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 pottant 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 pottant 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

- CELL POSITIVE
- CELL NEGATIVE

○ WITHOUT BACKSHEET
■ WITH BACKSHEET

TIME, h
Influence of Electrochemical Damage on Cell I-V Performance
Observed Current Paths

- Metallization ions follow electric field lines

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

- Metallization ions often proceed to, and then along, interfacial surfaces
Current Response for Large-Gap Sample

Current Response of Minimodules, Comparing PVB and EVA Encapsulants
Physical Deductions

- At large cell-frame gaps and/or low voltages, capacitive charging and polarization currents are absent because
  - Electrode 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: \( Q = I_T = V \cdot (\sigma_T) \cdot (g_{\text{netric terms}}) \)
- Field time, in years equivalent to \( T_T \) hours at test conditions:
  \[
  Y_{\text{EQ}} = \frac{Q_T}{Q_F} = \left( \frac{V_T}{V_F} \right) \frac{(\sigma_T)_T}{(\sum \sigma_i T_i)_F}
  \]
  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

![Graph showing the relationship between test chamber time and chamber humidity (RH)]

*Note: The graph illustrates the effect of chamber humidity on test chamber time, with different temperatures represented by various lines. The graph is used to determine the equivalent test chamber time for products in the field.*
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 $Q_T = 1 - 2 \text{ C/cm}$ 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
RELIABILITY PHYSICS

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>Metal Substrate</th>
<th>Q200, C/cm</th>
<th>PIP, %</th>
<th>HIL, %</th>
<th>Equivalent 500-V Field Exposure Miami, yr*</th>
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<tr>
<td>MO 5107</td>
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<td>Pd/Ni-solder</td>
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* 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 potting layers and polymer substrate films to reduce equilibrium leakage current values
  - A metallized substrate layer, if used, should be isolated from the potting 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)