ELECTRICAL ISOLATION DESIGN AND ELECTROCHEMICAL CORROSION IN THIN-FILM PHOTOVOLTAIC MODULES*

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ABSTRACT

Laboratory research directed toward understanding issues and eliminating problems associated with electrical isolation of thin-film photovoltaic module circuitry has led to the development of a proposed Wet Insulation-Resistance Qualification Test Specification for production-line modules. Test results can serve to measure module field life as limited by electrochemical corrosion degradation mechanisms. Current module-level research covering encapsulant voltage withstand capability is also described and suggestions for improving module electrical isolation are offered.

INTRODUCTION

The electrical circuitry of thin-film (TF) photovoltaic (PV) modules must be isolated from the external environment to reduce the threat to human safety, and to minimize stray leakage currents which, however small, may electrochemically corrode module current-carrying elements and structural parts. Electrical isolation is presently achieved by edge-sealing the TF layers with compounds such as soft polymers, epoxies, and acrylics, Fig. 1.

The isolation problem in TF modules is particularly challenging because the conductive elements are not bulk-encapsulated wires or ribbon conductors as used in crystalline-silicon (C-Si) module designs, but rather are non bulk-encapsulated, fractions-of-microns-thick laminae, such as transparent conductive oxide (TCO) or aluminum metallization, that directly interface with the substrate or superstrate. Thus, in some TF modules, conductive elements exist to the very edge of the module, and the edge sealant becomes the key electrical isolation material. But even with high quality encapsulants and edge sealants, there will still be an interface connecting module current-carrying elements to the environment, along which moisture can enter and leakage current can exit.

TF module problems associated with less-than-adequate isolation are identified and suggestions for improving isolation design are offered. Additionally, efforts to develop TF module qualification tests, focusing upon the effectiveness of the isolation system, are presented.

ISOLATION PROBLEMS IN THE USE ENVIRONMENT

Human Safety. Exposed conductive module elements can be a safety hazard to people coming in contact with operating arrays. For example, several manufacturers apply the TCO (usually SnO_2) by a vapor deposition process that results in an "overspray" condition whereby the TCO wraps around the edge of the glass superstrate and may extend beyond the edge seal, Fig. 1. "Breaking" the TCO extension by laser scribing does not provide an adequate level of isolation, and edge grinding is uneconomical.

Excessive Leakage Currents. Generally, the electrical insulating system is not perfect and a small but measurable (nA- to uA-level) leakage current is

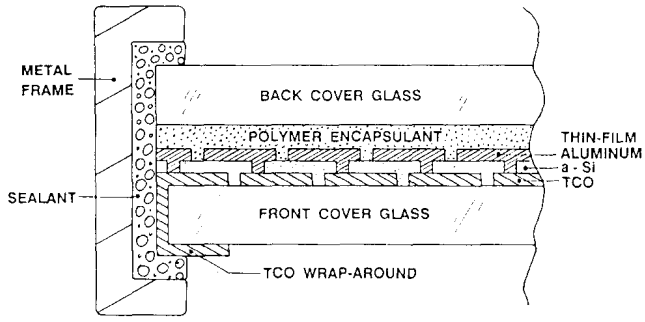

Figure 1. Typical Thin-Film Photovoltaic Module Construction.

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detectable between the module electrical parts (the cell plane) and the external environment (the frame or mounting structure). This small leakage current is enhanced by orders-of-magnitude in the presence of moisture and is responsible for a broad range of life-limiting degradation effects categorized under the generic name, "electrochemical corrosion" [1]. Electrochemical corrosion involves redox electrode reactions driven by impressed potential differences in which anodic metallizations usually dissolve and cathodic metallizations usually delaminate. The formation of non-conductive reaction products and ionic diffusion within an interelectrode electrolyte further characterize the process.

Different forms of corrosion responsible for PV module field failures have been observed, including "bar graph" corrosion, general metallization attack, "picture framing", interfacial material delaminations, and scribe line corrosion [1,2]. Additionally, excessive leakage currents can result in nuisance tripping of array ground-fault detection equipment [3].

Voltage Breakdown. In the event of insulation failure, all of the generated module or array current is diverted to the failure site, resulting in arcing and/or short-circuiting. This "voltage breakdown" condition results from electrical concentrations stressing weak regions in the insulation (flaws, such as voids) to the point of failure [4]. Moisture can exacerbate voltage breakdown by creating new voids through delamination. In fielded modules exhibiting "bar-graph" corrosion, arcing and voltage breakdown have also been observed.

SOLVING THE ELECTRICAL ISOLATION PROBLEM

To achieve effective electrical isolation, all electrical leakage paths into the module must be blocked by materials having high bulk and interfacial resistances and good voltage withstand capability. Bulk-encapsulating the module current-carrying elements will reduce the rate of moisture ingress. The requirement for high resistance ensures that leakage currents remain small, and the requirement for good voltage withstand capability suggests that electrical stress enhancement sites within the insulation, i.e., void-type flaws, must have a high tolerance to erosion stemming from internal electronic discharges (partial discharges) induced by the applied voltage. If the tolerance to such erosion is low, the weakest void will grow ("tree") to ultimately span the cell-frame spacing -- voltage breakdown!

A commonly used encapsulating polymer is EVA. Its favorable features include low moisture sorption and high bulk and interfacial resistances [5], but it does not exhibit especially good voltage withstand characteristics [4]. Sheet insulations such as Tedlar and Mylar do feature high resistances and exhibit favorable withstand characteristics as well, but unlike EVA, their chemistries do not permit liquefaction during lamination, rendering them unsuitable, from a processing viewpoint, as single-component bulk encapsulants. Thus, most encapsulants are a combination of EVA together with a material having high voltage withstand capability such as Tedlar or Mylar.

QUALIFICATION TEST DEVELOPMENT

The PV industry desires simple, safe, and effective tests to determine if production modules will perform reliably over their intended life [6]. In support of SERI's module qualification test development program, JPL is extending the applicability of the JPL-developed Block V C-Si qualification test specifications [7] to TF modules. Current JPL research focuses upon developing a test to verify the quality of TF module insulation systems.

A consensus among the PV community underscores the need for a "wet" hi-pot test. The present qualification test for PV module insulation systems is the "dry" hi-pot test; its purpose is to identify leakage currents prior to field installation that may create safety hazards to personnel and cause nuisance tripping of ground-fault-interrupt systems. The test has been used on C-Si modules for several years as part of the Underwriters Laboratories, Inc. (UL) listing process [8]; it has recently been extended to cover TF modules.

A hi-pot test yields information about module insulation resistance and leakage current levels only, but not necessarily about insulation voltage-withstand capability -- unless, of course, breakdown occurs during testing. Catastrophic insulation failure during hi-pot testing can indicate a flaw in the insulation itself and not necessarily a poor module design concept. Thus, information derived from hi-pot testing has more relevance for ascertaining the likelihood of electrochemical degradation than it does for ascertaining the likelihood of voltage breakdown.

Efforts to date at JPL have resulted in combining a wet hi-pot test and an electrochemical test (since both focus on module leakage current levels) into a single verification test for TF module isolation systems. This test of module "corrosion susceptibility" is rapid and uncomplicated, is firmly rooted in module-level research and is safe. The test specifications are presented in Appendix A as "Wet Insulation-Resistance Test" for consideration for adoption by the photovoltaic community.

The research from which this proposed specification evolved will now be reviewed. In work done prior to establishing a module electrochemical failure criterion, the results of exposing C-Si modules to a modified humidity-freeze test (10 24-hour cycles, each cycle consisting of 20 hours at 85°C/85%RH/500V followed by 4 hours at -40°C, monitoring leakage current) were interpreted with an eye toward developing a module electrochemical qualification test [9]. Having then developed a module failure criterion [10, 11], results from recent tests on TF modules, reported here, are used to calculate module median-times-to-failure from electrochemical effects.

Voltage Withstand Testing. Testing the voltage withstand capability of a module insulation requires specialized equipment that may not be readily available to most module manufacturers. Various module insulations have been tested in the past [4], and the newer TF modules are continually being tested by JPL using a Biddle Instruments partial-discharge detection apparatus [12]. The equipment measures: (1) the corona inception voltage (CIV),

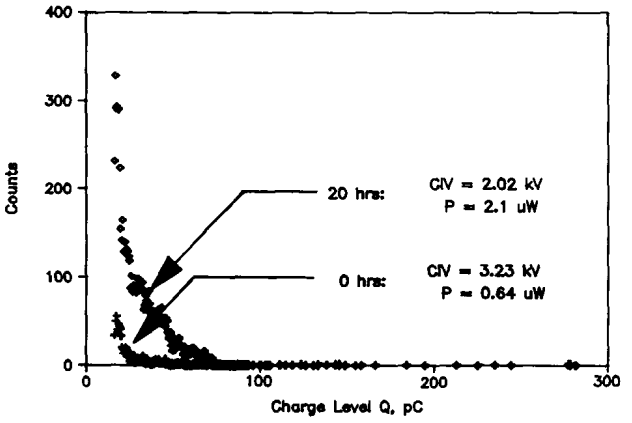

Figure 2. Pulse Energy Spectra of a T-F Module, One Edge in Solution with Wetting Agent.

the cell-to-frame voltage at which the average magnitude of detected pulses within the insulation (or edge-seal) voids is 1 or 5 pC; and (2) a 60-second pulse-energy spectrum of the insulation, Fig. 2, from which the average power dissipated in void discharges can be determined. This latter quantity is important because each discharge results in a small amount of damage to the void walls; continual discharges form trees within the insulation that ultimately develop into breakdown channels. Many, often conflicting, electrical breakdown models have been formulated [14, 15] and some analysts have constructed life-prediction procedures based upon their favored breakdown concepts [15, 16]. Common to all these models is a strong dependence of predicted time-to-failure on applied or average electrical stress, which is the source of the energy dissipated in partial discharges within insulation voids.

For selected TF modules the CIV and power dissipation have been measured, Table 1, both before (CIV_0, $POWER_0$) and after (CIV_1, $POWER_1$) the 10-day electrochemical exposure test (described below under "Electrochemical Susceptibility Testing"). Despite expectations, the post-exposure CIV and power dissipation measurements tended to be higher than their pre-exposure counterparts, as indicated in Table 1. Others have also noticed that humid environments increase breakdown voltage levels [12] and may similarly affect the CIV. The mechanism is probably due to moisture on void walls hindering charge buildup and subsequent discharge. Increased power dissipation probably results from additional voids (delaminations) created by the moisture exposure.

Typical TF module CIV's measure from 0.5 - 3.0 kVdc, higher in most instances than field operating voltages, yet within the voltage level (twice system voltage + 1000 Vdc) used by the industry as a measure of satisfactory long-term field performance. This raises a concern for TF modules that long-term, high-voltage withstand testing may be more detrimental than beneficial, stimulating failure mechanisms (i.e., partial discharges, treeing) that may only occur in a statistically insignificant sample of fielded modules.

Table 1. CIV and Power Dissipation in Insulation Voids in Module-Level Voltage Withstand Testing.

Module ID (polarity)	CIV_0 (kV)	CIV_1 (kV)	$POWER_0$ (nW)	$POWER_1$ (nW)
A (+)	2.50	2.55	262	393
A (-)	1.88	1.62	123	98
B1 (+)	1.05	1.62	50	65
B1 (-)	0.93	1.46	39	38
B2 (+)	1.14	1.92	58	62
B2 (-)	0.99	1.90	49	112

For example, CIV's and pulse-energy spectra of "dry" modules (cell-to-frame) and of modules with an edge immersed in a trough containing a wetting agent (cell-to-solution) have been obtained. Fig. 2 shows two pulse-energy spectra, obtained 20 hours apart, of the same module having one edge immersed in the trough wetting agent. The 0-hr data, obtained just after immersion, is nearly identical to the data obtained from the dry module (not shown). After 20 hours of edge immersion, the CIV (5 pC level) has dropped by about 35% and the power dissipation has increased three-fold, the latter due largely to the greater number of discharges occurring below the 75 pC level. The result indicates that the insulation system has deteriorated because of exposure to the solution. This type of testing may more accurately reflect a voltage withstand test of TF module insulation.

A meaningful test for voltage-breakdown susceptibility would involve electrically stressing the insulation system for a brief period of time, measuring the number and energy levels of internal discharges, and determining from this the time required for such discharges to form within the insulation a conductive channel between the cell string and the frame. Long-term, high-voltage field testing is planned for next year to determine if electrical breakdown phenomena in the interfacial regions of the insulation system is applicable to TF modules, and until that research is complete, application of high voltage (twice system voltage + 1,000 Vdc) for long periods of time is not recommended.

Field test data gathered at voltages of ±1,500 Vdc and ±3,000 Vdc over several years on C-Si modules [5] indicate that leakage currents under wet conditions are several orders of magnitude above the leakage currents under dry conditions. Electrical breakdown resulting from treeing is not relevant, and voltage stresses are relatively low compared to applications such as underground cables. On that basis, work has focused on breakdown due to excessive leakage currents presenting a safety hazard to personnel and creating unacceptable levels of electrochemical corrosion.

Wet Hi-Pot Testing. The development of a wet insulation-resistance test procedure is based on a number of experimental wet hi-pot test approaches that included: (1) wetting a module with a solution

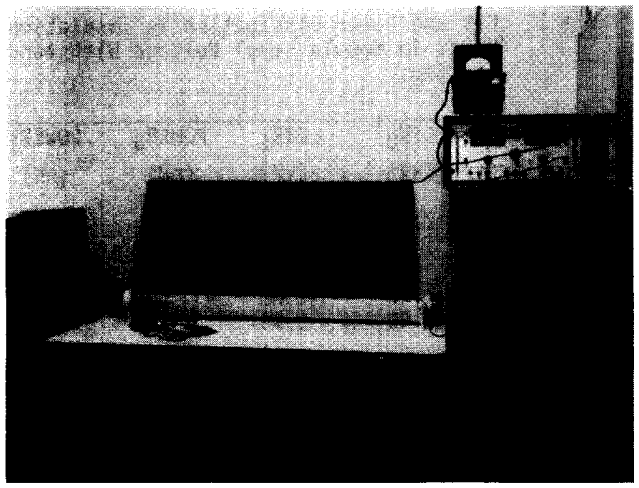

Fig. 3. Wet Insulation-Resistance Test Set-up.

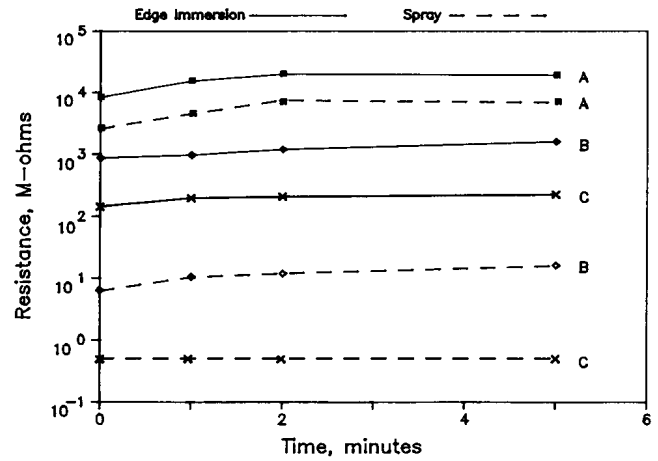

Fig. 4. Wet Insulation-Resistance Test Results.

from a hand held spray container; (2) immersing one edge of a module into a solution-filled trough; (3) submerging the entire module (with terminals both wet and dry); and (4) subjecting the module to a sequence of steps in a temperature/humidity chamber specially equipped with "mist" nozzles. The last approach tested a module three times -- once at room ambient, once at a typical noontime field environment (hot, dry), and once at a typical morning environment (cool, wet). During all developmental test sequences, the 50 uA pass/fail threshold was used as a starting point. Modules were stressed at voltage levels of ±500 Vdc, ±1,500 Vdc, and ±3,000 Vdc. Since test results for all voltage levels were comparable, emphasis was directed toward lower voltage testing levels.

In the wet hi-pot test from which the Wet Insulation-Resistance Test finally evolved, each edge of a test module was dipped in sequence into a trough containing a wetting agent (exercising care not to immerse J-boxes) and, using a Megohmmeter at 500 Vdc, resistances between the shorted cell plane and the trough solution were measured at intervals of 0, 1, 2 and 5 minutes, Fig. 3. The edge having the lowest resistance was redipped, and all surfaces were sprayed, including the module edges and sealed J-boxes, using the same wetting agent as in the trough. The resistance of that edge was measured at 0, 1, 2 and 5 minutes.

A plot of representative test module resistances using the above procedure, Fig. 4, indicates that the spray immediately lowers the resistance by more than two orders of magnitude (Modules B and C) for some modules, while for other modules, the effect is either minimal or not immediate (Module A). Additionally, there is indication that one-to-two minutes is adequate for stabilization of current transients.

Fig. 5 shows the measured resistivities of various solutions used. With the exception of deionized water, there is little difference among the candidates. Resistivity is a measure of ionic concentration (i.e., amount of dissolved solids) and is not indicative of a solution's surface-active properties ("wettability"), a characteristic necessary to reduce surface tension. For example, the dissolved solids content of Windex at 1000 ohm-cm is equivalent to more than 100 ppm of NaCl in deionized water, while deionized water at 3 x 10^5 ohm-cm has the equivalent of about 1 ppm NaCl. Windex was chosen for most of the testing because of its ability to reduce surface tension, its resistivity, and its availability. Although Windex is suitable for qualification testing, there is a concern that the ammonia it contains may be too corrosive for 100% production-line tests.

Electrochemical Susceptibility Testing. The initial approach to an electrochemical qualification test procedure was based upon two previous results: (1) the JPL Block V 10-day humidity/freeze test [7, 9], and (2) the observation that TF modules abruptly lose power as a result of electrochemical corrosion degradation after approximately 0.1 Coulomb of ionic charge per centimeter of module perimeter has been transferred between cell plane and frame [11]. In recent JPL tests, modules were exposed to ten 24-hour cycles, each cycle consisting of 16 hours

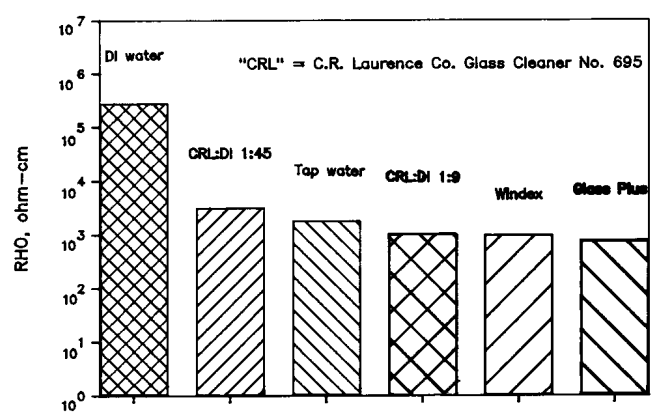

Fig. 5. Resistivity of Candidate Wet Insulation-Resistance Test Solutions.

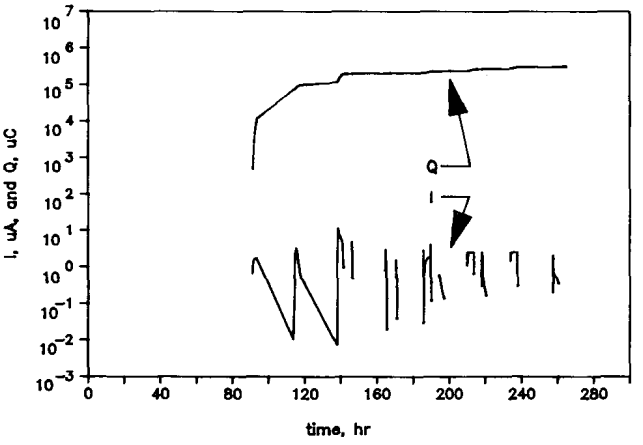

Fig. 6. 11-Day Electrochemical Qualification Test Results.

at 65°C/20%RH, 4 hours of tap water mist at 22°C, and a 4 hour freeze at -10°C; a 500 Vdc potential was applied to the modules during the high temperature and mist phases of each cycle. Leakage currents were monitored, and when integrated, gave the total charge transferred.

A rough estimate of the field time equivalent to one chamber cycle is as follows: the 16-hr phase represents two sunny 8-hr days; the 4-hr mist phase can represent two 2-hr dewy mornings or a rainy period. As a result of this simulation of the diurnal cycle, one chamber day is equivalent to two field days.

Fig. 6 shows typical data obtained from one module cycled 11 times as described above. The total charge transferred in 22 equivalent field days was 0.3 Coulomb; this translates to about 5 C/yr. The perimeter of this particular module measured 305 cm, so the module will fail, with 50% probability, after the passage of 0.1 x 305 = 30.5 C; i.e., this particular module is expected to fail after 30.5/5 = 6 years -- more, actually, considering that not all days are sunny or rainy and not all mornings are dewy.

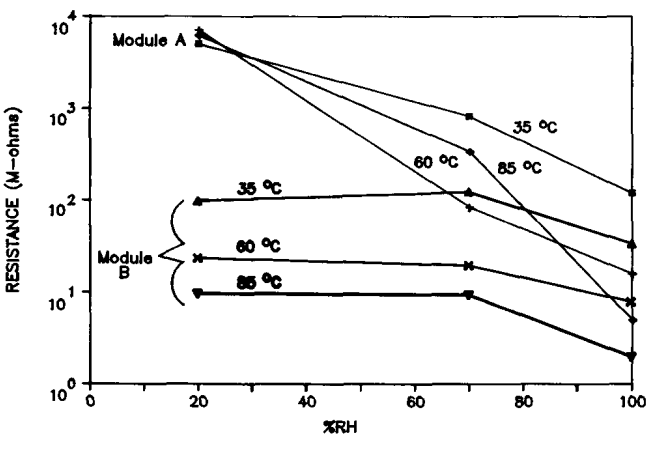

Fig. 7. Results of Module Insulation-Resistance Characterization.

Another approach to electrochemical susceptibility testing of modules is to "characterize" the cell-to-frame resistance. Using a Megohmmeter at 500 Vdc to measure resistance at several equilibrium environments, data was obtained at nine set points: 35°C/20%RH, 35°C/70%RH, 35°C/100%RH, 60°C/20%RH, 60°C/70%RH, 60°C/100%RH, 85°C/20%RH, 85°C/70%RH, and 85°C/100%RH. Fig. 7 shows a typical test result. Clearly, Module A has a better isolation system and will experience lower leakage currents in the use environment than Module B.

This type of data is not only useful for differentiating among alternative module designs, but also for predicting resistance levels (or leakage currents) in varying field environments and, together with SOLMET weather data, may actually be useful in predicting module life [11].

WET INSULATION-RESISTANCE TEST PROCEDURE

The draft Wet Insulation-Resistance Test, Appendix A, evolved from the above-described research. Immersing each module peripheral edge was considered valid since previous laboratory and field experiences have verified that the module corners and edges are the most susceptible to moisture ingress, whereas requiring total immersion might result in creating unfair stresses to the module junction boxes and terminations. The two-minute waiting period allows the transients to settle out and provides some finite time to allow moisture penetration to occur. The thorough spraying of all exposed surface areas of the module and electrical termination area provides a check to verify integrity of remaining module elements. Use of a wetting agent is a means of breaking down surface tension and provides a path across the surface of the module. Using the wetting agent at full strength simulates what one could expect under field conditions when washing the array (a plausible maintenance scenario). The applied voltage level of 500 Vdc in each polarity was selected on the basis of determining leakage currents and not on the basis of stressing the insulation system to seek out flaws or voids. Even though most of the modules tested had CIV's well above 1 kV, a test voltage of 500 Vdc is recommended so as <u>not</u> to stimulate the partial discharge mechanism, which does not occur at typical applications voltages. Use of a suitable high-impedance ohmmeter (Megger or Megohmmeter) would allow sufficient voltage to measure leakage without subjecting the operator to a high voltage. For example, the Megohmmeter used for these tests is current-limited to 10 mA. The pass/fail criterion is based on the amount of charge transfer to effect electrochemical degradation.

Two important features of the above procedure are that all of the necessary equipment is relatively simple to obtain or construct and all measurements are made with a single piece of measurement equipment -- a Megohmmeter or Megger -- which is a versatile, portable, and relatively inexpensive resistance measuring device [17].

DISCUSSION AND CONCLUDING REMARKS

From a PV module reliability and safety viewpoint, it is desirable not only to physically iso-

late the module electrical circuitry from the environment, but also to eliminate, or at least minimize, cell-to-frame leakage currents. To achieve the goal of effective electrical isolation, all readily accessible electrical leakage paths into the module must be effectively blocked by an insulator having high resistance (to minimize leakage currents) and excellent voltage withstand capability. Bulk-encapsulating conductive elements in an encapsulant such as EVA will provide the requisite blocking of moisture ingress. Satisfying the requirement for a high resistance ensures that leakage currents remain small even during exposure to moist environments. Meeting the requirement for excellent voltage withstand capability means that electrical stress enhancement sites within the insulation, i.e., void-type flaws, will have a high tolerance to erosion from internal electronic discharges (partial discharges) induced by the applied voltage. Maintaining a high tolerance against such erosion will hinder the weakest void from growing to ultimately span the cell-frame spacing, minimizing the possibility of voltage breakdown.

Perfect isolation implies that no measurable current levels can be detected; a superior module insulation design would consist of a fully-encapsulated cell string permitting only bulk paths to the environment. The proposed wet insulation-resistance test measures the cell-to-environment resistance or leakage current of a test module. The pass/fail criterion is intended to provide information that (1) the module may or may not withstand the initial application of the field voltage and (2) electrochemical corrosion may or may not limit the intended life of the module. Because the effects on the module of the field environment are so uncertain, a sampling of fielded modules should perhaps be periodically retested for lifetime reevaluation purposes. Further development of the draft wet insulation-resistance test through the evaluation of fielded modules is a positive step toward verifying the effectiveness of a module's isolation design.

Interpretation of withstand or breakdown testing data is difficult because of the complexity of the breakdown process and its dependence on many parameters. The effects of moisture when combined with local environmental stresses (i.e., acid rain, soilants) are unclear. As previously mentioned, in the literature can be found statements that moisture actually increases breakdown voltage levels, presumably by preventing charge buildup on void walls, an instance wherein moisture actually plays a favorable role. However its effect upon the CIV is uncertain, but its known ability to delaminate thin-film and insulation layers is clearly detrimental. Additional research using partial discharge equipment on thin-film modules exposed in an outdoor test facility is underway to better understand and measure module voltage breakdown susceptibility.

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APPENDIX A

WET INSULATION-RESISTANCE TEST

1. Purpose

The purpose of the wet insulation-resistance test is to verify that the electrical insulation system of a photovoltaic module is consistent with safety, electrochemical corrosion, and PV system ground-fault sensing requirements under wet operating conditions.

2. Commentary

Field and laboratory testing have established that the largest module leakage currents occur when the module is wet. These wet-condition leakage currents are a primary cause of electrochemical corrosion damage and spurious ground-fault interrupter tripping, and represent a potential safety hazard. To achieve long operating life, the total integrated leakage current must not exceed a particular level dependent upon the length of the module perimeter. These parameters together with the test time and voltage level under wet conditions establish the minimum allowable wet insulation resistance.

3. Test Procedure

The module shall be tested by immersing each edge in turn in a water/wetting agent solution and measuring the insulation resistance between the shorted output terminations and the solution; the applied voltage shall be 500 Vdc in each polarity; the temperature of the module and solution shall be $22 \pm 3^{o}C$ ($72 \pm 5^{o}F$).

Suitable water/wetting agent solutions include: Windex Glass Cleaner (undiluted); Glass Plus (undiluted); C.R. Laurence Co., Inc. Concentrate Glass Cleaner No. 695 (1 part concentrate to 9 parts distilled water).

Apply the test voltage and read the wet insulation resistance after 2 minutes. With the test voltage still applied, thoroughly wet all exposed surfaces of the module for approximately 10 seconds, particularly the electrical termination area, using a handheld spray containing the same solution. Record the insulation resistance reading after 2 minutes. All wiring connections should be representative of the recommended field wiring installation; insure that leakage currents are not originating from the instrumentation wiring attached to the module. Terminations and terminal boxes shall be maintained at least 1/2-inch above the solution level, but shall be thoroughly wetted with the spray.

All resistance measurements shall exceed TBD* megohms as measured with a suitable high-impedance ohmmeter (Megohmmeter or Megger).

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* A value between 100 megohms and 1,000 megohms is being considered.

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