickness \( t \) and directly proportional to the areas of the cell and frame as represented by their widths \( W \) and \( w \), respectively, Fig. 13. This is true for PVB modules only in wet, low temperature environments, as may occur on dewy mornings or rainy days. For
PVB/glass modules in a dry environment ($\rho_{SI}/\rho_{PV} > 10.0$), the conduction is dominated by lateral paths through the encapsulant bulk; the gap spacing and the total encapsulant thickness $T$ are the governing parameters.

We point out that cells of C-Si modules are totally surrounded by insulation; hence all cell-to-frame paths have one or more bulk components. On the other hand, in a-Si modules interfacial paths directly connect the cells to the frame. The consequences of this for water entry into, and distribution within, PV modules are discussed in a companion paper (12) in this journal.

**DISCUSSION AND CONCLUSIONS**

In this paper we have noted the crucial role ionic leakage current plays in contributing to PV module corrosion processes. We have provided some important material ionic conduction data and have indicated how variations in module design parameters impact module leakage current levels. We have indicated likely module leakage current paths for various temperature/humidity environments and have demonstrated the greater severity of an outdoor environment over that of typical laboratory temperature/humidity test environments, emphasizing the key role of liquid water.

This paper and its antecedent (1) establish a database and the germ of a procedure for quantitatively analyzing and predicting PV module field life. Still lacking are transient performance models that integrate the many interactive parameters into a single reliable analytical algorithm. Present transient response models are simplistic at best and a quantitative understanding of the link between the form and concentration of moisture in a polymeric material (much less a PV module), and the consequent ionic conduction and corrosion, is not now available.

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ABSTRACT

This paper reports on corrosion/erosion phenomena observed in exposing a-Si cells, modules, and specially designed test structures to natural and accelerated test environments. Relevant cell and module I-V curve data, monitoring degradation, are presented. The causes of observed degradations, methods of mitigation, and consequences for fielded modules are discussed.

BACKGROUND

In a previous paper (1) two of the current authors presented data and observations on the degradations experienced by a-Si cells and modules upon exposure to various steady temperature/humidity environments. In summary, it was observed that unencapsulated modules exposed to an 85°C/100%RH environment developed pinholes that enlarged with time of exposure. In the intercell zone (Region A-A in Fig. 1) of the a-Si module, the pinholes tend to aggregate and interfuse, particularly along the a-Si layer laser scribe line boundaries (Regions D-E and D-C, Fig. 1) along which the thin-film layers are highly directionally stressed, to form a metallization-free line tending to open-circuit the module. The SEM micrographs in Fig. 2 quite emphatically depict this form of intercell corrosion. Another observed form of degradation is filiform corrosion, the loss of back surface (aluminum) metallization in worm-like patterns. Both of the above phenomena are manifestations of stress corrosion cracking in the thin-film module layers.

Energy dispersive X-ray analysis of modules exposed for long periods of time to an 85°C/100%RH environment confirmed the loss of aluminum along the a-Si laser scribe boundaries.

Fig. 1. Schematic of a-Si Module Intercell Zone.

Fig. 2. SEM Micrographs of Intercell Zone -- Bare Module Exposure to 85°C/100%RH.
In Figs. 3 and 4 are presented additional data collected during these tests. Note in Fig. 3 how the dark I-V curves "fan out", exhibiting ever increasing series resistance. Figs. 4 and 5 exhibit the effects of exposure on series resistance and on power output for two modules of different manufacture. The module of Mfgr. A featured a polymeric substrate design and exhibited little post-test degradation. The module of Mfgr. B featured a polymer/glass substrate design. It exhibited "picture framing", i.e., fogging of the metallization around the module edges, where moisture enters and slowly diffuses inward, Fig. 6. The module design differences are crucial to the observation--moisture penetrated both modules, to be sure, but the aluminum metallization of Module A was thicker and purer, hence more corrosion resistant, than that of Module B.

This paper will describe the results of additional tests to determine the nature of moisture/module interaction, will confront the many questions raised by these studies, and will attempt to provide an integrated explanation of results to date, together with consequences for fielded modules and suggestions for design and performance improvement.

DESIGN CONSIDERATIONS

Just what are the moisture-induced degradation processes in a-Si modules that the design engineer must address? Laboratory evidence, based upon unencapsulated modules exposed to humid 85°C environments, suggests that it is intercell corrosion/erosion of aluminum metallization along the a-Si scribe line boundaries in the intercell region, as previously described, involving the erosive processes of pinhole formation and coalescence by stress corrosion cracking, and the corrosive processes of aluminum oxide and hydroxide formation. However, observations on encapsulated modules suggest other possibilities. Encapsulated modules were observed to suffer a much reduced metallization corrosion/erosion process that occurred more uniformly throughout both the active and intercell regions of the module. Some modules in the field exhibited severe degradation of the active cell region but very little degradation of

Fig. 3. Dark I-V Curves of 4"x4" a-Si Modules.

Fig. 4. Series Resistance vs. 85°C/100%RH Exposure Time for Two 1"x1" a-Si Modules of Different Manufacture.

Fig. 5. Maximum Power Output vs. 85°C/100%RH Exposure Time for Two 1"x1" a-Si Modules of Different Manufacture.

Fig. 6. "Picture Framing" of Glass Superstrate a-Si Module Resulting from Moisture Ingress.
the intercell zone. The glass substrate module shown in Fig. 6 suffered degradation due to moisture creeping inwardly from its edges—in both regions, but apparently more severely in the active cell region than in the intercell zone.

The two basic design strategies for inhibiting moisture-induced degradation of a-Si modules are to use corrosion-resistant metallization and moisture-resistant encapsulation.

Metallization.

Concerning metallization, experimental evidence suggests that purer and thicker aluminum metallization layers quite effectively retard corrosion. Sputtered metallization adheres better than vapor deposited metallization and may afford greater corrosion protection, but at significantly greater cost. Laser scribing is to be preferred to mechanical scribing, and masking is preferable to metallization etching.

The actual details of aluminum metallization corrosion involves the formation of aluminum oxides (Al₂O₃) and hydroxides (AlO(OH)). Aluminum dissociates anodically to form mono- and tri-valent aluminum ions, but the former react with water to form tri-valent aluminum ions and hydrogen gas. The process involves multiple reactions but can be summarized in two all-inclusive reactions. In the presence of oxygen:

\[ 6\text{Al} + 3\text{H}_2\text{O} + 4\text{O}_2 \rightarrow 4\text{AlOOH} + \text{Al}_2\text{O}_3 + \text{H}_2 \]

and in the absence of oxygen:

\[ 4\text{Al} + 7\text{H}_2\text{O} \rightarrow 2\text{AlOOH} + \text{Al}_2\text{O}_3 + 6\text{H}_2 \]

The evolution of hydrogen gas may be a source of bubble formation and material delamination in the fielded module.

Additional factors relating to aluminum metallization corrosion include the facts (2) that aluminum corrodes rapidly for pH < 4.5 and pH > 7 and that the Cu-Al and Cu-Ag couples are very galvanically active. Regarding the former fact, at temperatures below 250°C, the pH of water is greater than 7 and aluminum/moisture corrosion reaction rates accelerate. Regarding the latter fact, it is bad practice to couple copper (or silver) lead wire to aluminum metallization or interconnect strips anywhere within the module to where moisture is likely to penetrate.

Encapsulation.

Moisture accelerates corrosion; thus to reduce performance degradation of a-Si modules, moisture interaction with module materials must be retarded or eliminated. One approach to electronic packaging is hermetic sealing, which significantly retards the moisture ingress leakage rate and thus delays the onset of corrosion. A less expensive technique employs polymeric encapsulations. Although moisture penetrates most polymers in a short time, these materials generally have very low water sorption capacity and provide an environment with low ionic conductivity. They are weak electrolytes; hence through their use, an otherwise active electrochemical environment can be considerably passivated.

There are two basic encapsulation schemes: (1) a polymer substrate; and (2) a polymer/glass substrate addition to the monolithically fabricated a-Si module. Which design will best inhibit moisture-induced degradation? The answer is not yet conclusive.

Polymer Substrate.

In polymer-encapsulated modules, one function of the polymer is to hamper the transport of moisture to the metallization surface and to inactivate metallization surface adsorption sites (3). Nevertheless, moisture can more freely enter and exit such modules, there being much greater encapsulant surface area in contact with the ambient. Their greater interplay with moisture makes them more susceptible to corrosion phenomena but less susceptible to hydro-thermo-mechanical degradation than glass substrate modules. Encapsulant thickness may be a critical design parameter.

Polymer/glass Substrate.

In a glass substrate module, moisture that enters via interfacial paths originating at the module edge, slowly diffuses toward the center of the module. An effective design strategy, albeit somewhat compromising efficiency, may be to provide a cell-free zone around the module periphery and an effective edge sealant. Moisture that enters such a module usually cannot exit; this moisture buildup within the module can have adverse consequences for performance—chemical, leading to corrosion, and thermo-mechanical, resulting in delaminations.

MOISTURE INGRESS

The several corrosion and moisture/module interaction experiments performed to date raise many questions about these subjects—perhaps more than they answer. Not the least among these is: How does moisture enter an a-Si module? A key entry point is the lead-wire/module interface. Evidence suggests that, in addition, material interfaces and scribe lines provide opportune paths for moisture ingress and diffusion to the module interior. It appears (Fig. 6) that moisture diffusion along organosilane-primed glass/polymer interfaces is a relatively slow process, and that diffusion through the polymer bulk is even slower.

The glass substrate module shown in Fig. 6 suffered degradation even more severely than it did previously, and apparently more severely in the active cell region than in the intercell zone.

A series of experiments were performed to determine the nature of the moisture/module interaction mechanism. In all of these, glass/polymer or glass/polymer/glass test structures featuring different types of moisture sensors embedded in the polymer surface, or bulk, or at the polymer-glass interface, were exposed to humid environments and the rate or quantity of physical distribution of absorbed moisture was monitored. When the sensors used were ionic current detectors, rapid increases in measured currents in response to isothermal humidity increases were observed; this
observation was ultimately attributed to moisture entering via the lead wires. When the sensors were wireless chemical indicators, there was no evidence for rapid ingress of moisture. Moisture does enter, however, at cracks in the glass or along the edges of the module (Fig. 6) and proceeds to diffuse slowly along the primed interfacial paths.

DISCUSSION

Tests at 85°C/85%RH and 85°C/100%RH on encapsulated and unencapsulated fully aluminized back surface modules revealed that encapsulation effectively retards gross metallization loss in the active cell region (1). When the metallization is highly corrosion resistant, however, the addition of encapsulation does not seem to retard the rate of increase of measured sheet resistivity over that observed for unencapsulated specimens: see Figs. 7 and 8, Reference (1).

In two recent papers Ross (4,5) presented I-V curve results of aging modules in dark temperature/humidity environments and in accelerated and real-time outdoor environments. The results of dark oven aging, Fig. 7, in dry and moist environments demonstrate the important influence of moisture upon series resistance, a parameter generally regarded as being allied to corrosive degradation. A comparison of the responses of unbiased and forward biased modules demonstrates the light induced (Staebler-Wronski) effect—an immediate but modest short-circuit current loss, approaching a stable asymptote, accompanied by a shunt-like loss in fill factor (6).

The results of accelerated outdoor testing indicate that modules uniformly heated to 100°C degraded more severely, perhaps as expected, than modules uniformly heated to 85°C. These modules exhibited both series-like and shunt-like losses in fill factor. In general, modules exposed to the natural environment exhibited greater degradation than modules exposed to uniform temperature/humidity environments. The postulation is that the outdoor environment is considerably more severe, involving actual liquid water contact (dew, rain, snow) and stress-inducing temperature/humidity cycles. The moisture sorption and diffusion dynamics are such that moisture concentration within the module tends to increase over long periods of outdoor exposure—modules tend to retain sorbed moisture.

Water/module interaction physics are discussed in some detail in a companion paper in this journal (7). In it are presented material sorption and ionic conductivity data of PV module polymers and glass/polymer composites, and data comparing ionic leakage currents in laboratory and outdoor environments.

CONCLUDING REMARKS

Ongoing research is focussed upon continuing the study of the deleterious effects of moisture on a-Si modules. The aim is to optimize a-Si module design. The procedure is to assess the performance of various module design types by measuring their degradation rates in a "standard" moist environment. Techniques for reducing moisture entry into substrate modules, such as edge sealing, and of mitigating the effects of moisture, such as by means of cell-free perimeters or sacrificial electrodes, are being tested.

In light of the extreme sensitivity of a-Si modules to interaction with moisture, however, it may ultimately prove more cost effective to develop a truly water-tight module than to attempt to mitigate the effects of moisture in water-active modules.

ACKNOWLEDGEMENTS

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REFERENCES


AMORPHOUS-SILICON MODULE INTERCELL CORROSION
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ABSTRACT

Three non-electrochemical, moisture-induced a-Si module degradation modes have been observed and their mechanisms studied: (1) the formation and growth of pinholes in the thin-film layers; (2) the directional interfusion of pinholes along process scribe lines to form metallization-free regions that tend to open-circuit the module; and (3) worm-like filiform corrosion in the aluminum layer. The dependency on time-of-exposure to moist environments of the amount of material erosion in the module intercell zone has been quantified by two methods—directly by EDS analysis, and indirectly by sheet resistivity measurements on fully alumínized back surface modules. In addition, changes in maximum power output, series resistance, and open circuit voltage have been documented. Consequences for fielded modules are discussed.

INTRODUCTION

A much-studied and by now well-known amorphous-silicon module instability factor is the Staebler-Wronski effect. Macroscopically, the effect manifests as a loss of efficiency due to fill factor decay. The effect is reversible in that annealing will restore module efficiency to nearly its original value. An equally well-known module reliability problem is corrosion; it manifests as loss of power output and increase of series resistance. The types of corrosion directly affecting the performance of amorphous-silicon (a-Si) and crystalline-silicon (C-Si) photovoltaic devices include electrochemical corrosion and galvanic corrosion. Electrochemical corrosion results from applied voltage differentials between different module parts (e.g., cell and frame in C-Si modules), while galvanic corrosion results from self-generated potential differences between contacting conductors (as, for instance, between the back-cell metallization and the transparent conductive oxide (TCO) layer in adjacent cells of a-Si modules).

Electrochemical corrosion in both C-Si and a-Si modules has been well documented. Galvanic corrosion is less well understood. It results from direct contact between conductive parts of a module; hence it is not driven by light-generated potentials and may occur day or night. The major concern is that corrosion may open-circuit the a-Si module. This is most likely to result from loss of the conductive oxide layer and/or the contact metallization in the "parasitic cell" region between two adjacent active cells, Fig. 1. Of particular concern are anticipated losses of conductive oxide in regions B, C and D, and of back-surface metallization in regions D, E and F. Some module manufacturers use a conductive filler, such as silver paste, in region D to enhance intercell conductivity; this
practice adds an additional galvanic couple to which the above concern extends.

![Fig. 1. Series-Connected Thin-Film Cells](image)

A tendency toward open-circuiting will cause increases in contact resistance between the conductive oxide and the rear surface metallization. If this resistance \( R_c \) should become too large, the diode characteristic of the parasitic cell will evidence itself as an upward curvature in the active cell's fourth-quadrant I-V characteristic, a reduction of \( V_{oc} \), and loss of maximum power output as a result of the forward drop of the parasitic diode.

A loss of contact metallization has indeed been observed both for unencapsulated and EVA-encapsulated modules, and the losses are in fact most pronounced in the contact scribe zone (region D, Fig. 1). The relatively larger losses that occur in this region are attributable to high mechanical stresses induced in the metallization at the sharp corners formed in the laser scribing of the a-Si layer. Other observed degradation patterns include extensive pinhole formation in the aluminum layer and in the combined aluminum and a-Si layers (and perhaps even the conductive oxide layer), and filiform corrosion in the aluminum layer. The study of these degradation processes and their consequences for a-Si module performance, are described in the remainder of this paper.

**EXPERIMENTAL APPROACH**

Four separate but related experiments were undertaken to ascertain the non-electrochemical corrosion aspects of a-Si modules. In the first experiment, a number of unencapsulated a-Si modules was exposed for variable intervals to controlled 85°C/100%RH chamber conditions over an extended period of time. Prior to exposure, and after each exposure interval, these samples were removed from the oven and dark I-V curve data were acquired. From these data, progressive series resistance values were obtained. In addition, photomicrographs of the intercell regions of select samples were
obtained using a scanning electron microscope (SEM), and atomic concentration profiles of the intercell region were obtained using energy dispersive X-ray (EDS) techniques. Optical photographs of the intercell region were also obtained.

The exposure times and experimental measurement techniques employed on the second batch of a-Si modules were similar to those used on the first, with the exception that light I-V curve data rather than dark I-V curve data were obtained.

The experimental approach employed for the third batch of samples was as for the first batch except that during exposure the samples in the third batch were forward voltage (reverse current) biased at 3/4-volt differential per cell, approximately equivalent to that experienced during exposure to light. It is known\(^8\) that forward bias conditions stress the a-Si in a manner equivalent to light exposure. This phase of the experiment, then, focussed on differentiating galvanic and other corrosions from the light induced Staebler-Wronski effect.

A fourth set of samples featured a-Si modules encapsulated in the polymer ethylene vinyl acetate (EVA) and then subjected to an exposure and I-V curve acquisition program similar to that for Batch 1 and 2 samples.

When in the course of interpreting the data it became clear that loss of back surface (Al) metallization was a major degradation mode, a fifth batch of samples was subjected to both 85°C/85%RH and 85°C/100%Rh environments. The samples in this batch consisted of thin-film modules featuring fully metallized back surfaces (no break in the aluminum layer). After successive exposures, the sheet resistance of the aluminum layer was measured, using a Kelvin (four-point) probe apparatus, to detect expected increases in surface resistivity values.

Batch identification and pertinent sample and measurement characterization is provided in Table 1.

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>ENVIRONMENT ((°C/%RH))</th>
<th>MODULE CHARACTERIZATION</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>BATCH</td>
<td>1</td>
<td>85/100</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>85/100</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>85/100</td>
<td>U,FB</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>85/100</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>85/85</td>
<td>M,E,U</td>
</tr>
<tr>
<td></td>
<td>85/100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

U = unencapsulated  
E = encapsulated  
FB = forward bias  
M = full back metallization  
D = dark I-V  
L = light I-V  
X = EDS  
P = photos  
R = Al sheet resistivity  

Table 1. Experimental Parameters

The rationale of this experimental approach is that each sample be exposed to as little light as possible so as to allow an unequi-
vocal differentiation of light-induced instability effects from corrosion degradation. Unfortunately, some exposure to light was necessary, particularly during photography and light I-V curve data acquisition sessions. Exposure during photography, although relatively intense, was generally localized and was never for more than a few minutes. LAPSS exposure during I-V curve data acquisition was at a level of one sun for a period of no more than a few milliseconds and is not considered to be detrimental.

EXPERIMENTAL RESULTS AND DISCUSSION

The rapid deterioration of a-Si module I-V characteristics resulting from exposure to moist environments has been previously demonstrated and reconfirmed in these experiments. The most striking observation is the very visually obvious loss of material from the aluminum and a-Si layers of the exposed modules. Such material losses manifest in three forms: (1) as pinholes in either the aluminum layer or in the aluminum and a-Si layers (or perhaps even in all layers) that form and enlarge in time, Fig. 3; (2) as continuous regional losses that can occur anywhere but are apparently more likely to occur along the scribe, etch, and mask lines, Fig. 4; and (3) as wormy lines of aluminum loss that we call filiform corrosion, Fig. 5.

Pinholes (Fig. 3) form in the manner of blisters, most likely at sites of localized contamination on, or defects within, the thin-film layers. Moisture penetrates the layers and chemically reacts at such sites to weaken or destroy the interlayer bonds. Surface tension stress relaxes the uplifted material and opens the blister to form the pinhole. Continued exposure expands the periphery of the pinhole by processes of continual bond breaking and stress relief.

Material losses in the intercell region (Fig. 4) occur in a similar fashion. But here pinholes tend to form, aggregate, and interfuse along the sharp edges of the various scribe, etch, and/or mask lines. These zones in the thin-film layers are highly prestressed by the various forming processes and provide a directional bias along which material losses occur. This form of material degradation is most detrimental to a-Si module performance as it results in a tendency to open-circuit the module. This phenomenon is clearly evident not only in Fig. 4 but also in Fig. 3, wherein
aluminum back-surface metallization loss along the copper busbar edges have open-circuited the module.

Unlike the highly directional scribe line corrosion described above, filiform corrosion (Fig. 5) proceeds in more random directions within the aluminum layer. Filiform corrosion combines the elements of pinhole formation and stress corrosion cracking: hydrochemical effects weaken the bond of the aluminum layer to its substrate, and stress-relieving in the weakened aluminum bond layer drives the cracking process. The crack front opens perpendicularly to the direction of the normal plane stresses acting upon it, but the direction of crack propagation is along lines of maximum shear stresses, which makes a 45° angle with the direction of maximum tensile stresses. This is why this type of corrosion tends to occur in spiral patterns.

Filiform corrosion, which requires oxygen, occurs in the aluminum layer, with which atmospheric oxygen interacts. The phenomenon is not observed in a-Si because the oxygen molecule, even if it can penetrate the aluminum layer and any underlying diffusion barrier, is relatively non-reactive with a-Si—even in the presence of moisture.

Material losses in the intercell zone of a-Si modules has been quantified by means of EDS analysis. EDS profiles were monitored to seek evidence for species concentration changes (chemical reactions, material erosion, etc.). The bar graphs in Fig. 6, showing changes with time of exposure of fractional elemental concentrations in the regions D, E, and F (Fig. 1) in the intercell zone of a typical module substantiate the visual observation of aluminum losses in a region critical to module performance. Loss of conductive oxide in region 11 will also critically impact module performance, but only a-Si losses were observed in this region.

Resistivity increases with loss of metallization have been quantified by four-point probe resistance measurements on 5-cm.-wide strips cut from fully aluminized back surface modules. These modules suffered extensive progressive loss of aluminum over large portions of their back surfaces (Fig. 7), perhaps by the formation and flaking
of oxide powder, but the resistivity measurements were confined to regions where such losses had not yet occurred. The intent was to quantify aluminum loss rate in the intercell zones by monitoring sheet resistivity increases. A plot of resistivity versus exposure time (Fig. 8) reveals that encapsulation does not effectively prevent aluminum micro-losses in the intercell zone, to which measured resistivity increases are attributed. The photograph in Fig. 7 clearly attests to the effectiveness of encapsulation in preventing gross regional material losses. The speculation is that the process scribe lines provide ready access to the intercell zone for moisture entering the module at its edges. Additional features of the data (Fig. 8) include a distinct response profile—an initial increase in resistivity followed by a long period of constancy—and a clear differentiation of response to 85% and 100% humidity environments.

A large quantity of light and dark I-V curve numerical data were generated for Batch 1-4 samples, including series resistance, power output, and open circuit voltage versus time. Observed trends were as expected: for unencapsulated modules, series resistance values tended to increase and maximum power output tended to decrease with time of exposure by about a factor of 2 in 2000 hours of exposure at 85°C/100%RH; no significant changes in these parameters were observed for encapsulated modules undergoing the same exposure.

### Fig. 6. Elemental Concentration in Intercell Zone of a-Si Module

<table>
<thead>
<tr>
<th>HOURS AT 85°C/100%RH</th>
<th>FRACTION OF TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>101</td>
<td>0</td>
</tr>
<tr>
<td>2042</td>
<td>0</td>
</tr>
</tbody>
</table>

REGION IN INTERCELL ZONE

### Fig. 7. Material Loss from Fully-Aluminized Back-Surface Modules

<table>
<thead>
<tr>
<th>117 HRS AT 85°C/100%RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENCAPSULATED</td>
</tr>
<tr>
<td>UNENCAPSULATED</td>
</tr>
</tbody>
</table>
Open circuit voltage did not change significantly for EVA-encapsulated modules. A 5-10% reduction was observed after 2000 hours of exposure for unencapsulated modules, a no more serious change than was reported by Lathrop after 2000 hours of exposure at 140°C.

Lathrop attributed decreases in open circuit voltage and reductions in maximum power output to shunt resistance decreases presumed to result from diffusion of aluminum metallization into the a-Si layers. This particular mechanism was not observed in these experiments, possibly because that alleged diffusion occurs too slowly at 85°C to cause degradation before the pinhole interfusion and stress corrosion cracking mechanisms erode away the aluminum. In other words, the moisture-induced degradation mechanisms described here occur at a much greater rate than the temperature-dependent diffusion degradation mechanism suggested by Lathrop.

It was visually apparent that forward biased, unencapsulated modules suffered a greater degree of corrosion than their unbiased counterparts. For these modules, gathering credible serial resistance data proved difficult. Accessing the series resistance region of the I-V characteristic required larger voltage and current levels with each measurement. At the higher voltage levels, the modules could not sustain the required currents. Thus, quantitative differentiation of corrosion/erosion degradation and Staebler-Wronski effect was not achieved.

CONCERNS AND CONCLUSIONS

Moisture will enter and degrade even well-sealed glass-glass modules. At present no technique for preventing this type of degradation, short of hermetic sealing, is known. Low moisture absorbing/retaining encapsulants are recommended.

Annealing a-Si modules prior to installation may stress-relieve the aluminum in the critically important intercell zone and reduce the likelihood of the occurrence of these types of erosion.

REFERENCES

This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.
LONG-TERM EXPERIMENTAL TESTING OF a-SILICON MODULES*

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ABSTRACT

Long-term stability of photovoltaic module electrical performance is critically important to the economic viability of PV in large-scale energy-generation applications. Equally important is having the means to conclusively demonstrate long life to potential users; this requires proven test methods that accurately predict field performance trends. To assess the long-term stability of a-Si modules and the usefulness of existing crystalline-Si test methods a number of first generation a-Si photovoltaic modules have been acquired from leading manufacturers and subjected to a variety of accelerated and real-time outdoor aging tests. Data to date indicate that the degradation of a-Si modules involves complex dependencies that negate some of the key test correlations previously established for crystalline-Si modules. Key research priorities are highlighted including light induced effects, cell corrosion leading to increased series resistance, glass breakage strength for large modules, and the development of protective encapsulants that meet the outdoor weathering and voltage isolation required for long module life.

INTRODUCTION

Large-scale energy-generation applications are normally sized for the highest prevailing irradiance levels and have little tolerance for array performance degradation. After considerations of present-value discounting and escalation of the worth of electricity in future years, a 30-year-life PV energy-generating plant, for example, is worth 25 to 30 percent more than a 20-year-life plant. Based on this economic sensitivity to plant life, the national photovoltaics program of the U.S. Department of Energy has chosen a 30-year-life as the target goal for PV modules.

* This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

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Conference on Stability of Amorphous Silicon
Alloy Materials and Devices
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. The objectives of the research effort were to assess the reliability characteristics of amorphous silicon modules, assess the viability of various test methods, and establish research priorities.

**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 determined 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 (1). 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, $%/yr 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

<table>
<thead>
<tr>
<th>Type of Degradation</th>
<th>Failure Mechanism</th>
<th>Units of Degrad.</th>
<th>Level for 10% Energy Cost Increase*</th>
<th>Allocation for 30-Year Life Module</th>
<th>Economic Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component failures</td>
<td>Open-circuit between cells</td>
<td>%/yr</td>
<td>0.08 0.13 0.02</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Short-circuit cells</td>
<td>%/yr</td>
<td>0.24 0.48 0.05</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td>Power degradation</td>
<td>Light induced effects</td>
<td>%</td>
<td>10 10 5</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cell gradual power loss</td>
<td>%/yr</td>
<td>0.57 1.15 0.20</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Module optical degradation</td>
<td>%/yr</td>
<td>0.57 1.15 0.02</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Front surface soiling</td>
<td>%</td>
<td>10 10 3</td>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td>Module failures</td>
<td>Module glass breakage</td>
<td>%/yr</td>
<td>0.33 1.18 0.1</td>
<td>O&amp;M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Module open circuits</td>
<td>%/yr</td>
<td>0.33 1.18 0.1</td>
<td>O&amp;M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Module hot-spot failures</td>
<td>%/yr</td>
<td>0.33 1.18 0.1</td>
<td>O&amp;M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bypass diode failures</td>
<td>%/yr</td>
<td>0.78 2.40 0.05</td>
<td>O&amp;M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Module shorts to ground</td>
<td>%/yr</td>
<td>0.022 0.122 0.01</td>
<td>O&amp;M</td>
<td></td>
</tr>
<tr>
<td>Life-limiting wearout</td>
<td>Encapsulant failure due to loss of stabilizers</td>
<td>Years of life</td>
<td>27 20 35</td>
<td>End of life</td>
<td></td>
</tr>
</tbody>
</table>

* $k = $ Discount rate
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. 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

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 (2) developed for crystalline-Si modules, 2) field aging at both ambient conditions and at fixed elevated temperatures of 70°C, 85°C and 100°C, 3) long-term temperature-humidity testing at 85°C 5% RH and 85°C 85% RH conditions with various bias voltages, and 4) specialized laboratory hot-spot and corrosion testing. The overall research methodology followed that developed earlier at JPL for crystalline-Si modules (3).

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/cm², 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 (4).

The findings from the various tests 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
incorporation of bypass diodes to serve as redundant circuit elements is indicated.

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 for modules at ambient operating temperature was typified by modest short-circuit current loss accompanied with a shunt-like loss in fill factor. As reported by other investigators, the initial rapid rate of degradation slowed to a stable asymptotic level after a few months of field exposure. Also as previously reported, 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.

In studies to determine the dependency of degradation on stress parameters, and to test the effects of temperature and possible annealing, modules were installed in the field, equipped with rear-side heaters to control the operating temperature. These modules were operated at peak-power loading at fixed elevated temperatures of 70°C, 85°C, and 100°C. For some of the modules the elevated temperature was imposed 24 hours each day; for the others the elevated temperature was only maintained during daylight hours.

Modules operated in the field at fixed elevated temperatures of 85°C and 100°C for daylight periods of 9 hours per day degraded very rapidly (Fig. 2), but stabilized at the same modest level of degradation as the unheated samples. After completing 160 days of testing, current-voltage (I-V) curve comparisons showed progressive increases in average peak power losses, up to 38% for the 85°C samples, and up to 62.1% for the 100°C samples.

For the 100°C samples heated continuously, the degradation was significantly accelerated; degradation levels reached 93% after 40 days, and complete failure occurred after 80 days. Additional
Continuous-heating tests at 70°C revealed identical trends at the 80-day inspection period to those observed for the continuous 100°C heated modules. After that time, the degradation rate slowed (levelled off) compared to the rapid degradation observed from day 0 through day 40.

One difficulty in studying light induced effects is the absence of readily available laboratory tests for accelerating these effects observed in the field. For example, the Block V qualification test sequence (2) does not test for light induced effects nor trigger the degradation. In an attempt to identify a relatively inexpensive procedure to test for light induced effects, a-Si modules were also 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.

Call 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 and was particularly evident in the modules tested continuously in the field at 100°C. 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 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 (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 3mm (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 specific 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 conducting a systematic research effort addressed to understanding the failure and degradation mechanisms and to developing solution concepts. The strawman reliability allocations presented in Table I 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. Additionally, the experimental tests have provided a first-order assessment of the viability of existing test methods. This assessment suggests that current qualification test procedures in use with crystalline-Si modules are useful with a-Si modules, but do not excite the principal degradation mechanisms affecting the a-Si modules. Key research priorities identified include developing the needed technologies in the areas of light induced effects, cell corrosion leading to increased series resistance, glass breaking strength for large modules, and protective encapsulants that meet the outdoor weathering and voltage isolation required for long-life modules. Aggressive research on these subjects will be required to achieve 30-year-life a-Si modules.

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RESPONSE OF AMORPHOUS SILICON CELLS TO REVERSE BIASING*

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ABSTRACT

This paper discusses the results of a study to determine the hot-spot susceptibility of amorphous silicon cells and modules, and to provide guidelines and develop a qualification test for reducing module hot-spot susceptibility.

Amorphous cells are shown to have hot-spot susceptibility levels similar to crystalline-Si cells leading to the fact that the same general guidelines apply for protecting amorphous cells from hot-spot stressing as apply to crystalline-Si cells.

Recommendations are made on ways of reducing module hot-spot susceptibility including the traditional method of using bypass diodes and a method unique to thin-film cells, limiting the string current by limiting the cell areal size.

INTRODUCTION

Hot-spot heating occurs in a photovoltaic module when the short circuit current of a cell becomes lower than the string operating current causing the affected cell to go into reverse bias and absorb power equal to the product of the cell reverse-bias voltage and the string current. Field experience has demonstrated that hot-spot heating can lead to cell and module degradation.

Since the degree of hot-spot heating is a function of the series-parallel configuration of the circuit in which the cell is located, there are circuit-design techniques that can be used, both in a module and in an array, to ameliorate the effects of the heating. In the past, the primary technique for crystalline silicon modules was the use of bypass diodes which limit the reverse-bias voltage. A more important technique for amorphous-silicon modules is that of limiting current by limiting cell size.

In the past a laboratory test has been developed at JPL to determine the hot-spot susceptibility of crystalline-Si modules (1,2). The test conditions are meant to simulate the thermal boundary

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conditions for a 100 mW/cm², 40°C ambient environment. This test, which has been used extensively in the qualification testing of modules, formed the basis for the testing described in this paper and the initial testing phase described in an earlier paper (3).

Initial testing was performed on three- and four-inch-square a-Si submodules, as well as, one-foot-square a-Si modules. These initial tests indicated that, because of the limited thermal capacity of thin-film cells, the amount of lateral thermal conduction provided by the substrates and superstrates has a significant impact on the hot-spot temperature incurred.

The principal objective of the current work was to develop guidelines that can be used by manufacturers of amorphous modules and arrays to reduce hot-spot susceptibility. A second key objective was to provide the PV community with a suitable hot-spot qualification test for amorphous-silicon modules.

APPROACH

The test procedures employed in the current task, modified as described previously (3), are essentially those used to test crystalline silicon cells (1,2).

The testing of modules with the cells sandwiched between two sheets of glass required that special test modules be prepared by the manufacturer. Several of the modules tested were of this type; for these modules a ribbon lead was attached along the back of each cell. This lead-attachment technique is also required to distribute the back-bias current along the entire cell surface area because of the poor conductivity of the transparent top conductor. Otherwise, with leads attached at the edge only, the hot-spots tend to occur at the same edge of the cell where the electrical leads are attached. This was the case with several of the other modules tested. Two current-input schemes were used with edge-attached leads. In one case, current was input at the same module edge to two adjacent cells. In the second case, current was input at opposite ends of the module for each of the cells. Figure 1 gives a schematic of the different current-input techniques used.

There are two kinds of cell reverse-quadrant characteristics that must be considered when selecting the hot-spot test parameters.

Figure 1. Schematic of the current-input techniques used.
of voltage, current, and illumination level. One kind, which manifests high shunt resistance (referred to previously as type A, (1,2,3)) exists when the back-bias voltage is limited only by the level of the applied voltage. The applied voltage is determined by the number of series cells per bypass diode, or the number of series cells in the array source circuit if no bypass diodes are used. This type of cell achieves the greatest amount of back-bias heating under conditions of partial shadowing.

The second kind of characteristic (type B) is associated with low shunt resistance cells where the breakdown voltage is less than the available back-bias voltage. Consequently, the hot-spot heating in these cells is limited by the available string current and the breakdown voltage of the cells, not the number of series cells as defined above. The back-bias voltage of these cells reaches its maximum value under conditions of full shadow; therefore, low-shunt-resistance cells suffer the greatest hot-spot heating dissipation when fully shadowed.

In the experiment conducted the back-bias current and voltage were provided by a power supply; a chart recorder was used to record the reverse-quadrant response of the test cell. A radiant heating source was used to raise the test-cell temperature to the nominal operating cell temperature (NOCT). The hot-spot temperature was measured with an infrared (IR) camera. This method provides a parametric representation of power dissipation versus hot-spot temperature for the test with recording of the hot-spot temperature as the test proceeds. A photograph of the test setup is shown in Figure 2.

Both exploratory testing and the standard 100-hour cyclic hot-spot susceptibility test were performed on cells in several modules. The tests simulated operation at short circuit and at a field operating temperature of 45-50°C. The cells were found to be type B cells and the tests were performed in the absence of illumination as discussed below.

Actual hot-spot-test acceptance criteria (2) involve a visual

![Figure 2. Photograph of hot-spot test setup.](image-url)
inspection, a post-test electrical performance measurement, and an isolation test. The study discussed here did not involve the latter two tests.

OBSERVATIONS AND RESULTS

The overall response of amorphous-silicon cells to back biasing is similar to crystalline cells with several notable exceptions. The most significant difference between the second-quadrant responses of amorphous and crystalline cells is the lower and more sharply defined breakdown voltage in the current-voltage curve of amorphous cells. The most important consequence is that a cell in series with more than 10-15 cells will act as a type B cell with the back-bias voltage limited by the breakdown voltage. Therefore, hot-spot tests performed on modules with more than this number of cells should be performed in the absence of illumination, as were the tests performed on the modules in this study.

In general, amorphous cells are more sensitive to back-bias conditions than crystalline cells, exhibiting rapidly changing characteristics, some more so than others. As discussed previously (3), amorphous cells exhibit a dichotomous behavior in their second quadrant response with initial back biasing indicating a high shunt resistance with a sharp voltage breakdown in the 8-12 volt range. After thermal runaway and subsequent cool down the cells have a lower shunt resistance. Figure 3 compares some typical second-quadrant responses of the cells from three different manufacturers that were tested.

Figure 3. Typical amorphous-cell-second-quadrant I-V curves.
Another interesting phenomenon was the occurrence of multiple hot-spots where there is a shift of the dominant hot-spot (one with highest temperature) among the different hot-spots. In some cases this resulted in the sharing of power leading to lower hot-spot temperatures for the same total power dissipated. The visual effects observed were cell erosion, cracked glass, encapsulation discoloration, blistering of the module backing, and arcing. Except for cell erosion, not all of the effects were noted on all modules. For instance, cracked glass was most prevalent on modules with only one layer of glass. Cell erosion refers to the apparent highly localized loss of cell material from the hot-spot area, and is shown in Figure 4, which is a photograph of one of the cells tested. Cell erosion has two effects on the cell performance. It can lead simply to loss of power resulting from the loss of cell area, or, in addition, it can lead to increased shunting of the cell.

As explained previously (3), a direct dependence does not exist between the highest temperature achieved on a cell and the total power dissipated in the cell. However, it is useful to bound the range of observed temperatures for a given power dissipation because the temperature obtained can be related to the effects observed in cells and module materials.

Experience with crystalline-silicon cells (1) indicated that the onset of degradation occurs in the 120-140°C range, with severe degradation occurring above that range. In the case of amorphous cells, erosion started at about 80°C and became quite noticeable above 120°C. In one module cracked glass was noted even at the relatively low temperature of 100°C. As with crystalline cells, most of the effects were noted above 120°C.

Figure 5 gives a plot of the temperature rise above NOCT per hot-spot power dissipated for the modules of three manufacturers; the cells and modules were of various sizes as noted. The spread in data for the same module type is indicative of the variable dependence of temperature on power dissipation. The variability in the observed data also is a function of the differences in the heat-sinking capability of the modules. This latter aspect was made evident when glass cracking occurred in modules with a glass superstrate and no
Figure 5. Temperature rise above NOCT per watt of hot-spot power dissipation.

substrate, and not in modules with a combined glass super/substrate twice as thick.

RECOMMENDATIONS AND CONCLUSIONS

Figure 6 gives the hot-spot temperature as a function of back-bias current for some of the modules tested. This type of plot is particularly significant for amorphous modules. For crystalline-silicon modules the best technique to ameliorate hot-spot heating is the use of bypass diodes, which limit the potential back-bias voltage. However, the use of bypass diodes with amorphous modules is less advantageous for two reasons. First, since they tend to have higher voltages for the same size as compared to crystalline

Figure 6. Hot-spot temperature as a function of back-bias current.
modules, and the cells have lower breakdown voltages, multiple diodes would be required internal to each module. Secondly, bypass diodes are difficult to integrate easily into the monolithic structure of a-Si module circuits. Because hot-spot heating can also be controlled by reducing the available current, a promising approach to controlling hot-spots in an a-Si modules consists of limiting the cell size (and thus the current) by scribing a module into two or more parallel strings of smaller cells. Plots such as Figure 6 are useful as guidelines for determining maximum cell size to limit hot-spot temperature to a given level.

A second approach for reducing hot-spot temperature involves improving lateral heat transfer within the module. The actual hot-spot temperature reached is a strong function of the amount of lateral thermal conductance provided by the module's glass superstrate and substrate. Thus, the thermal design of the module can be used to ameliorate hot-spot heating and reduce the module's susceptibility to back biasing. This is illustrated in Figure 5 where the hot-spot temperatures of modules with different lateral thermal conductances are compared.

The use of bypass diodes with amorphous cells to reduce back-bias voltage requires consideration of the low cell-breakdown voltage. If diodes are required it means that the voltage must be reduced below 8-12 volts and therefore the diode frequency must be at least one diode every 10-15 cells. This implies that the diodes must be mounted internally in modules having more than this many series cells. The use of diodes should be traded off against reducing cell size to lower the current, and also against improved lateral heat transfer to reduce the hot-spot temperature.

HOT-SPOT QUALIFICATION TEST FOR AMORPHOUS SILICON MODULES

The recommended hot-spot qualification test for amorphous silicon modules (1,2) is basically the same as for crystalline silicon modules. One unique consideration for a-Si modules is the difficulty in attaching electrical leads to the individual cells within a module. The leads are required to carry full one-sun (100mW/cm²) current and must distribute the current into the cells without causing excessive current crowding near the lead attachment or shunting of the cell by damaging the thin cell metallization. Another important consideration is minimizing disturbance of the cell's poor lateral electrical conductance which resists the ability of the module current to crowd into a highly localized hot spot. Attaching leads along the entire length of the cells reduces the current crowding near the attachment point, but increases the chance of cell shunting and greatly reduces the natural resistance to current crowding into a hot-spot region.

An alternative lead-attachment approach is to attach to opposite ends of the adjacent cells. This requires that the current flow down the entire length of the cells, thus introducing the natural sheet-resistivity in series with the hot-spot shunt. However, current crowding near the lead attachment is a possible problem.
None of these lead-attachment techniques as used was completely without problems. More testing and comparison of the results obtained using different attachment techniques is required before a final recommendation can be made.

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