Experimental Determination of Potential Induced Degradation Acceleration Factors for Various Encapsulants, Test Conditions, and Installation Locations.

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Abstract

Several test protocols are in use for assessing the potential induced degradation (PID) resistance of solar modules; however, little information exists correlating the various testing conditions to time in the field. This work proposes a methodology for determining an acceleration factor which takes into account system operating voltage, the install site's prevailing weather, and the impact of conductive surface contamination. By carefully measuring module leakage current in an environmental chamber, a functional dependence upon temperature, humidity, system voltage, and surface contamination is determined for leakage current of a module for a defined bill of materials (BOM). This empirically determined function is coupled with TMY datasets and the Sandia/King PV Array Performance Model to predict leakage current within the field for various installation locations. Results are presented for a number of encapsulants, PID testing protocols, and installation locations. The draft IEC62804 test protocol is found to represent only 4 to 5 years of field deployment in Miami, Florida for modules using a standard EVA-based encapsulant having a conductive frame.

2. Experimental Setup

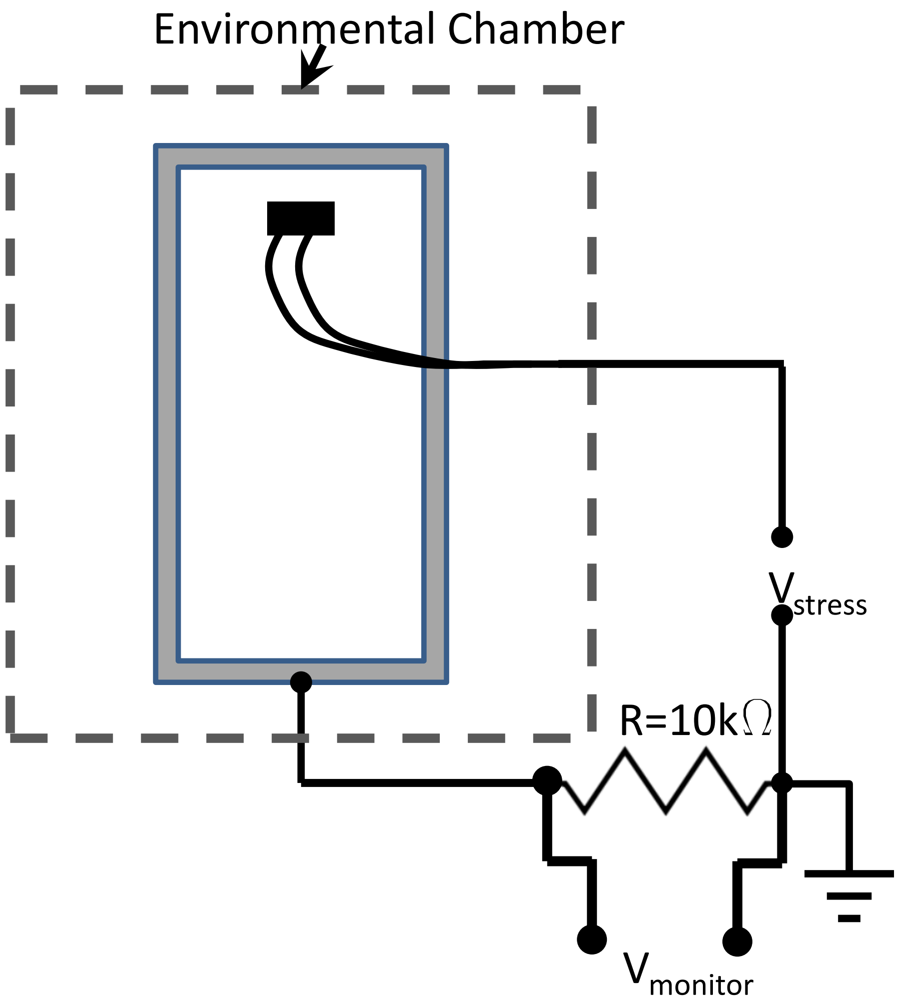


Figure 1: Schematic of leakage current measurement system

A module is placed in an environmental chamber so as to control module temperature and relative humidity. A Megger MIT 1025 Insulation Tester is used to supply V_{stress} between the solar cells and module frame and log the applied voltage (the MIT 1025 design allows either the negative or positive output to be tied to ground depending upon the bias you wish to place on the solar cells and has a maximum current limit of 300 µA). The voltage drop across the 10 kΩ monitor resistor is used to determine leakage from cells to frame; this voltage drop, module temperature and relative humidity is logged using an Agilent 34970A Data Acquisition control unit with 34901A, 20 Channel Multiplexer Module. This setup allows the leakage current to be measured under any desired exposure.

3. Experimental Procedure: Map Leakage

The leakage current from the solar cell to the module frame is logged while the temperature, relative humidity, bias, and surface contamination state are varied according to the sequence below:

1. Set applied bias to 400V, RH=25%
    a) Ramp temperature from 25°C to 85°C at a20°C/hr ramp rate
    b) Hold at 85C for 10 minutes while incrementing humidity by 10% absolute
    c) Ramp down temperature from 85C to 25C at a 20C/hr ramp rate
    d) Hold at 25C for 10 minutes while increasing humidity 10% from its current setting.
    e) Repeat steps ‘a’ thru ‘d’ until a temperature transition at 85% RH has been completed (temperature transitions should be completed at 25%, 35%, 45%, 55%, 65%, 75%, 85% RH)
    f) Reset temperature and humidity to 25C/25% RH
    g) Increase applied bias to 600V and repeat steps ‘a’ thru ‘f’
    h) Increase applied bias to 1000V and repeat steps ‘a’ thru ‘f’
2. Reduce applied Voltage to zero; remove module from chamber and saturate with 5% NaCl by weight aqueous solution; allow module to dry (module will now be coated with a salt crust); reload module into test apparatus and repeat Step 1 ‘a’ thu ‘h’

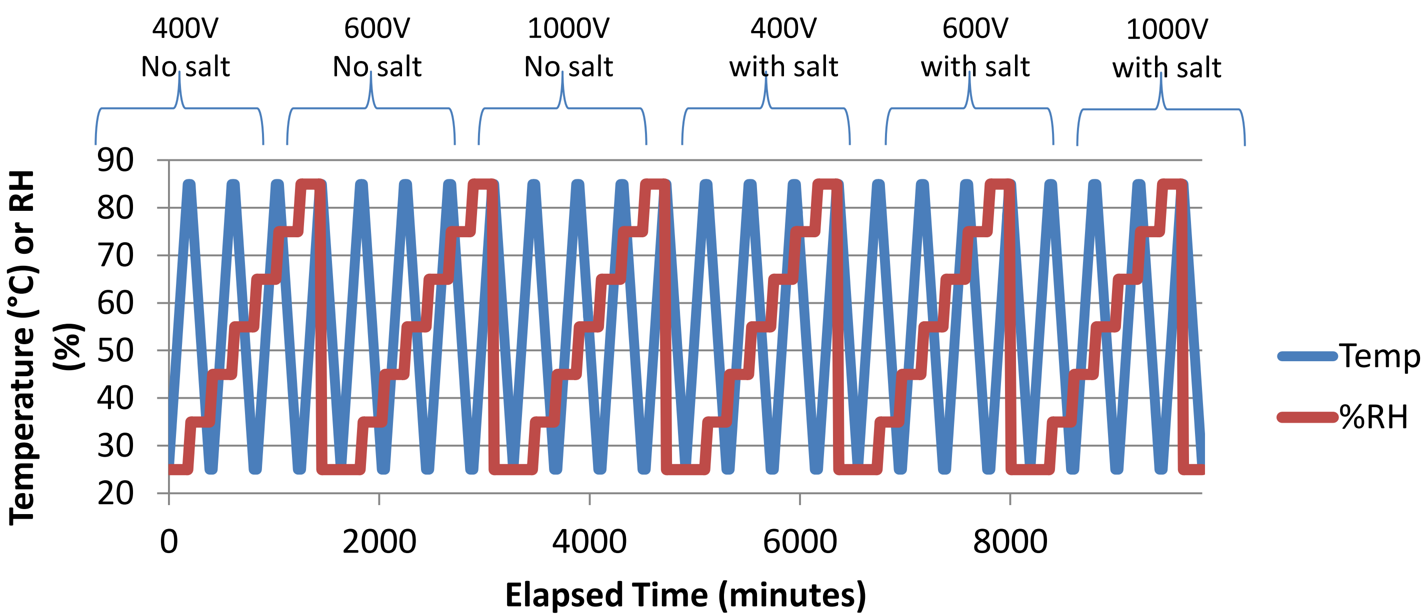


Figure 2: Temperature, humidity, voltage, and surface contamination profile applied to module during leakage current mapping

Figure 3 shows a subsection of the collected data that is used to perform an empirical fit that relates temperature, humidity and voltage to leakage current from a module. Data shown is for a 60 cell module 1.650m x 0.992 m in size.

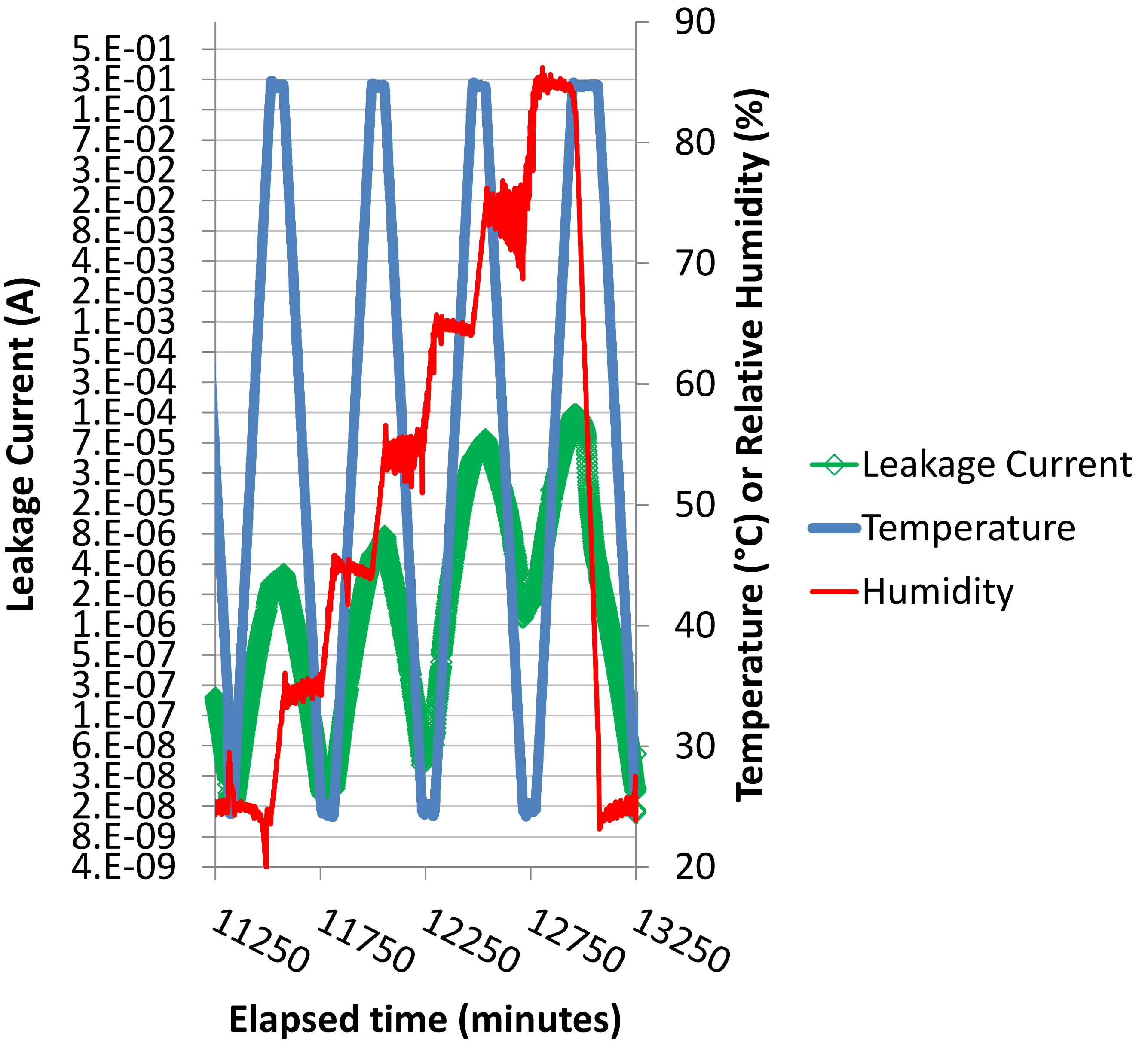


Figure 3: Measured Leakage Current for module with V_{stress}= –600V and surface encrusted in salt

4. Regression Fit

Once data is collected for all voltage, temperature, humidity, and surface contamination conditions, regression analysis is used to determine the best fit to the following predictive form:

$$\ln(I) = C_1 \ln(RH) + C_2 \frac{1}{T} + C_3 \ln(V) + C_4 S + C_0 \qquad \text{Eqn 1}$$

Where:

I ≡ leakage current in Amperes
RH ≡ relative humidity as fraction (0 to 1)
T ≡ temperature in Kelvin
V ≡ voltage between cells and frame in Volts
S ≡ surface salt factor which varies from 0 for no salt to 1 for completely salt encrusted,unitless
C_1 ≡ humidity regression coefficient
C_2 ≡ temperature regression coefficient
C_3 ≡ voltage regression coefficient
C_4 ≡ salt regression coefficient
C_0 ≡ constant

The regression coefficients C_1 thru C_5 are obtained via linear regression of the of the response, *ln(I)*, to the predictor variables *ln(RH)*, *1/T, ln(V)*, and *S*. The following table summarizes the results of the regression fit and provides values for the regression coefficients:

coefficient	*Value*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
C0	10.9777	0.103117	106	0	10.776	11.18
C1	2.65382	0.00987	269	0	2.6345	2.673
C2	-9213.9	20.39838	-452	0	-9254	-9174
C3	0.66051	0.012751	51.8	0	0.6355	0.686
C4	1.42123	0.010824	131	0	1.4	1.442

Regression Statistics	
Multiple R	0.953962
R Square	0.910044
Adjusted R Square	0.910031
Standard Error	0.686225
Observations	27641

5. Using the Fit to Predict Leakage

Equation 1 above, we can now determine the leakage current under any conditions found in the field. Additional resources are required before this can be accomplished:

- Weather data files provide geographically specific irradiance, temperature, relative humidity information over the course of a typical year on an hour by hour basis:
  - http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm
  - http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
- Solar Performance Model (I have used the David King/ Sandia model): used to determine module system voltage and module temperature as a function of irradiance, wind speed, ambient temperature. Other commercially available software packages can also be used to generate this data (PVSYST, Maui)
- Translate relative humidity at ambient temperature from the weather data file to a relative humidity at the higher module surface temperature.

$$\%RH_{surface} = \%RH_{ambient} \frac{VD_{ambient}}{VD_{surface}} \qquad \text{Eqn 2}$$

Where:

$\%RH_{surface}$ ≡ relative humidity of air at module surface with a temperature different than the ambient air.
$\%RH_{ambient}$ ≡ relative humidity of ambient air
$VD_{ambient}$ ≡ saturated water vapor density of ambient air at a given air temperature
$VD_{surface}$ ≡ saturated water vapor density of air at a module surface temperature

The saturated vapor density of water vapor in air, VD, can be calculated over the temperature range of interest here using the following empirical fit for a give temperature T in Celsius (credit Hyperphysics) :

$$VD = 5.018 + 0.32321T + 8.1847\times10^{-3}T^2 + 3.1243\times10^{-4}T^3 \qquad \text{Eqn 3}$$

Now we have all inputs required to calculate the leakage current for a module in the field for an entire year. It is now a simple matter to calculate the cumulative charge transfer per year for a given installation location and string length.

6. Acceleration Factor

The Acceleration Factor, AF, for a given PID laboratory test condition is dependent upon the system installation location (i.e. weather conditions) and system design (i.e. string length). In fact, the acceleration factor for a deployed module is also a function of the fielded module's position within the DC string since this determines the modules voltage relative to ground.

AF of a given PID test protocol is given by the ratio of the average leakage during the test, $I_{test,}$ relative to the average leakage current over the coarse of one year in a given installation location and string position, I_{field}.

$$AF = \frac{\bar{I}_{test}}{\bar{I}_{field}} = \frac{\left(\exp\left[C_1 \ln(RH_{test}) + C_2 \frac{1}{T_{test}} + C_3 \ln(V_{test}) + C_4 S_{test} + C_0\right]\right)}{\left(\sum_{i=1}^{i=year} \Delta t_i \exp\left[C_1 \ln(RH_i) + C_2 \frac{1}{T_i} + C_3 \ln(V_i) + C_4 S_i + C_0\right]\right)\left(\sum_{i=1}^{i=year} \Delta t_i\right)^{-1}} \qquad \text{Eqn 4}$$

Where:

RH_{test} ≡ relative humidity of PID test protocol (0 to 1)
T_{test} ≡ temperature of PID test protocol in Kelvin
V_{test} ≡ applied voltage of PID test protocol in Volts
S_{test} ≡ surface contamination status of PID test protocol (0 for clean surface, 1 for conductive surface coating)

Δt_i ≡ time increment between datapoints in the annual weather file (typically one hour)
RH_i ≡ relative humidity at the module's surface during time interval ,i from 0 to 1 (adjusted from ambient RH)
T_i ≡ temperature of module's surface during time interval ,i ,in Kelvins (Sandia performance model calculation)
V_i ≡ voltage of module during time interval , i, in Volts (Sandia model calculation)
S_i ≡ surface contamination status of fielded module during time interval, i, (0 for clean surface, 1 for conductive)

The summations arise in Eqn 4 due to the need to calculated the average leakage current over one year; this is done by determining the total charge transfer over one year by summing the incremental charge transfer of each time interval and then normalize back to an average leakage current by dividing out by one year.

Please Note: Coefficients, C_0 thru C_4, are valid only for a given BOM and module size. Any modification to the module package which alters module insulation resistance or the temperature dependence of insulation resistance necessitates reestablishing the coefficients for the new material system.

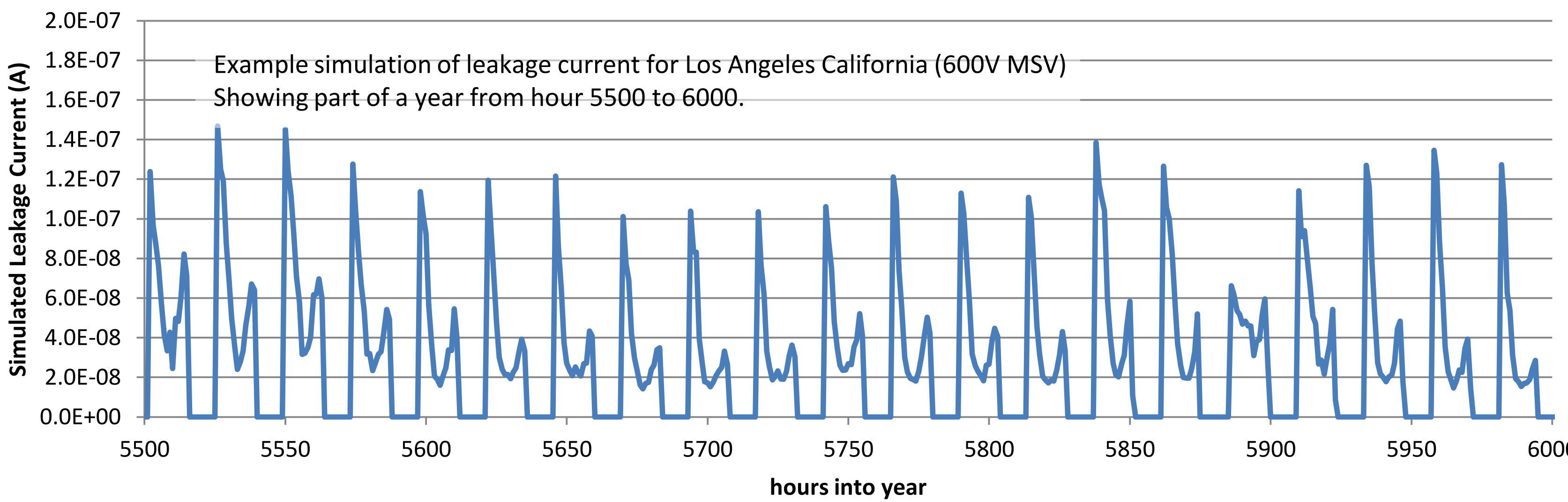
When using Eqn 4, evaluations during night will result in a calculation error because since V=0 and Ln(0) is negative infinity. However, simply assign these intervals zero current and/or charge transfer to maintain a physically accurate calculation.

6. Acceleration Factor (continued)

Table II: Calculated Acceleration Factors at Various US Cities for Two Common PID Test Conditions

city	state	Effective Leakage Current (A)	Acceleration Factor for 60°C/85%RH	Acceleration Factor for 85°C/85%RH
MIAMI	FL	4.2E-08	84	580
PHOENIX	AZ	4.2E-09	831	5741
WILMINGTON	DE	1.8E-08	191	1319
ANCHORAGE	AK	7.9E-09	445	3074
LOS_ANGELES	CA	1.7E-08	205	1418
BOULDER	CO	4.0E-09	868	5995

The table above applies to the highest voltage module in a string designed to maximum system voltage for the location in question. Results apply to typical glass/EVA/Backsheet modules with EVA having bulk resistivity of mid 10^{14} Ohm-cm.



7. Lab Data Compared to Field Data

Below shows EL images of test samples constructed using cells of known various PID resistance levels and for several different EVA types following a 4 day exposure to 60°C , 85%RH with -1000V applied between cells and frame. This exposure is equivalent to 2 years of field service in Delaware. These combinatorial samples allow for rapid evaluation of many cell and encapsulant types.

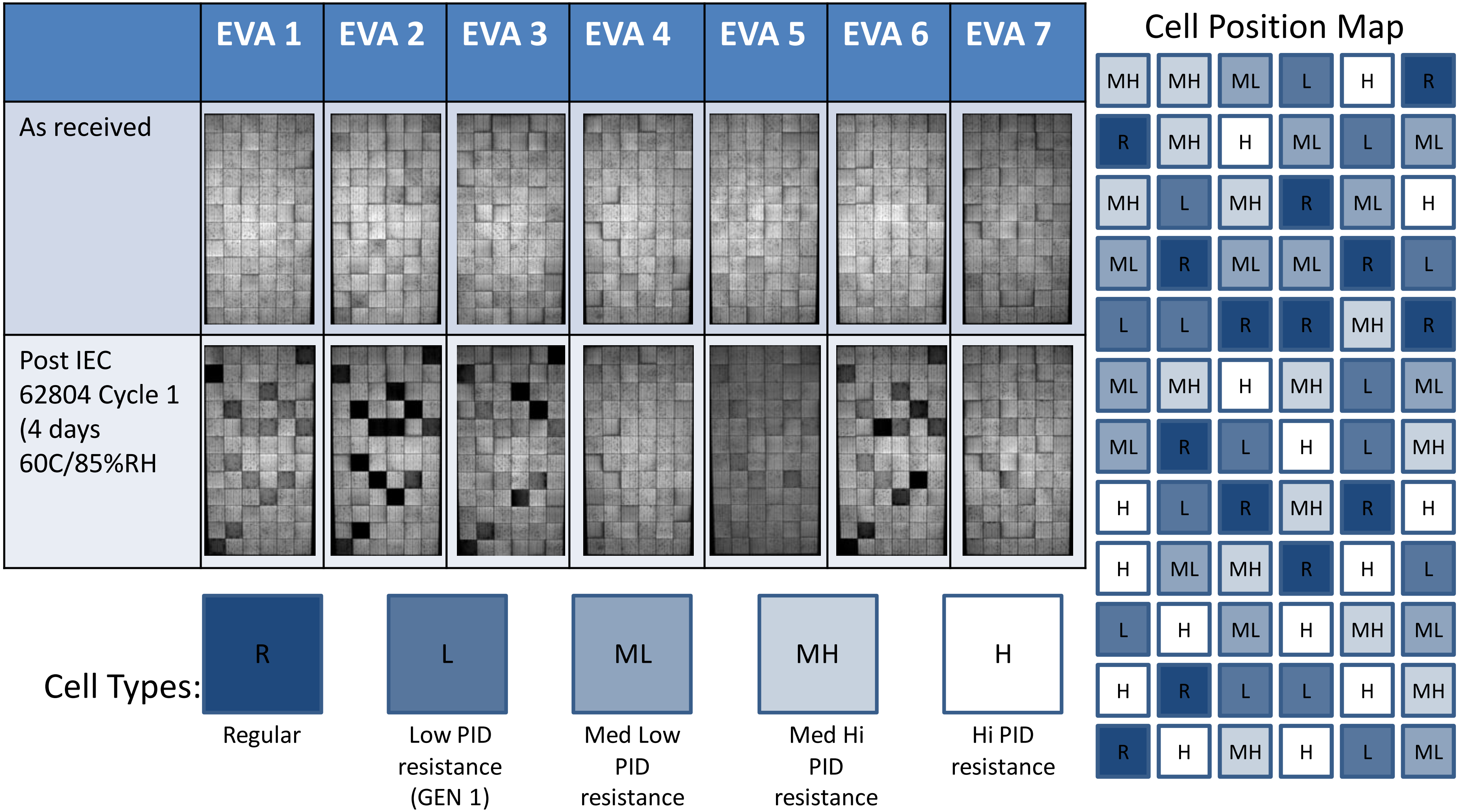


Figure 4: PID Laboratory test results at 60C/85% RH/-1000V for combinatorial modules

Individual cell characteristics dominate response to the system voltage stress.

7. Lab Data Compared to Field Data (continued)

After 2 years, fielded modules from the negative side of a bipolar array were collected from a Delaware site were collected from the negative side of a bipolar array designed to 600V MSV limitations. Samples were constructed of EVA 1 and cell type 'R' shown below in order of string position:

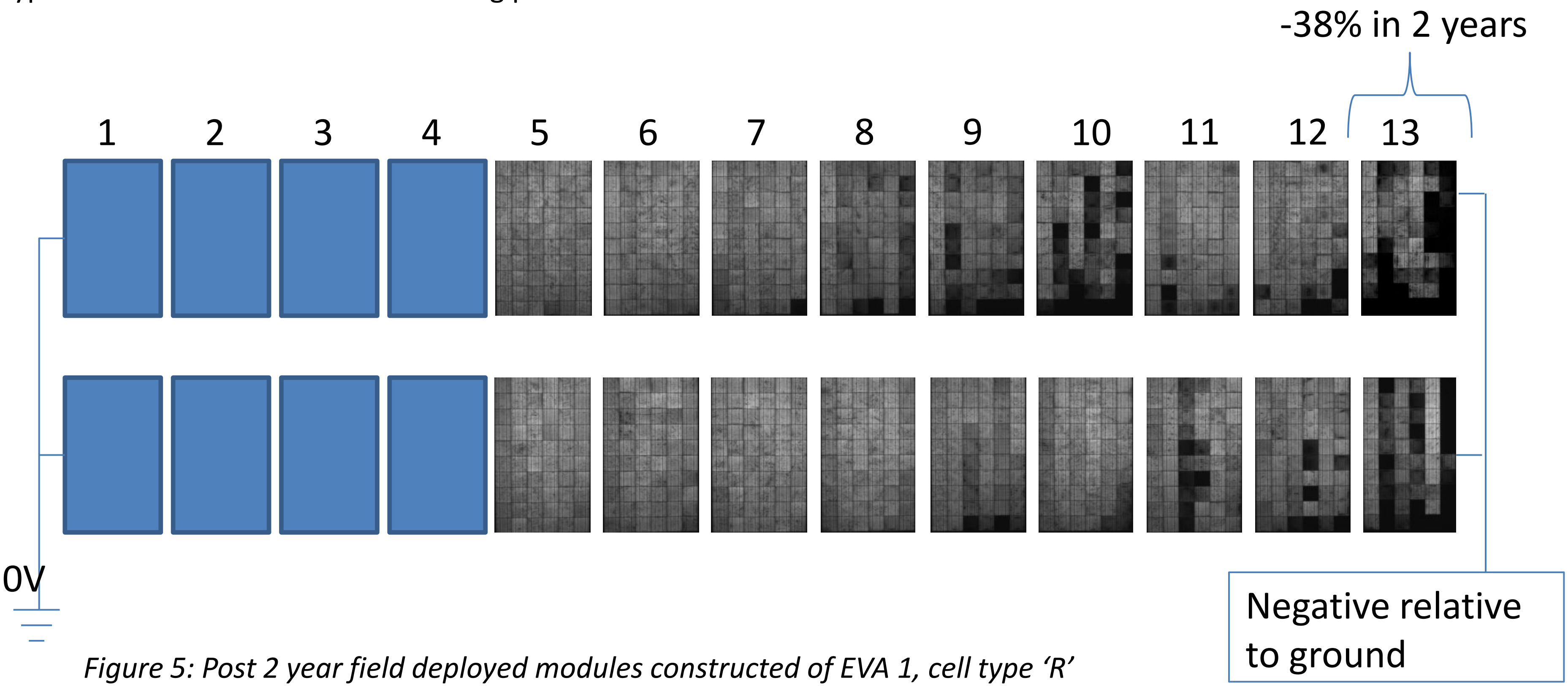


Figure 5: Post 2 year field deployed modules constructed of EVA 1, cell type 'R'

Note the general trend for increasing degradation at the far end of the string (i.e. as the applied voltage on the module is increased.) . Also note the similarity of the laboratory degradation shown in Figure 4 which should simulate the same field deployment as shown above.

Also note that the amount of degradation a solar cell experiences following exposure to the same amount PID stress is highly dependent upon the individual cell's characteristics.

8. Summary

•A laboratory methodology is presented to allow a module's leakage current under different environmental conditions to be mapped as a function of surface contamination, relative humidity, system voltage, and temperature.

•This response surface can be used to predict effective annual leakage rates from field deployed modules for various system designs and installation locations

•Since solar cells that are susceptible to system voltage degradation will degrade proportionally to the amount of leakage current (for negatively biased portions of a string), an acceleration factor can be determined from the ratio of leakage current of the laboratory test condition to the effective annual field leakage.

•An extremely wide range of acceleration factors are shown to exist within the USA for the draft standard IEC 62804 test conditions ranging from 84 for Miami, Florida to 831 for Phoenix, Arizona. This order of magnitude variance delineates the paramount importance of being able to relate laboratory test conditions back to field conditions.