TEST TECHNIQUES FOR VOLTAGE/HUMIDITY-INDUCED DEGRADATION OF THIN-FILM PHOTOVOLTAIC MODULES*

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SUMMARY

Thin-film photovoltaic modules, deployed worldwide in various applications, experience considerably different levels of environmental and electrical stresses. Test techniques, combining both accelerated and real-time laboratory and outdoor field tests, have been utilized to develop a proposed qualification test that rapidly assesses the level of susceptibility of a module to voltage/humidity-induced degradation.

1. INTRODUCTION

An important requirement for achieving safe high-reliability thin-film (TF) modules is to minimize stray leakage currents by isolating the electrical circuitry from the external environment. Qualification levels for stray leakage currents must address three factors: 1) human safety, 2) leakage-current driven life-limiting mechanisms such as electrochemical corrosion (degradation resulting from electrode-dielectric interaction [1]), and 3) ground-fault arcing associated with total breakdown of the module insulation system [2]. In order of leakage level, mitigating against long-term corrosion is probably the most demanding criteria. This is because mechanisms such as electrochemical corrosion are driven by the integrated current over the entire life of the array, not just the instantaneous current during a particular incident, as with personal safety or ground-fault arcing. Whereas typical maximum leakage currents for personal safety are on the order of 1 to 5 mA, the maximum leakage currents for minimizing excessive long-term corrosion are on the order of 1 to 5 microamps -- a thousand times less.

A second important factor that leakage-current qualification levels must address is the strong (many orders of magnitude) dependence of leakage currents on environmental parameters such as module temperature and humidity level. Historically, module safety and voltage-withstand reliability have been assured by testing modules against the standard hi-pot test [3]; the pass/fail criteria of this test is that leakage current levels must be below 50 microamps at an impressed cell/frame voltage of twice the system application voltage plus 1000 V_{dc} for a one-minute duration. The test is conducted under typical room-ambient (20 °C, 50% RH) conditions.

To build safe, high-reliability modules it is important to both understand the mechanisms responsible for excessive leakage currents in modules, and to have a simple, inexpensive test for module characterization and qualification. Over the last several years JPL has extensively studied module leakage-current mechanisms in TF and crystalline silicon modules [4 - 9], and has drafted a preliminary "wet insulation-resistance test" [10] to fill the short-comings found in the historical "dry hi-pot test". This paper describes the rationale behind the

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test, and experience to date in comparing the test results with in situ measurements of leakage currents in actual fielded modules.

2. BACKGROUND

Electrical isolation of typical TF modules is achieved by edge-sealing the TF layers with polymer materials. Fig. 1 shows a representative sealant configuration between the metal frame and the successive fractions-of-micron-thick layers (transparent conductive oxide, TF semiconductor, and aluminum metallization) monolithically deposited on glass. For these TF modules, the problem of excessive leakage currents is aggravated by the presence of the transparent conductive oxide (TCO) that often causes portions of the front surface and edges of the glass to be electrically connected to the cell string. In many cases the TCO wrap-around is the dominant leakage path between the cells and the environment.

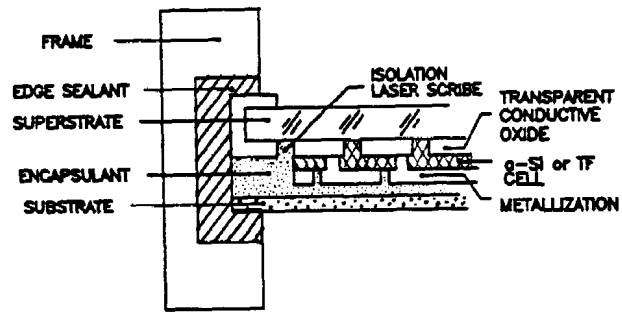

Fig. 1. Typical TF Module Construction.

Although the TCO wrap-around of TF modules creates a troublesome leakage-current path to the front glass, it is not until the module is wet, that this path is completed to the module frame and earth ground. Thus, TF modules provide one of the most dramatic examples of the significant effect of surface moisture on module leakage currents.

Field experience with first generation TF modules has demonstrated many instances of failures due to unacceptable leakage current levels. A particularly illuminating example involved a number of first-generation 1-foot square a-Si modules that failed due to excessive leakage currents in a high-voltage array (500 V_{dc}) representative of the conditions of a future central power plant.

Test measurements were made on submodules that had been removed from the field and stored in a relatively dry environment at JPL for a period of approximately 3 months prior to testing. Partial discharge measurements made on two subpanels indicated that, for the dry condition (as received), the corona inception voltage (the voltage for which the largest detected pulses within the insulation voids are 5 picocoulombs) was well above 5000 Vdc, indicating that, in a totally dry condition, the subpanel's dielectric strength was excellent, and more than adequate for the intended application. Additional insulation-resistance measurements, using a General Radio Megohmmeter between the shorted cell string and the conductive frame, confirmed the partial discharge measurement data, and were on the order of 10^5 megohms.

Subsequent to the dry testing, the modules were sprayed with a glass-cleaner solution while their leakage resistance was simultaneously monitored. The result was a six order-of-magnitude increase in leakage current -- reaching a totally unacceptable level. Post-test inspection revealed that the wetting agent solution had successfully found and penetrated minor breaches in the polymeric insulation system where the system was spliced at corners of the module.

This incident, among many, highlighted the growing recognition that a test that specifically recognized the wet insulation-resistance condition was needed.

3. WET INSULATION-RESISTANCE TEST PROCEDURE

3.1 Approach and Methodology

The procedure used by JPL over the past year to develop the wet insulation-resistance measurement test employs the same iterative process and approach successfully used to develop the JPL Block V Test Specifications [11]; the four steps consist of:

1) problem identification -- analysis of voltage/humidity induced field failures,

2) failure mechanism research -- studies of the physics of electrochemical corrosion due to excessive leakage currents,

3) candidate requirements generation and test procedure definition -- devising a simple wet insulation-resistance test with established threshold levels for TF modules,

4) verification and procedure refinement -- using outdoor test results to validate and update the proposed procedure.

Although presented in a previous paper [10], details of the proposed insulation-resistance test are provided as Appendix A of this paper, incorporating a procedure refinement explained in Appendix B - Properties of a Suitable Wetting Agent.

The proposed test procedure is currently under consideration by research laboratories such as JPL and SERI, individual module manufacturers, and industry users; it consists of using a simple trough apparatus, shown in Fig. 2, containing a tap water/surfactant solution, and of using a spray bottle to thoroughly "wet" both surfaces of the module. The test procedure consists of immersing each module edge in turn in a tap water/surfactant solution and measuring the resistance between the shorted module terminations and the solution with an applied 500 V_{dc} test voltage. The edge with the lowest resistance is thus determined, and this edge is now re-immersed in the solution and the test voltage of 500 V_{dc} is applied between the shorted module terminations and the solution. The module is then sprayed with the same tap water/surfactant solution and the resistance is recorded after two minutes. The pass/fail criteria presently under consideration is between 100 and 1,000 megohms. Factors behind the selection of this level are described next.

3.2 Wet Insulation-Resistance Pass/Fail Criteria

The basis of the proposed qualification test is the characterization of the module's insulation resistance, which can be described by two different values: a dry insulation resistance, R_D for low-humidity environments, and a wet insulation-resistance, R_W, for high-humidity environments.

For considerations of personal safety and ground-fault arcing, it is the worst-case lowest value of R_W which is likely to be the critical level. However, for long-term electrochemical corrosion one must also consider the integrated effects of leakage currents during dry periods.

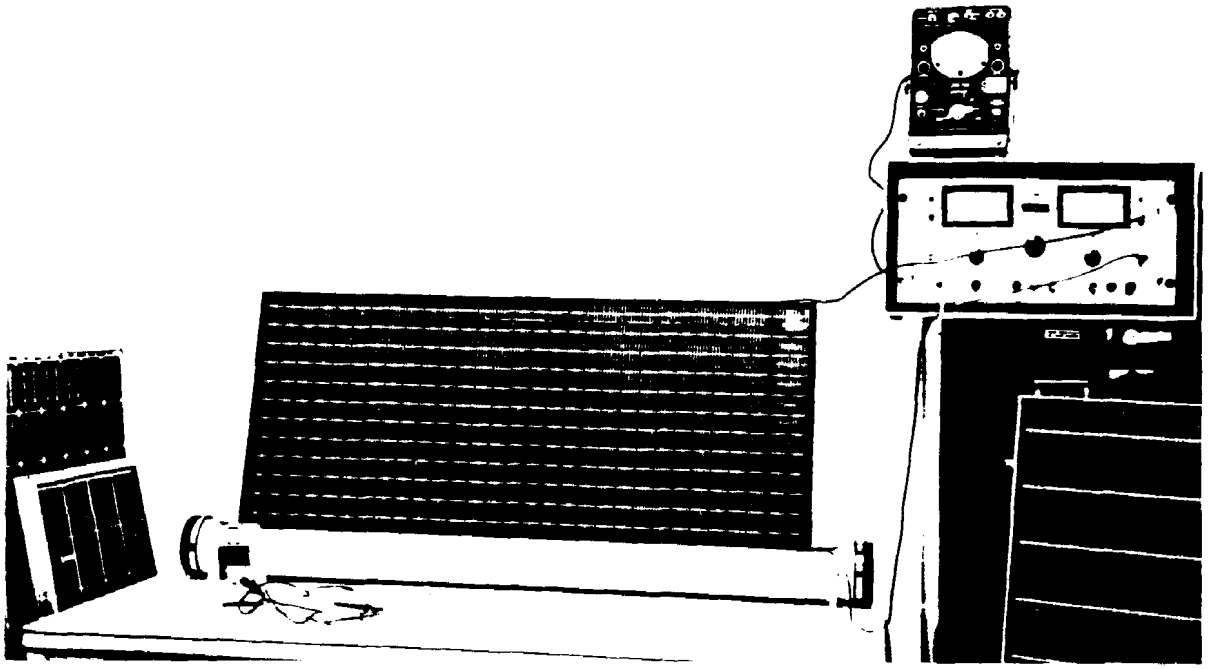

Fig. 2. Test Apparatus for Wet Insulation-Resistance Test.

Charge transfer as integrated leakage current can be approximated by the equation

$$Q = V[(T_D/R_D) + (T_W/R_W)] \quad (1)$$

where V = Maximum system voltage, 500 V_{dc}
R_D = Dry resistance, Ohms
R_W = Wet resistance, Ohms
T_D = Operation time under dry conditions, seconds
T_W = Operation time under wet conditions, seconds

For simplification purposes a typical day may be considered to be 8 hours of sunlight exposure with an average of 25% wetness (rain or dew) and 75% dryness in a typical year. Under these conditions, the total integrated leakage current in a module's lifetime, L, would become

$$Q_L = [VL][0.25/R_W + 0.75/R_D]$$

$$Q_L = [VL/4R_W][1 + 3R_W/R_D] \quad \text{where } L = \text{module life in seconds.} \quad (2)$$

Based on these simplifying assumptions, a quantitative pass/fail criterion can be established by equating Q_L to the critical level of charge transfer Q^* required for failure of a typical TF module. Thus,

$$R_W^* = [VL]/[4Q^*] \qquad \text{where } R_W/R_D << 1 \quad (3)$$

Past JPL research using small 4" x 4" coupons indicates that the critical charge transfer level Q^* for a-Si modules is in the range of 3 to 30 Coulombs [4], or 0.1 to 1.0 Coulombs/cm, if the effect is proportional to the module circumference.

Unfortunately, scaling the test-coupon data to larger modules is strongly dependent on whether the failure mechanism is a point defect, is proportional to module perimeter, or is proportional to module area. From field experience, ground-fault arcs, appear to be the result of localized point-breakdowns in the module insulation system; other failure mechanisms, such as bar-graph corrosion, appear to more of a perimeter effect due to moisture accumulation along the lower edge of a module.

Clearly, point defects, perimeter dependence, and area dependence are all possible. The problem is the variability in the pass/fail criteria that these different dependencies imply when attempting to scale up from the test coupon results to various size modules.

For example, using a 1′ x 4′ module, the critical charge scales to between 30 and 305 Coulombs based on perimeter, and to between 111 and 1,115 Coulombs based on area. Note that keeping the area constant but changing the aspect ratio to a square (i.e., 2′ x 2′), results in yet a different value for critical charge for perimeter, to between 24 and 244 Coulombs.

For a 500 V_{dc} system with 1′ x 4′ modules designed for 30-year life, and an electrochemical damage threshold or critical level of charge transfer, Q^*, between 30 and 305 Coulombs; the corresponding criteria for pass/fail wet insulation resistance, using Eqn. 3, is between 129 and 1,314 megohms.

The above considerations, in conjunction with the degree of uncertainty due to data scatter, has resulted in considering a "wet" insulation-resistance pass/fail criteria in the range between 100 and 1,000 megohms. Values of insulation resistance for the latest production TF modules typically fall in this range, while the values for modules that led to past field failures would fail these criteria by three orders of magnitude. In keeping with the JPL Block V approach, it would be appropriate to select a pass/fail criteria closer to the lower (100 megohms) bound, so as not to restrict the manufacturers in their attempt to produce low-cost modules, but with the provision that the criteria be raised if signs of poor field performance become evident. Another confusion factor is the presence of modules for which the wet and dry insulation resistance (R_D and R_W) are approximately equal. For modules of this type, Equation (2) argues for an increase in the allowable insulation resistance by a factor of four.

For now it is proposed that a simple, single wet insulation resistance criteria (such as 100 megohms) be selected, independent of the module construction and size. This criteria should then be revisited from time to time based on field experience with modules in real applications.

4. TEST VERIFICATION

As part of the verification and procedure refinement process, a number of representative TF modules have been mounted at the JPL outdoor test stand (Fig. 3) to provide in situ insulation-resistance data for comparison with resistance data obtained for the same modules tested indoors using the proposed wet insulation-resistance test.

A comparison of initial outdoor test measurements during dry conditions with indoor laboratory test data, also for dry conditions, is shown in Table I.

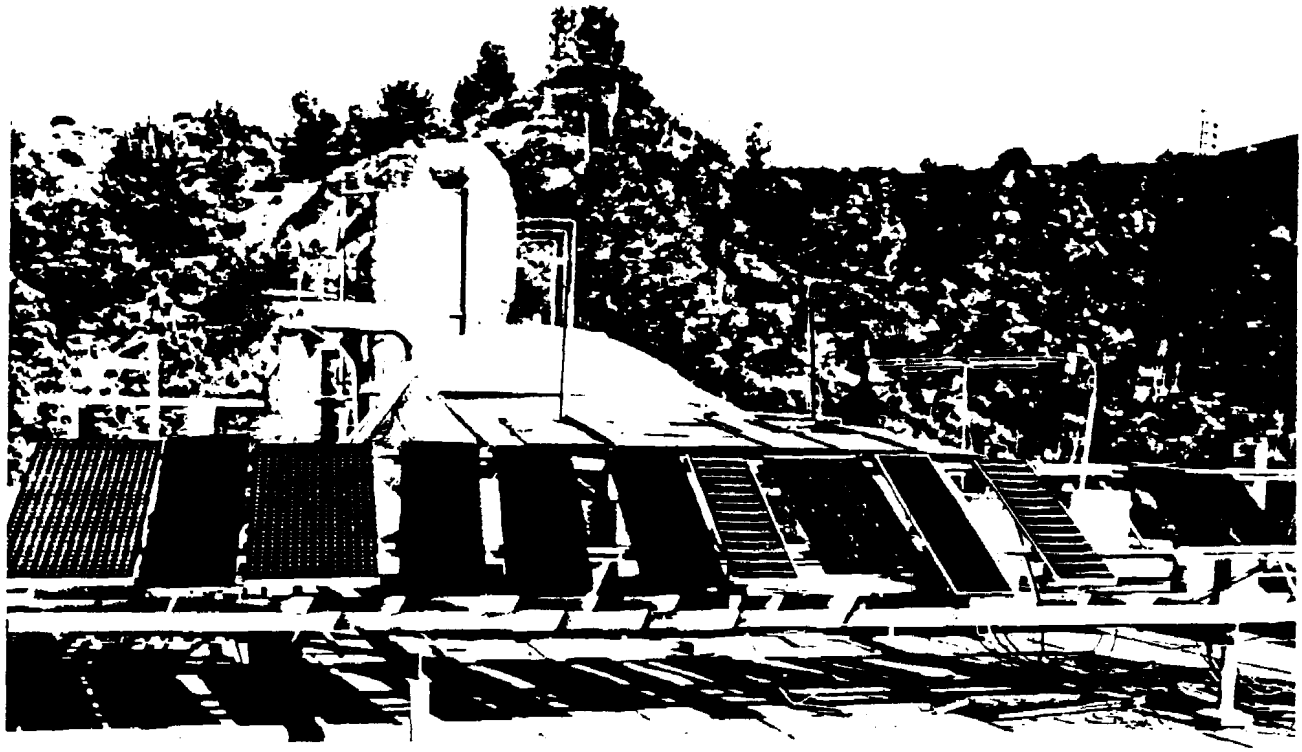

Fig. 3. Outdoor Exposure of TF Modules at JPL Field Test Site.

Results at both locations are relatively consistent. The larger amount of data scatter can be expected outdoors where high signal-to-noise ratios are more difficult to maintain.

Table II also shows insulation-resistance measurements obtained at the outdoor test facility under two conditions of natural wetness -- a very light

TABLE I.

Comparison of Outdoor Test Facility Results
with Indoor Laboratory Test Data
Under Dry Conditions

Module Type	Resistance (kilomegohms)	
	Indoor	Outdoor
1	22 - 82	4.5 - 22
2	0.3 - 0.45	0.3 - 1.4
3	700 - 1000	9 - 170
4	10 - 15	8.4 - 12

TABLE II.

Comparison of Outdoor Test Facility Results
with Indoor Laboratory Test Data
Under Wet Conditions

Module Type	Resistance (kilomegohms)				
	Indoor Trough	Outdoor Condensation	Outdoor Drizzle	Indoor Trough with Spray	Outdoor Hose
1	0.9 - 1.4	2.8 - 12	1.1 - 7.0	0.11 - 0.6	0.8 - 1.5
2	0.35 - 0.46	1.2 - 1.3	1.0	0.29	0.2 - 0.4
3	1.34 - 2.3	9.5 - 12	0.25 - 4.0	0.32 - 0.47	0.01 - 0.03
4	2.8 - 3.6	6.2 - 9.5	0.14 - 2.7	0.5 - 3.6	0.01 - 1.0

rain (drizzle) and a foggy morning where droplets had condensed on the surface of the modules (condensation); and an artificial condition -- a rainstorm simulated by a spray from a hose. Additionally shown are insulation-resistance measurements taken in the laboratory using the proposed test procedure and two simulated outdoor environments -- the column labeled "Indoor Trough" refers to the module edge with the lowest insulation resistance immersed in the wetting agent solution (tap water with a 0.1% concentration of Triton X-100) and the column labeled "Indoor Trough with Spray" refers to the same module edge immersed in the trough while being sprayed on both front and back surfaces with particular attention to the terminations.

With the exception of Module Type 2, whose insulation resistance is about the same order of magnitude under both wet and dry conditions, there is at least an order of magnitude decrease in insulation resistance between dry and wet measurements, the change being much more noticeable for the indoor measurements. Examination of the data in terms of indoor and outdoor insulation resistances is consistent with the expected trend; as conditions become more "wet", the insulation resistance decreases. The laboratory test does not appear overly severe, though attempting to correlate measurement data from the Indoor Trough with Outdoor Condensation and Outdoor Drizzle columns is difficult at best. The Outdoor Hose data is an attempt to simulate a rainstorm to compare with the Indoor Trough with Spray data. Unfortunately, there was no safe way to provide the water coverage necessary to accurately simulate a driving rainstorm, although the results are on a par with each other.

An additional observation relates to modules with non-conductive polymeric frames whose only contact with the metallic array structure is at the four mounting points. Dry insulation-resistance measurements are very good, but will decrease by at least an order of magnitude when wet. It is anticipated that the same or similar results would have been obtained with modules with metallic conductive frames that were isolated from the array structure by polymeric buttons or washers, and fasteners.

5. CONCLUSIONS

The solution to achieving acceptably low levels of leakage currents is to use edge sealants and encapsulants having low ionic conductivities, and to avoid any free-surface or interfacial-surface paths between the module exterior and the electrically live cell string. In the presence of moisture these surface paths are likely to become unacceptable conductors of stray leakage currents.

A wet insulation-resistance test has been developed to characterize and qualify modules with respect to this class of failure mechanisms--particularly with respect to personnel safety and long-term electrochemical corrosion. The test procedure builds on the Block V qualification tests for crystalline silicon modules, and has performed well in tests to date on both crystalline and thin-film modules.

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APPENDIX A

WET INSULATION-RESISTANCE TEST PROCEDURE

1. Purpose

The purpose of the wet insulation-resistance test is to verify that the module's electrical insulation system is consistent with safety, electrochemical corrosion, and PV system ground-fault sensing requirements under conditions where the module is saturated with water in the field.

2. Commentary

Field testing has established that the largest module leakage currents from cell string to frame ground occur during periods when the module is saturated with water from dew or rain. This is because the electrical resistance of the module insulation system is typically several orders of magnitude less under wet conditions than it is under dry conditions; this is particularly true for insulation paths along free surfaces and material bonded interfaces. 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 limit electrochemical corrosion to acceptable levels requires that total integrated leakage currents during the life of a module be limited. This, together with a representative wet-condition exposure time, establishes a minimum allowable wet insulation resistance.

3. Test Procedure

The module shall be tested by immersing each module peripheral 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 °C (72 $\pm$ 5 °F).

A 0.1% solution of Triton 100-X, a non-corrosive, non-ionic surfactant, in tap water is a suitable water/wetting agent. The modules should be thoroughly rinsed after the test.

Apply the test voltage and read the wet insulation resistance after 2 minutes. Re-immersing the module edge with the lowest resistance, apply the test voltage, and thoroughly wet all exposed surface areas of the module using a handheld spray (containing the same solution) for approximately 10 seconds, particularly the electrical termination area. Record the insulation resistance reading after initial capacitive charging currents have subsided (approximately 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 (a pass/fail criteria between 100 and 1000 megohms is currently being considered) megohms as measured with a suitable high-impedance ohmmeter (Megohmmeter or Megger).

APPENDIX B

WET INSULATION-RESISTANCE TEST REFINEMENTS -- PROPERTIES OF A SUITABLE WET ENVIRONMENT

As part of the test development process, another area of investigation has been identification of a suitable surfactant (wetting agent). The goal is to identify a non-ionic, non-corrosive, penetrating additive that is commercially available, and relatively benign in relation to human contact (at least in the diluted form). At issue are two properties of a suitable wetting agent: the resistivity (ionic conductivity) and the surface wettability of the solution.

During the development phase, the resistivities of several candidate wetting solutions were measured. With the exception of de-ionized water, all were within an order of magnitude of each other, and all had sufficient ionic content to function as a good conductor. Conductivity (mhos), the inverse of resistivity (ohm-cm), is the product of n, the number of ions, e, the electronic charge, and u, the ion mobility.

Although all the tested solutions, except de-ionized water, performed on a par with each other in terms of resistivity, several concerns with the use of glass cleaners and other detergents were expressed: 1) they are ionic, increasing the number of free ions in the solution, thus decreasing the resistivity of the solution, 2) they contain harmful additives (e.g., ammonia) that might have some adverse affect on long-term performance, and 3) they contain bulk fillers and other unknown additives that make reproducibility of the wetting solution properties, such as resistivity, difficult.

A more significant property is surface wettability. Lowering the surface tension results in a better sheeting action during the spray phase, and also provides better penetration of the solution into the gasket/module encapsulant interface. This decrease in surface tension can be expected to occur for most modules after a relatively short exposure period in the field, (analogous to the difference between a recently polished car and one that has been subjected to the elements). For example, a first generation single-crystal module, having exposed electrical terminations approximately 2 inches from the conductive frame, was sprayed with tap water. The surprise was that the module insulation system successfully passed the water spray test. Adding window cleaner (Windex) to the spray water immediately wetted the surface, resulting in a path between the terminations and frame. The surfactant in the Windex reduced the surface tension resulting in a short, the result expected of a module using this kind of construction.

Triton X-100 was selected from a group of likely candidate surfactants for further consideration. This compound is generically known as octyl phenoxy polyethoxyethanol, sold by Rohm and Haas Chemical Company, Independence Mall, Philadelphia, PA (215/592-3000); or SIGMA Chemical Company, P.O Box 14508, St. Louis, MO 63178, (800/325-8070), as Product # T6878 or Triton X-100.

From the literature, both 0.1% and 1.0% concentrations in distilled water result in lowering the surface tension to about 30 dynes/centimeter (the surface tension of distilled water is between 70-72 dynes/centimeter). A qualitative test was performed at JPL by dropping 1 ml solutions of Triton X-100 (concentrations of 0.1% and 1.0% in tap water) and tap water on the Tedlar back surface of a module. Both solutions of Triton X-100 were flatter, definitely

wetting the surface; the tap water was not as flat, tending to "bead up", even when the module was slightly tilted. By contrast the Triton X-100 droplets immediately began to sheet when the module was tilted. Additionally, resistivity measurement data results verify that Triton X-100 is non-ionic; when added to tap water there is no change in resistivity.

Other non-ionic, non-corrosive, relatively benign wetting agents are commercially available that may be suitable and used as substitutes for Triton X-100. JPL recommends that future wet insulation-resistance tests be performed using a solution of tap water combined with a 0.1% concentration of Triton X-100, or equivalent surfactant.