RELIABILITY STUDIES OF PHOTOVOLTAIC MODULE INSULATION SYSTEMS

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SUMMARY

Glass/polymer encapsulant systems are used in power generating photovoltaic (PV) modules to insulate the solar cell circuitry against environmental degradation and to provide for electrical safety. Leakage currents cause electrochemical corrosion of metallic elements that result in power degradation and reduced module lifetime, and which, if large enough, may lead to ground-fault arcing.

Three major PV module reliability issues are reviewed: 1) susceptibility to voltage breakdown, 2) hermeticity/water ingress, and 3) moisture-induced corrosion. Based upon research findings, a simple production-line qualification test was developed that combines the elements of a "wet" hi-pot test and an electrochemical corrosion test.

INTRODUCTION

The fundamental role of a PV module insulation system is to isolate the active electrical elements to reduce the threat to human safety and to minimize stray leakage currents that may electrochemically corrode module current-carrying elements and structural parts. Total charge transfer, obtained by integrating cell-to-frame leakage current over time, is a direct measure of the level of corrosion damage. The leakage current magnitude depends upon such module design parameters as encapsulation thickness and conduction properties, and upon such environmental parameters as temperature and relative humidity. A module end-of-life criterion has been established by measuring cell power output reduction as a function of charge transfer.

In this paper we merge these concepts and observations to describe module lifetime in terms of the interaction of two functions: a module susceptibility function, dependent upon material and design parameter selections, and a damage function defined by environmental parameters. To quantify the above concepts and better understand the role of module leakage current in limiting module life, moisture sorption isotherms, together with bulk, surface, and interface conductivities of the encapsulants polyvinyl butyral (PVB) and ethylene vinyl acetate (EVA) have been measured. The effect on total cell-to-frame leakage current can then be evaluated based upon the measured correlation between bulk and surface conductivities and environmental conditions.

Some module insulation systems are more susceptible to environmental changes than others. For example, crystaline-silicon (C-Si) modules are bulk-encapsulated; moisture must permeate the encapsulant in order to reach and interact with the cell circuitry, which typically consists of thick-film metallization (approximately 0.015 in.). In amorphous-silicon (a-Si) and other thin-film (TF), non-bulk-encapsulated modules, electrical isolation is achieved by edge-sealing the TF (fractions-of-microns-thick) layers with compounds such as soft polymers, epoxies, and acrylics, Figure 1. In

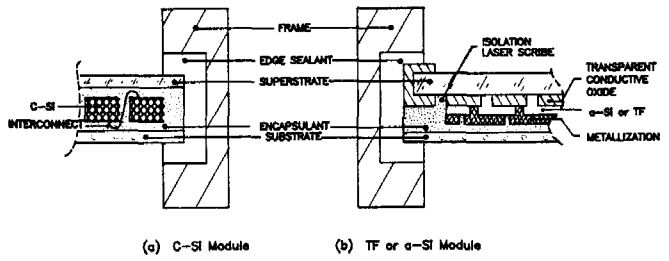

Fig. 1. Typical C-Si and a-Si Photovoltaic Module Construction.

this latter arrangement, conductive elements exist to the very edge of the module, and the edge sealant then becomes the key electrical isolation material. A disadvantage of this arrangement is that direct interfacial paths to the module interior exist that readily allow moisture ingress. These facts explain why C-Si modules have greater longevity than a-Si and TF modules. The above considerations have led us to study, not only moisture-induced PV module corrosion, but also the voltage withstand and hermeticity characteristics of typical module insulation and edge sealant systems.

BASIC RELIABILITY ISSUES

Voltage Withstand

The production line "hi-pot" test qualifies (or disqualifies) a module for immediate field service but gives little insight into the factors that determine module susceptibility to voltage breakdown. We have performed detailed studies of the voltage withstand characteristics of modules and of typical module insulating materials [1]. Figure 2 shows a typical test result of the breakdown testing of Mylar, a large-area polymeric film typically used as a module back-surface insulation -- the calculation of module failure probability as a function of applied voltage, number of insulating layers, and module size. Because the number of insulation flaws is area dependent, larger modules exhibit a greater failure probability; but this can be

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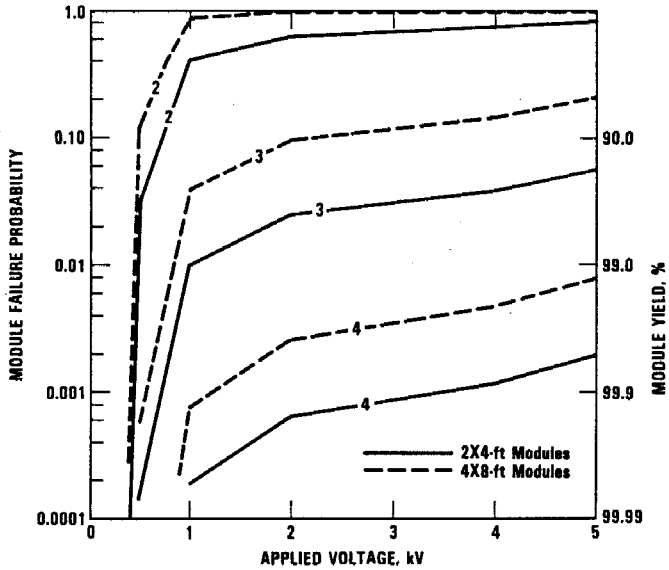


Fig. 2. Module Voltage Breakdown Failure Probability as a Function of Applied Voltage, Number of Insulating Plies, and Module Area.

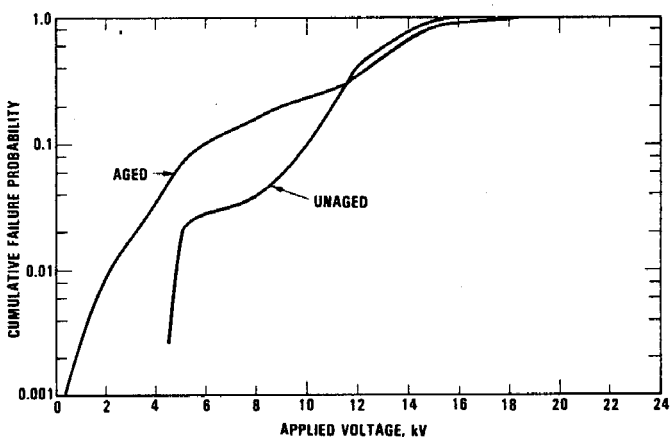


Fig. 3. Voltage Breakdown Failure Probability of 4-Mil Tedlar: Pristine and Aged by Exposure to Moist Air.

reduced, cost considerations permitting, by using multiple insulation layers. Figure 3 shows how long-term exposure of Tedlar, a popular module back-cover film, to temperature and moisture increases its voltage breakdown failure probability.

Moisture-Induced Corrosion

Moisture entering a PV module diffuses along interfaces and accumulates in the insulation. The quantity of moisture sorbed by the insulation is a function of the temperature and atmospheric vapor pressure; the amount of moisture sorbed by PV module encapsulants PVB and EVA has been measured and is presented in Figure 4 [2]. The retained moisture provides an electrolytic medium for the dissolution of ionizing species, thereby increasing the electrical conductance of the insulation and its interfaces. Increases in the bulk conductivity of PVB and EVA as functions of increasing relative humidity and temperature are shown in Figure 5 [3]. Interface conductivities of PVB-glass and EVA-glass combinations are presented in Figure 6 and 7, respectively. Surface conductivity data for the two encapsulants were also measured, but are not presented here.

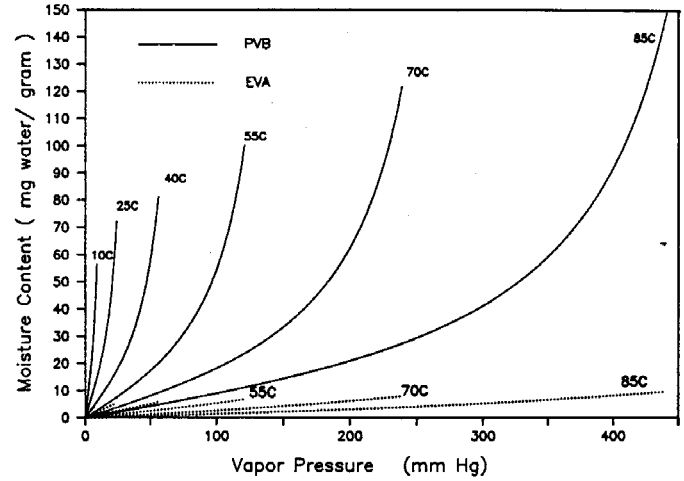


Fig. 4. Sorption Isotherms for PVB and EVA.

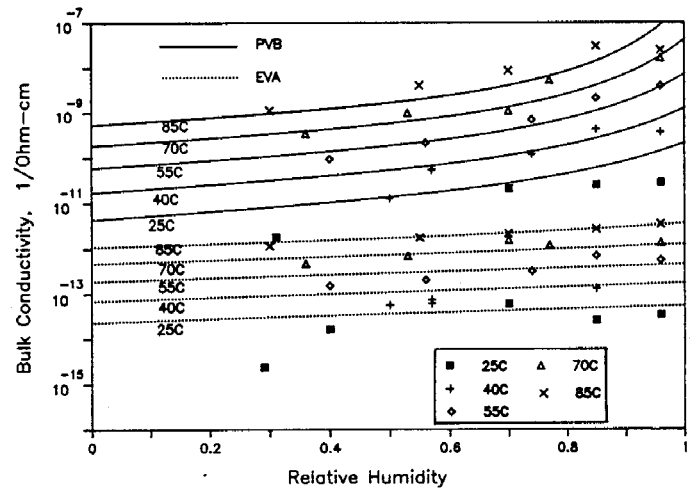


Fig. 5. Electrical Conductivity of PVB and EVA vs Relative Humidity and Temperature.

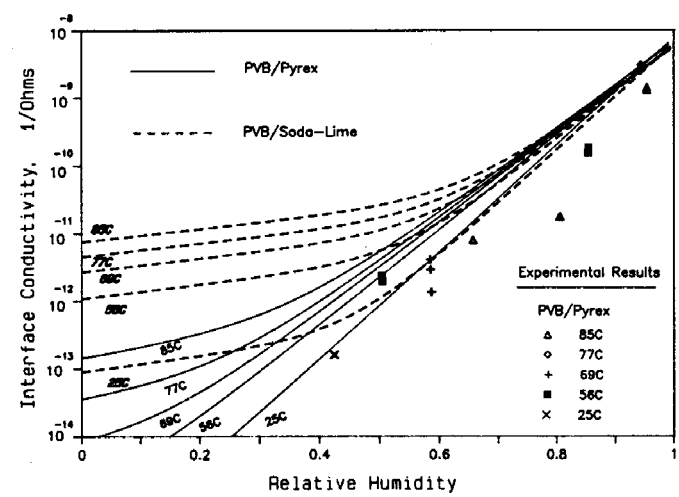


Fig. 6. PVB-Glass Interface Electrical Conductivity

Analytical curves were fitted to these data using physical models developed in [2].

Increased material and interface conductivities accelerate galvanic corrosion potentials within PV modules

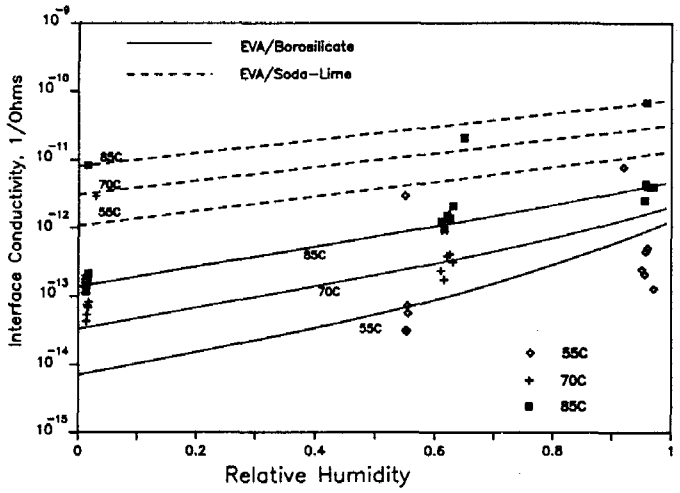


Fig. 7. EVA-Glass Interface Electrical Conductivity.

and result in larger anode-to-cathode (cell-to-frame or frame-to-cell) leakage currents, a key contributor to module electrochemical degradation. A single-encapsulated-cell model of a PV module was developed [2] to analyze the dependency of cell-to-frame leakage current on various module design and environmental parameters, Figure 8. The results of the analysis, Figure 9, reveal how the interplay of the environmental parameters temperature and relative humidity, with various module design parameters and material conduction properties, determine overall module cell-to-frame conduction.

The lower graph, depicting how the environmental parameters temperature and relative humidity determine

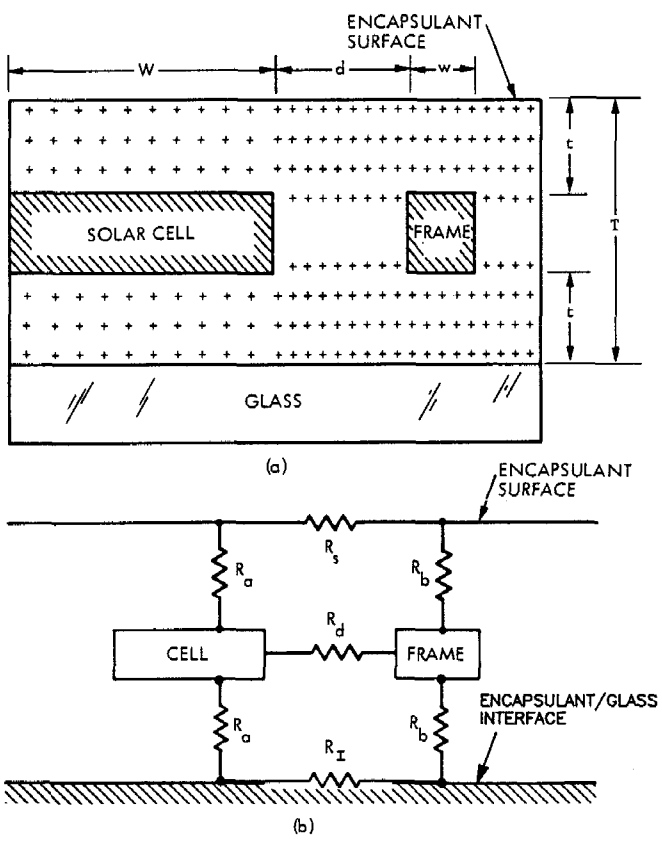


Fig. 8. One-Cell PV Coupon Conduction Model.

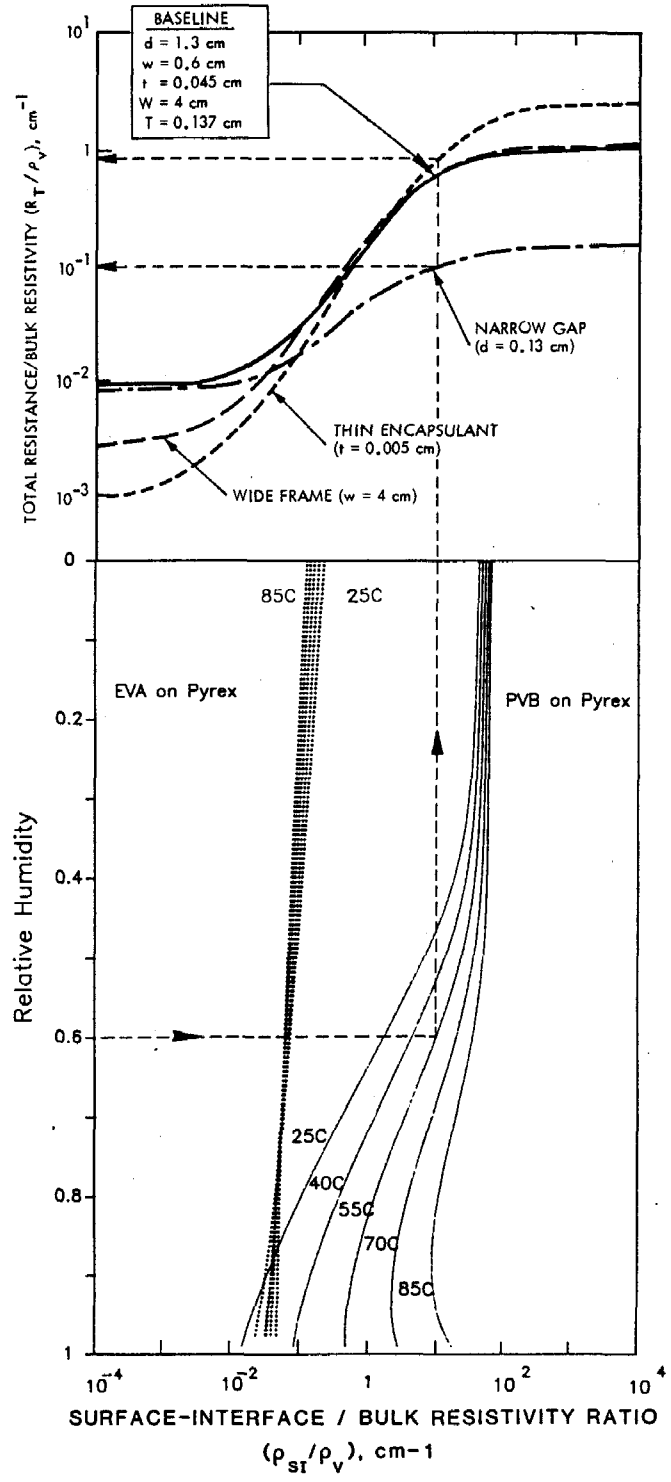


Fig. 9. Results of Model Analysis.

certain module electrical resistivity ratios, is an implicit module "exposure" function. The upper graph, showing how module performance changes with design parameters, is an implicit "susceptibility" function. In concert with application voltages, these functions determine a damage function, i.e., dose rates (leakage currents) of damage (charge transfer) accumulation.

The actual electrochemical failure mechanism is as follows [4]. Redox reactions at the electrodes (cell and frame), together with resultant electrode dissolution, product formation, and interelectrode ion

migration (charge transfer), discolor the encapsulant, reducing its optical transmissibility. As a consequence, cell power output is reduced to non-useful levels.

Reduction in output power as a function of charge transferred per unit length of module frame has been measured for both C-Si and a-Si cell modules [3,4]; the results, presented in Figure 10, show that a-Si and TF modules are more susceptible to this form of degradation by at least a factor of 10 in charge transfer, and hence, service lifetime.

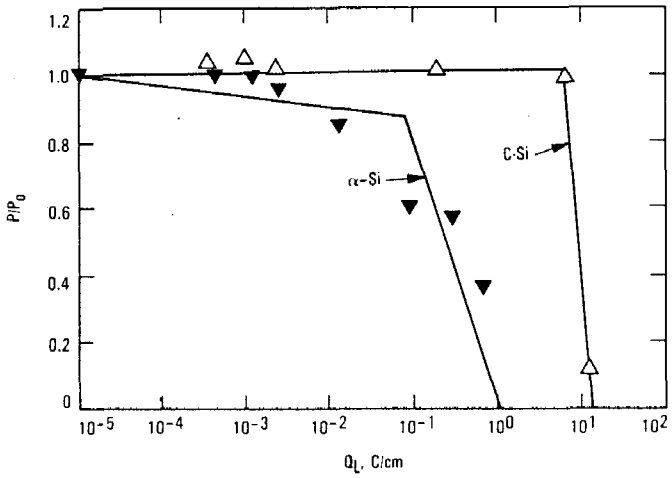


Fig. 10. PV Module Power Output Reduction as a Function of Cell-to-Frame Charge Transfer.

Hermeticity

C-Si modules feature individual cells bulk-encapsulated in a low moisture sorbing, low ion content polymer such as EVA. Moisture can reach the cells only via paths through the bulk of the insulation. A-Si and TF modules, on the other hand, are generally non bulk-encapsulated monolithic cell-on-glass (or cell-on-metal) structures; hence in these modules, direct interfacial paths exist from the external environment to the cells, pathways conducive to moisture ingress. A design strategy to curtail moisture-induced corrosion is to employ glass-on-glass (or glass-on-metal) construction and hermetically seal the module periphery.

Toward this end we have measured the bulk resistivities of available caulking compounds, Table 1 [5]; these were found to have bulk resistivity values considerably less than that of the encapsulant PVB, considered marginal for PV applications.

Table 1.

Bulk Resistivity of Module Sealants and Encapsulants @ 20 volts, 22°C/50%RH

Material	Resistivity, ohm-cm
Sikaflex 240	$3.0 - 9.0 \times 10^{10}$
Dynatrol 1	$.6 \times 10^{10}$
PRC Caulk	$3.0 - 5.0 \times 10^{09}$
PVB	$4.0 - 10.0 \times 10^{10}$
EVA	3.0×10^{13}

Next a series of candidate edge-sealant compounds, consisting of butyls, epoxies, and EVA, were tested by exposing in an 85°C/100%RH environment small module-like test coupons within which were sealed cobaltous chloride humidity sensors that would turn color upon exposure to moisture, should the sealant fail; see Figure 11 for a view of the experimental setup. Test results, Figure 12 [5], revealed that only two epoxy systems survived 300 hours of exposure.

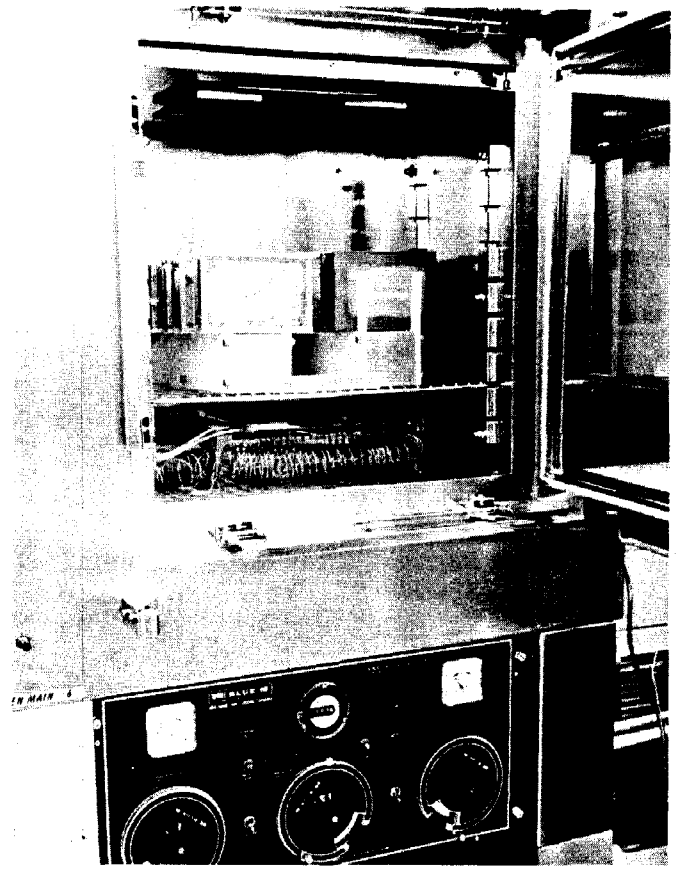


Fig. 11. Environmental Testing of Candidate Edge Sealants

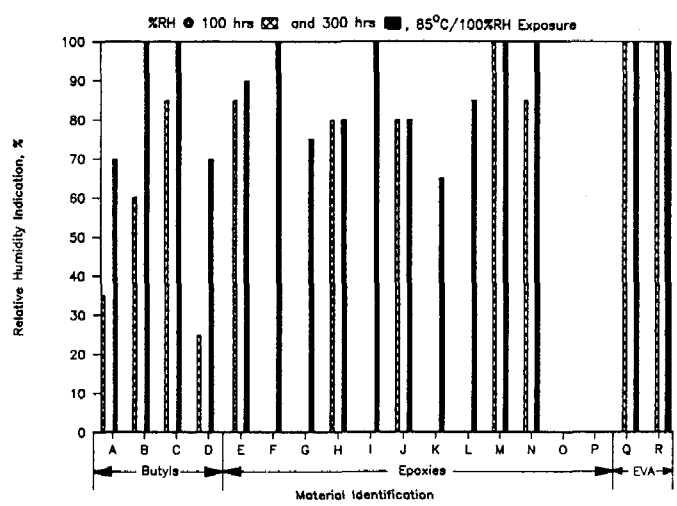


Fig. 12. Edge Sealant Study Test Results

Follow-up tests on these two successful epoxy systems revealed that, after exposure to a dry temperature cycling environment (-10°C to +60°C for 10 days), they subsequently failed an 85°C/85%RH exposure. This suggests that improved epoxies or alternative sealants and sealant concepts must be developed and tested to withstand the thermal cycling stresses common in the PV applications environment.

QUALIFICATION TEST DEVELOPMENT

These findings in PV module voltage withstand and corrosion research have been translated into a useful production-line module qualification test [6], which we refer to as a Wet Insulation Resistance (WIR) test. In essence, the WIR test combines the quantitative aspects we have developed in PV module electrochemical and galvanic corrosion research and testing with the qualitative aspects of the standard hi-pot test.

In the standard (dry) hi-pot test, twice working voltage plus 1000 volts (approximately 1500 Vdc to 3000 Vdc) is impressed between the shorted module internal current-carrying elements and external conductive structural elements for a period not exceeding one minute; the module is considered to "pass" if the leakage current does not exceed 50 uA. The test level of twice working voltage plus 1000 volts became standardized in the early days of voltage withstand testing of insulations; the 50 uA criterion derived from considerations of ground-fault detection and human safety levels for large PV arrays.

The hi-pot test, however, did not account for the effects of moisture. Toward this end the humidity/freeze test, also qualitative, was developed at JPL [7]. In this test, modules are cycled once a day for 10 days between an environment of -40°C (4 hrs) and 85°C/85%RH (20 hrs). The object is to force moisture into the module and, via visual inspection, observe mechanical and moisture-induced corrosion.

In the humidity/freeze test, the modules are not electrically biased, so electrochemical effects are not observed. We initially biased modules (500 volts, cell-to-frame, both polarities) in a humidity/freeze-type test and monitored leakage currents over the 10-day test period. Presuming that equal quantities of charge transfer (in <u>any</u> environment) result in equivalent levels of electrochemical damage, and utilizing the previously determined charge transfer based failure criterion, we were able to determine correlations between module exposure times in accelerated test chambers and in field environments, and, indeed, were able to predict module service lifetimes [8].

As awareness of the problem of moisture-induced module corrosion grew, i.e., as it became evident that the highest leakage currents occur when the module is wet, a clamor arose within the PV industry for a "wet" hi-pot qualification test. JPL responded by developing the WIR test [6], in which each module edge is immersed, in turn, in a water/surfactant solution (we recommend a tap water solution of 0.1% by volume Triton X-100: octyl phenoxy polyethoxy ethanol), and the resistance between the shorted terminations and the solution is measured. The "weakest" edge is thus determined. This edge is now re-immersed in the solution and a test voltage of 500 volts is applied for two minutes between the shorted output terminations and the solution, after which time the insulation resistance is recorded. The module is then sprayed with the same water/surfactant solution and the resistance after two minutes is again recorded. A suitable high-impedance ohmmeter (Megohmmeter or Megger) is recommended for use in this test. Our test set-up is shown in Figure 13.

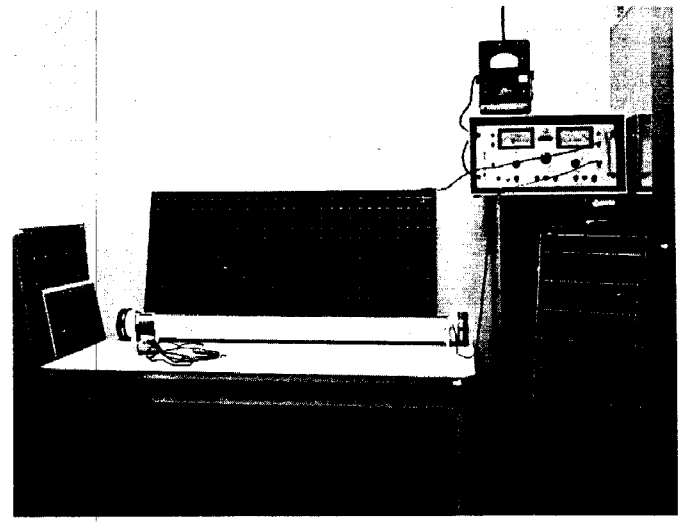


Fig. 13. Wet Insulation Resistance Test Set-up

The choice of pass-fail resistance criterion derives from the quantitative aspects of module electrochemical research: the quantity of cell-to-frame charge transfer that reduces module power output to non-useful levels, Figure 10. A reading of 1000 megohms will qualify a typical 1' x 4' module for approximately 30-year service (this criterion is based upon an assumed 2-hr period of rain or dew condensation each day and no increases in leakage current as the module "ages").

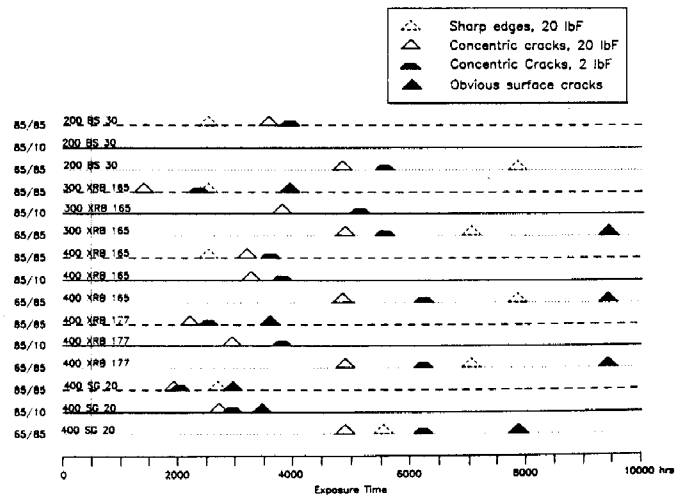
Such qualification tests and associated pass-fail criteria are under current development both by research laboratories such as JPL and SERI, and by individual module manufacturers. To date no standard qualification test procedure has been adopted by the PV industry.

ADDITIONAL ENVIRONMENTAL EFFECTS

We have exposed module front- and back-surface insulation films, mainly Tedlars, to three temperature\humidity\ultraviolet environments in an effort to determine

Table 2.

Defined Tedlar Degradation Levels vs Exposure Time



long-term environmental effects on these films. The environments include 85°C/10%RH, 85°C/85%RH, and 65°C/85%RH, with 1-sun UV in each environment. Evaluation of the insulations include visual inspection, weight loss measurements, pull tests (force - elongation), and push tests (similar to hardness tests). We have found in these tests that humidity plays an insignificant role. The major forms of degradation are material embrittlement induced by photo-thermal oxidation and polymer chain scission reactions [9].

Some push test results are presented in Table 2, which gives the time at which certain visual features relating to embrittlement became evident on the films when a 0.0625 in. diameter ball was impressed into the films. These data can serve as a basis for obtaining Arrhenius embrittlement rates and activation energies [9].

CONCLUSIONS

JPL has developed a Wet Insulation Resistance qualification test to measure the susceptibility of PV modules to interaction with moisture. The test determines whether or not the electrical insulation system is consistent with safety, electrochemical corrosion, and PV system ground-fault sensing requirements under wet operating conditions. The test combines elements of both an electrochemical corrosion test and a "wet" hi-pot test into a single, simple procedure for field, production-line, or laboratory use.

The adequacy of present PV module insulation systems to withstand a 30-year field environment depends upon the module type. C-Si modules, whose cells are bulk-encapsulated in a low moisture-sorbing, low-ion content polymer such as EVA, and featuring glass-superstrate, glass-substrate construction, have exhibited superior performance in both wet and dry environments. Because a-Si and TF modules are not bulk-encapsulated, the existence of interfacial paths from the environment to the module interior readily permit the ingress of moisture to the TF layers; as a result, the performance of TF modules, particularly in moist environments, is dependent upon the edge-sealing techniques and the quality of materials used.

Present approaches to improving TF module insulation performance focus on developing edge-sealants that not only exhibit low moisture permeability but also provide acceptable substrate-to-superstrate bondline resistance to moisture and cyclical environmental temperature and UV stresses. Use of various polymeric systems are under investigation, including acrylics, epoxies, and UV-curable compounds.

Novel PV module insulation systems equivalent to glassivation and/or hermetic sealing may augment traditional insulations, but for the present such approaches are not cost effective and require technical scrutiny at a level focused over the years on the traditional polymer film and encapsulant insulation systems.

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