TOPICS IN ELECTROCHEMICAL DEGRADATION OF PHOTOVOLTAIC MODULES

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Topics

• The relationship between leakage current and electrochemical degradation
  • Positive and negative polarity
  • Dependence on temperature and humidity

• Leakage-current response mechanisms
  • Experimental observations
    • The effect of non-metallized substrate films
    • The effect of cell-frame gap dimension
    • The effect of applied voltage magnitude
    • The effect of ionic ion mobility
  • Physical deductions

• Laboratory-field equivalence -- acceleration factors
  • Module life prediction
  • Module (electrochemical) qualification test
The Relationship Between Leakage Current and Electrochemical Damage

• Cell string and frame behave as opposite-polarity electrodes; the intervening potant behaves as a solid-state electrolyte

• Module leakage current increases with increasing temperature and relative humidity

• Observed and electrically measured electrochemical damage increases with increasing accumulated charge transfer

Electrochemical Damage: Positive and Negative Polarity

■ Positive polarity
  • Metallization dissolution and migration (from cell to frame)
  • Cathodic dendrite formation (from frame to cell)
  • Evolution of gas at cathode (frame)

■ Negative polarity
  • Evolution of gas at cathode (cell) between metallization and silicon substrate -- metallization delamination
  • Formation of corrosion salts at anode (frame)

■ Both polarities
  • Reduction of cell power output
  • Increase in cell series resistance
Power Reduction and Series Resistance vs Time,
Showing Effects of Polarity and Non-Metallized Substrate Films
Influence of Electrochemical Damage on Cell I-V Performance

$I_C = 0.67 \text{ A}$  
$R_{SH} = 2.75 \Omega$

$I_C = 1.03 \text{ A}$  
$R_{SH} = 3.05 \Omega$

$I_C = 1.154 \text{ A}$  
$R_{SH} = 2.23 \Omega$

$P_{mp} = 313.6 \text{ mW}$

$P_{mp} = 222.5 \text{ mW}$

$P_{mp} = 142.2 \text{ mW}$

$R_s = 0 \Omega$

$R_{sh} = 0 \Omega$

$R_{sh} = 0 \Omega$

PRE TEST

AFTER 99 hs

AT 70°C 98% RH.

500V
Observed Current Paths

- Metallization ions follow electric field lines

- Metallization ions often proceed to, and then along, interfacial surfaces

Current Response for Small-Gap Samples and the Effect of Non-Metallized Polymer Substrate Films

![Graph showing current response and the effect of non-metallized polymer substrate films.](image_url)
Current Response for Large-Gap Sample

Ac PRINT CELL, AI FRAME, PVB, 500 MIL GAP (70°C/85% RH, 500 V)

Current Response of Minimodules, Comparing PVB and EVA Encapsulants

85°C/85% RH, 500 V
Physical Deductions

- At large cell-frame gaps and/or low voltages, capacitive charging and polarization currents are absent because
  - Interelectrode capacitance is small
  - Electrode forces on interelectrode dipoles are weak
- Equilibrium current is independent of gap, other things being equal, because of the relatively low-resistance surface-active paths
- The magnitude of the equilibrium current is directly proportional to the pottant volume conductivity (actually, ion mobility) along paths in the bulk of the pottant
- Independent of voltage breakdown considerations, substrate polymer films provide higher surface resistance paths, hence lower equilibrium current levels

Electrochemical Damage: Laboratory-Field Equivalence

- Assumption: Equal quantities of charge transfer in the field and test environments produce equivalent amounts of electrochemical degradation
- Ohm's law: \( Q = IT = V \cdot (\sigma T) \cdot (\text{geometric terms}) \)
- Field time in years equivalent to \( T \) hours at test conditions:

\[
Y_{EQ} = \frac{Q_T}{Q_F} = \left( \frac{V_T}{V_F} \right) \frac{\left( \sigma_T \right)_T}{\left( \sum \sigma_i \right)_F} \cdot \left( \frac{\tau_i}{\tau_F} \right)
\]

- Ratio of test to field conductivity
- Time product
- Test to field voltage ratio
- Test to field charge transfer unit

- Field values are based on yearly compilations from reduced SOLMET weather data
Test Chamber Time: Equivalent To 30 Years In The Field

CHAMBER HUMIDITY (R.H.)

CHAMBER TEMPERATURE (°C)

10^0 10^1 10^2 10^3 10^4 10^5

MIA MIA
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Test Chamber Time $\tau$ Equivalent to 30 Years in the Field: EVA

Original page is of poor quality.
Module Life Prediction

- Median cell failures are experimentally determined to occur with the passage of about $Q_T = 1 - 2$ C/cm of charge between cell and frame.

- Median time to cell failure is $T_M = \frac{Q_T}{Q_F}$.

- Calculate charge transfer in the field, $Q_F$, using known dependencies on $T$ and $RH$ and SOLMET weather data.

- Assume a log-normal distribution of cell failures.

- Calculate average module field failure rate.
  - Without replacement (23rd PIM)
  - With replacement (this PIM)

Power Output Reduction vs Accumulated Charge Transfer
Module Failure Rate vs Time for 4 × 4-ft-Square-Celled Modules at Miami

Conclusions

- Calculated failure rates for unprotected PVB modules exceed allocation levels
- Failure rates for EVA modules fall within allocation guidelines
- Added mathematical rigor engendered by considering that replacement minimally impacts computed module failure rate results
Block V Qualification Test Temperature-Humidity Profile

Electrochemical Qualification Test Results: 500 Vdc, 85°C/85% RH for 20 h, -40°C for 4 h, 10 24-h Cycles

<table>
<thead>
<tr>
<th>Sample</th>
<th>Polarity</th>
<th>Metallization</th>
<th>Encapsulation</th>
<th>Foil?</th>
<th>Q200, C/cm</th>
<th>PIP, W</th>
<th>MIL*</th>
<th>Miami, yr*</th>
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<tr>
<td>MO 5107</td>
<td>P</td>
<td>Pd/Ni-solder</td>
<td>PVB</td>
<td>Y</td>
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</table>

* Values in last column assume that foil modules are water-free (temperature acceleration only) and that non-foil modules instantly track the environmental temperature and humidity.
Conclusions

- An equivalence relationship for electrochemical degradation, based upon equal charge transfer levels, establishes a correspondence between years in the field and hours in an accelerated stress test chamber.

- Adding voltage to the Block V temperature-humidity test provides an electrochemical qualification test of modules:
  - Equivalent to 1 to 2 years for foil-back modules
  - Equivalent to 4 to 80 years for non-foil-back modules
  - Equivalent field years are inversely proportional to the test voltage.

- Temperature acceleration ratios are similar for a wide variety of module constructions and materials (factor of 2 per 10°C).

- Humidity acceleration ratios vary considerably (40 to 1), depending upon module construction and materials.

Summary and Conclusions

- The extent of electrochemical damage is dependent on the integrated leakage current.

- PV electrochemical degradation mechanisms in the two polarities are different:
  - Degradation rates in the two polarities are of the same order of magnitude.
  - Center-tapped grounded arrays appear to be a preferred system configuration to minimize electrochemical degradation.

- There is encouraging agreement between theory and experiment in regard to leakage current response to applied voltage, gap magnitude, and encapsulant ion mobility.
Summary and Conclusions (Cont’d)

- Path resistance considerations suggest the use of thicker pottant layers and polymer substrate films to reduce equilibrium leakage current values
  - A metallized substrate layer, if used, should be isolated from the pottant and the frame by polyester layers
  - EVA modules appear to be consistent with 30-year-life allocation levels for electrochemical damage

- Temperature acceleration factors are well behaved and moderately well understood; humidity acceleration factors vary radically with module construction and materials and require additional research

Additional Work Required to Finalize Understanding of Photovoltaic Electrochemical Corrosion

- Quantify temperature-humidity dependency of equilibrium leakage currents
- Quantify temperature-humidity levels of encapsulants in fielded modules
Leakage Current Response Mechanisms

Current response characteristics

A → Water absorption current (impurity ion removal)
B → Capacitive charging current
C → Polarization currents (polymer and water dipoles)
D → Equilibrium ion current (metallization ion diffusion)