TOPICS IN ELECTROCHEMICAL DEGRADATION OF PHOTOVOLTAIC MODULES

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Topics

- The relationship between leakage current and electrochemical degradation
    - ositive 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
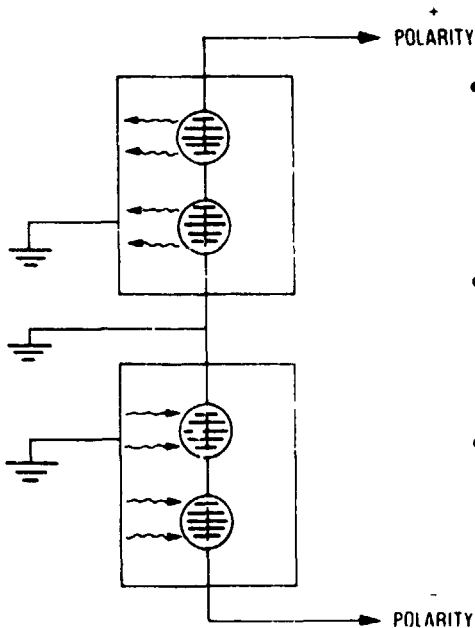
POLARITY

- 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

POLARITY

Electrochemical Damage: Positive and Negative Polarity

■ **Positive polarity**

- **Metallization dissolution and migration (from cell to frame)**
- **Cathodic dendrite formation (from frame to cell)**
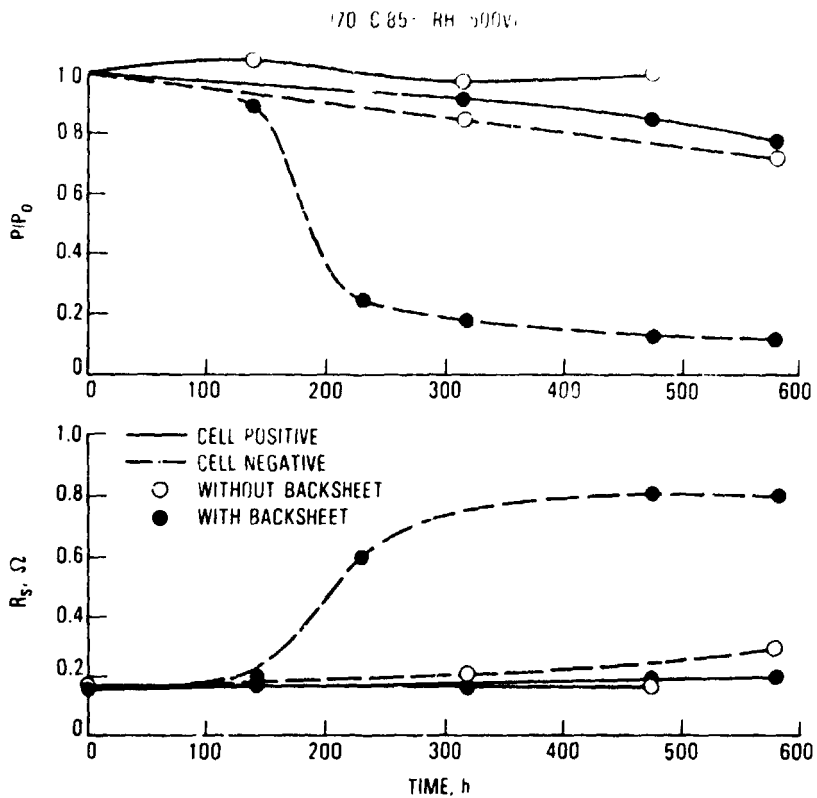- **Evolution of gas at cathode (frame)**

■ **Negative polarity**

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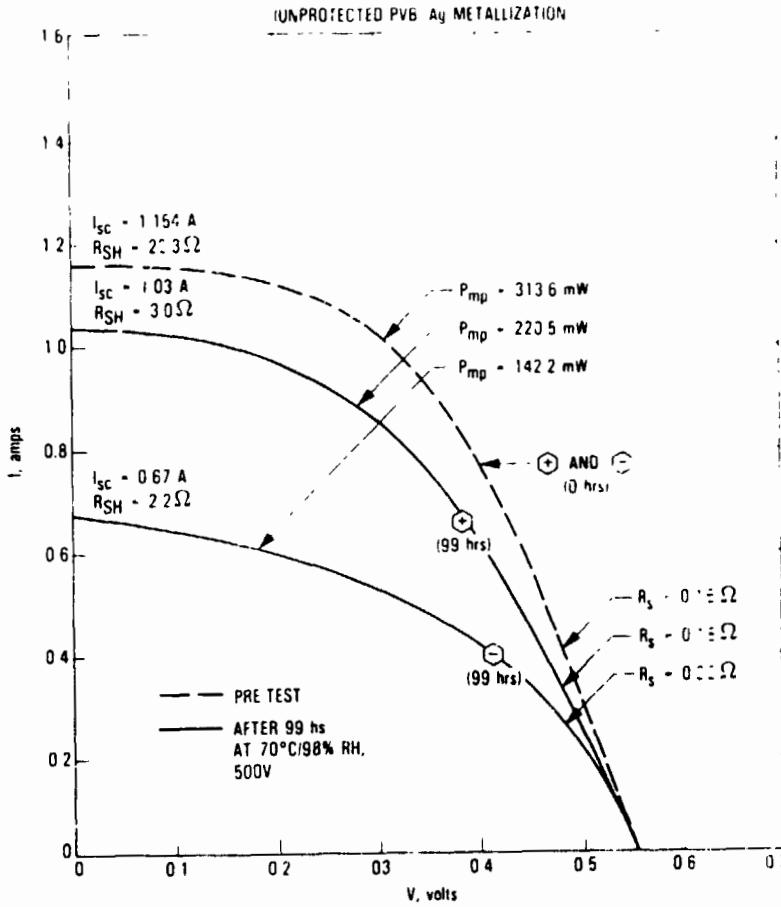- **Formation of corrosion salts at anode (frame)**

■ **Both polarities**

- **Reduction of cell power output**
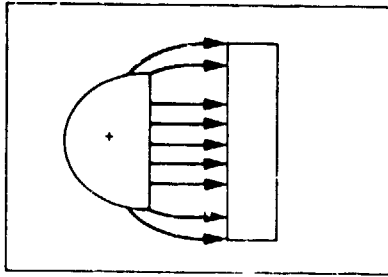- **Increase in cell series resistance**

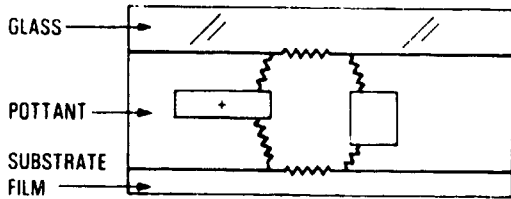# Power Reduction and Series Resistance vs Time, Showing Effects of Polarity and Non-Metallized Substrate Films

Influence of Electrochemical Damage
on Cell I-V Performance

(UNPROTECTED PV6 Ag METALLIZATION)

I_{sc} = 1 154 A
R_{SH} = 2C 3 Ω

I_{sc} = 1 03 A
R_{SH} = 3 0 Ω

I_{sc} = 0 67 A
R_{SH} = 2 2 Ω

P_{mp} = 313 6 mW

P_{mp} = 220 5 mW

P_{mp} = 142 2 mW

(+) AND (−)
(0 hrs)

(+)
(99 hrs)

(−)
(99 hrs)

R_s = 0 1 Ω

R_s = 0 1 Ω

R_s = 0 2 Ω

- - - PRE TEST
—— AFTER 99 hs
AT 70°C/98% RH,
500V

I, amps

V, volts

Observed Current Paths

- Metallization ions follow electric field lines

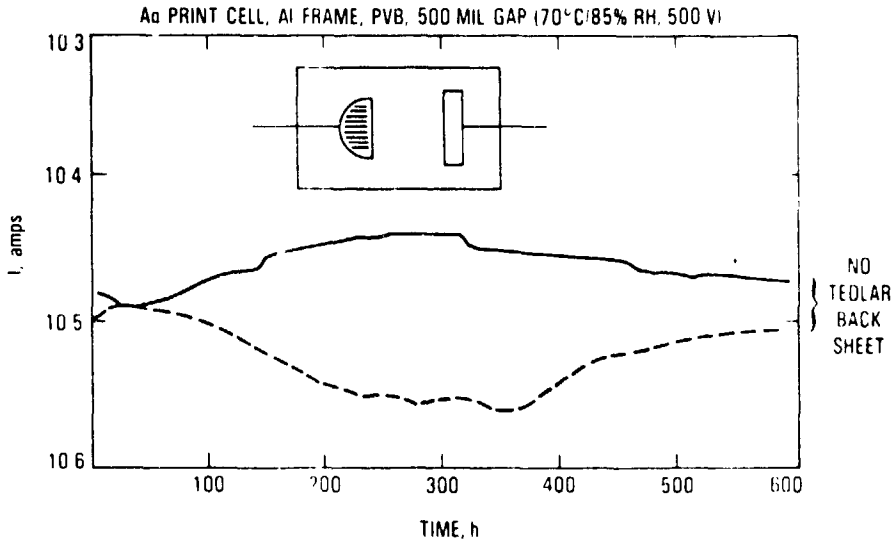GLASS

POTTANT

SUBSTRATE
FILM

- 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

Ag PRINT CELL, Al FRAME, PVB, 55-MIL GAP (70°C/85% RH)

500 V

NO
TEDLAR
BACK
SHEET

TEDLAR
BACK
SHEET

I, amps

TIME, h
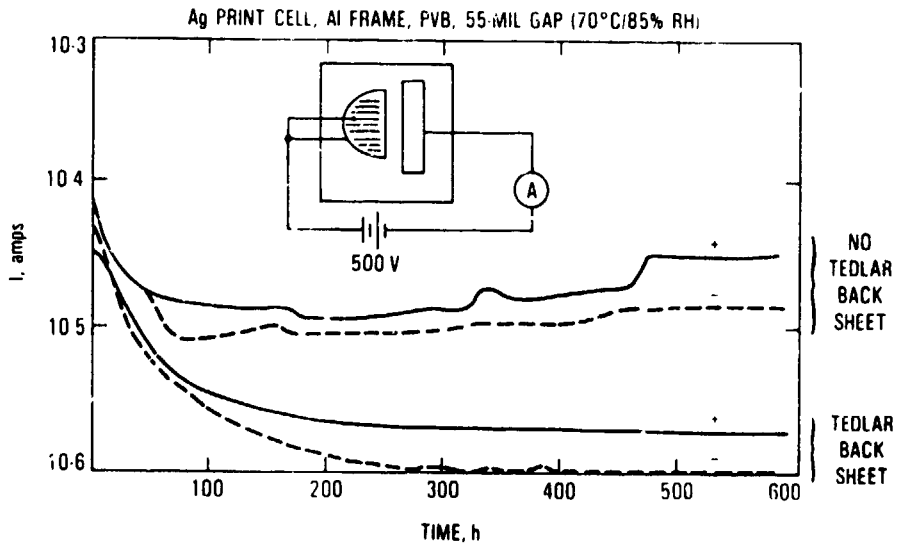
Current Response for Large-Gap Sample

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

Current Response of Minimodules, Comparing PVB and EVA Encapsulants
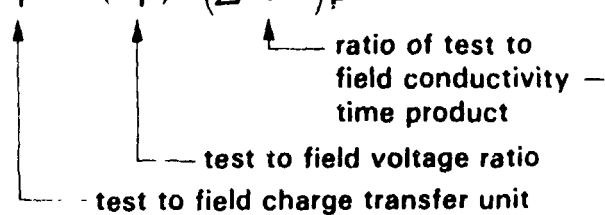
85°C/85% RH, 500 V
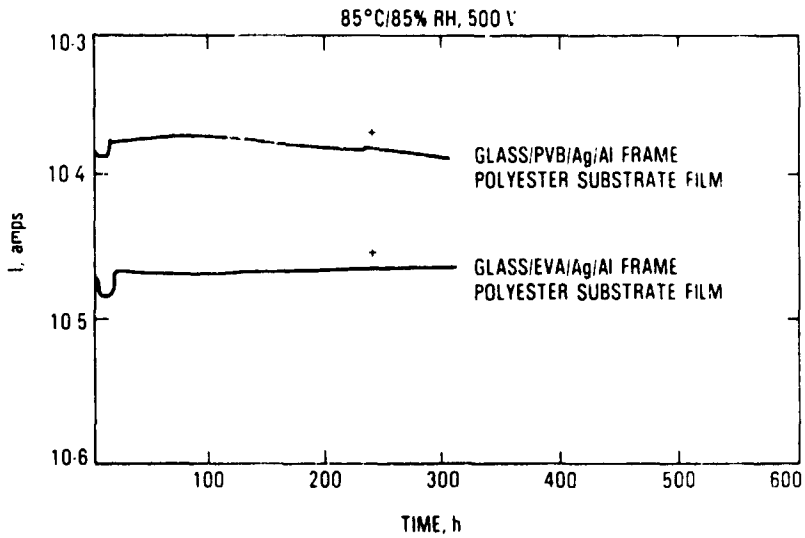
Physical Deductions

- 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

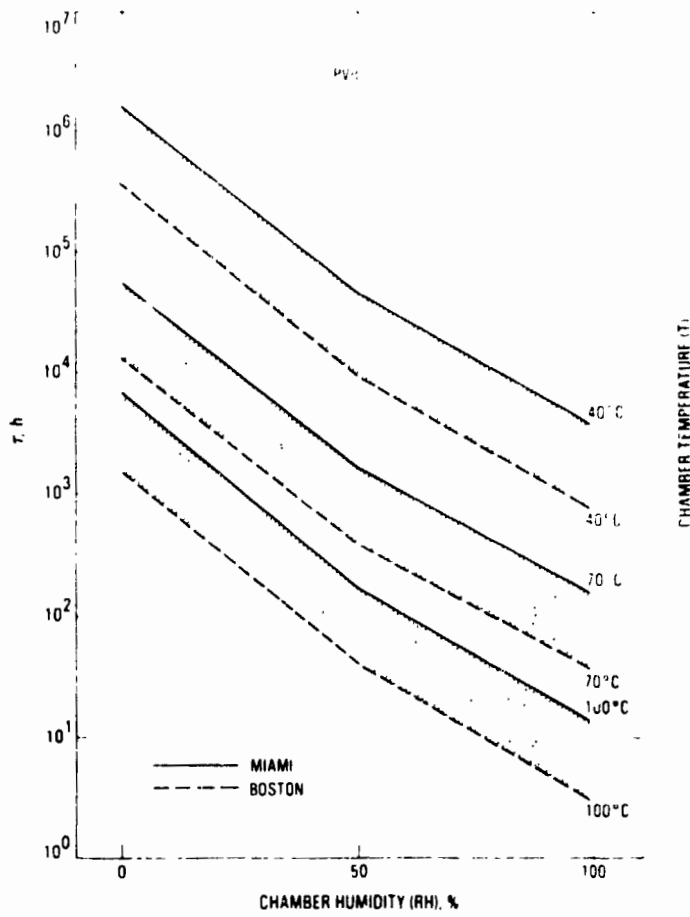## Electrochemical Damage: Laboratory-Field Equivalence

- Assumption: Equal quantities of charge transfer in the field and test environments produce equivalent amounts of electrochemical degradation

- Ohm's law: $Q = I\tau = V \cdot (\sigma\tau) \cdot$ (geometric terms)

- Field time in years equivalent to τ_T hours at test conditions:

$$Y_{EQ} = \frac{Q_T}{Q_F} = \left(\frac{V_T}{V_F}\right) \cdot \frac{(\sigma\tau)_T}{\left(\sum \sigma_i \tau_i\right)_F}$$

       ⌐— 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

## Test Chamber Time τ Equivalent to 30 Years
in the Field: EVA
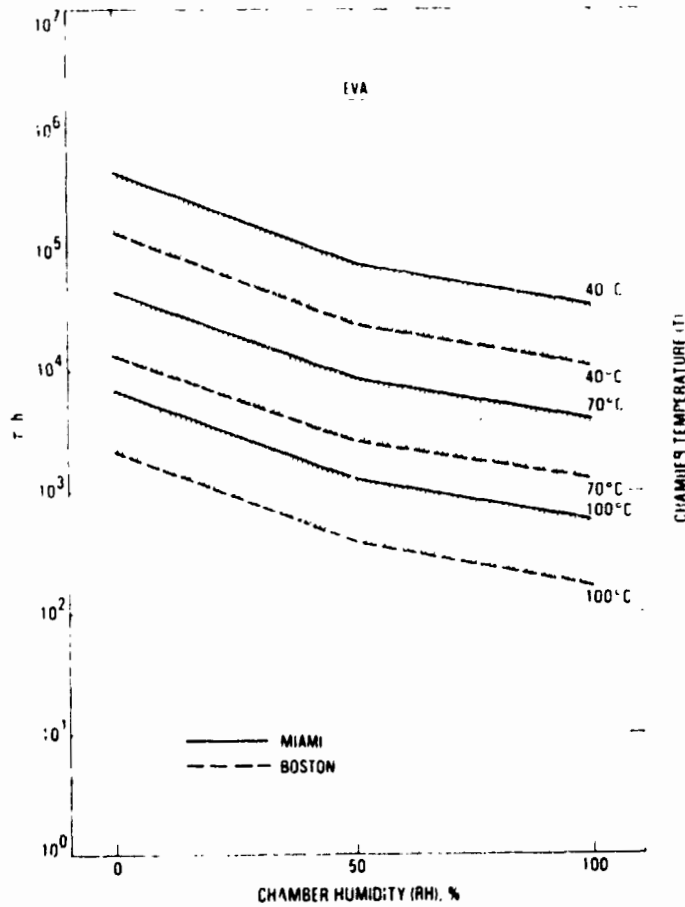
Module Life Prediction

- 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 $T_M = \dfrac{Q_T}{Q_F}$

  - 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
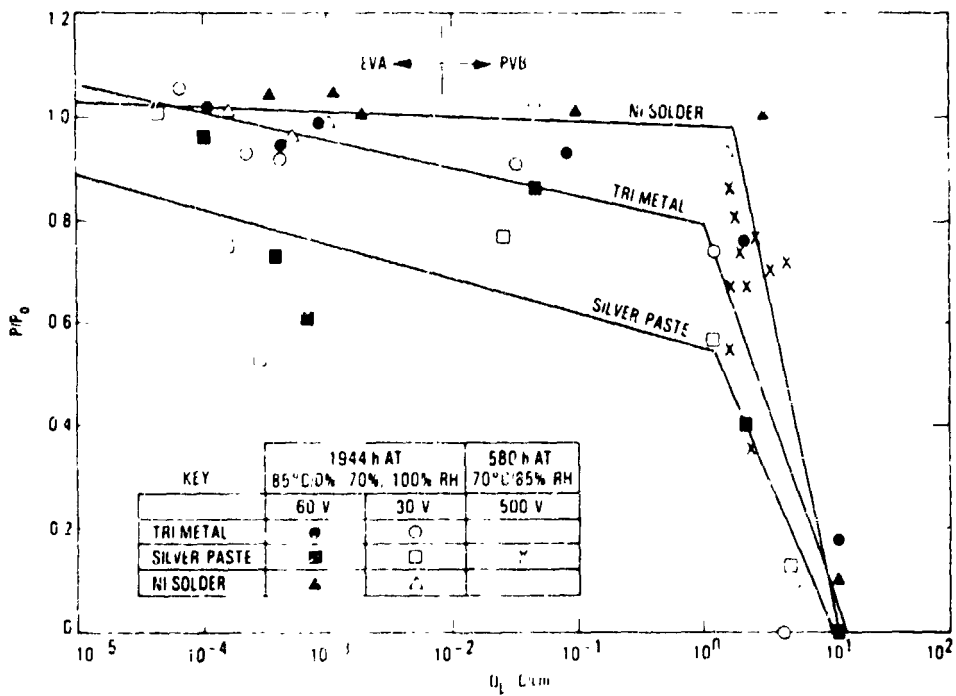
## Module Failure Rate vs Time for 4 × 4-ft-Square-Celled Modules at Miami
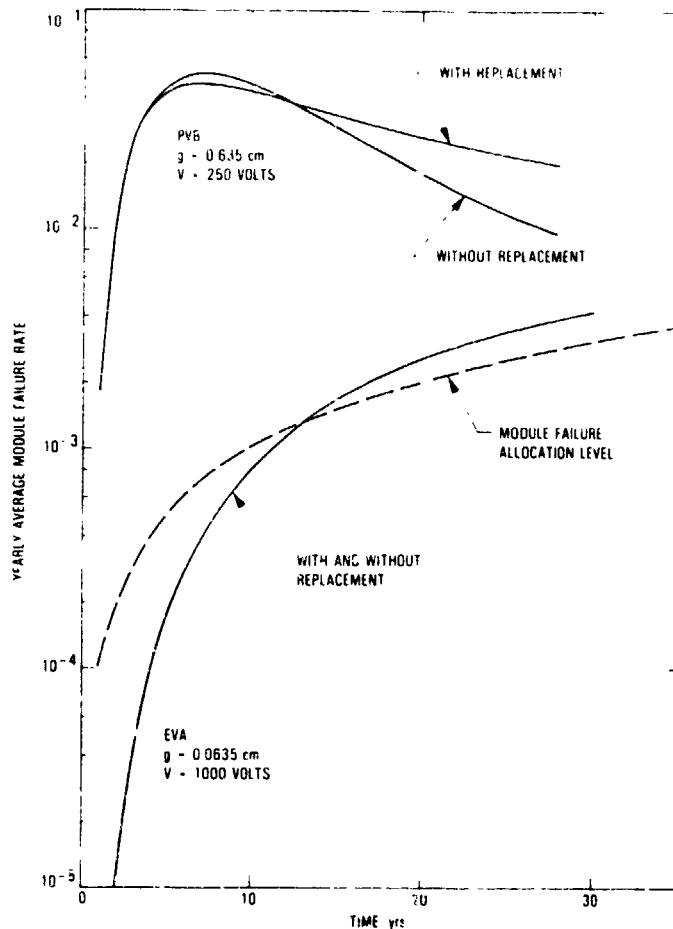
Conclusions

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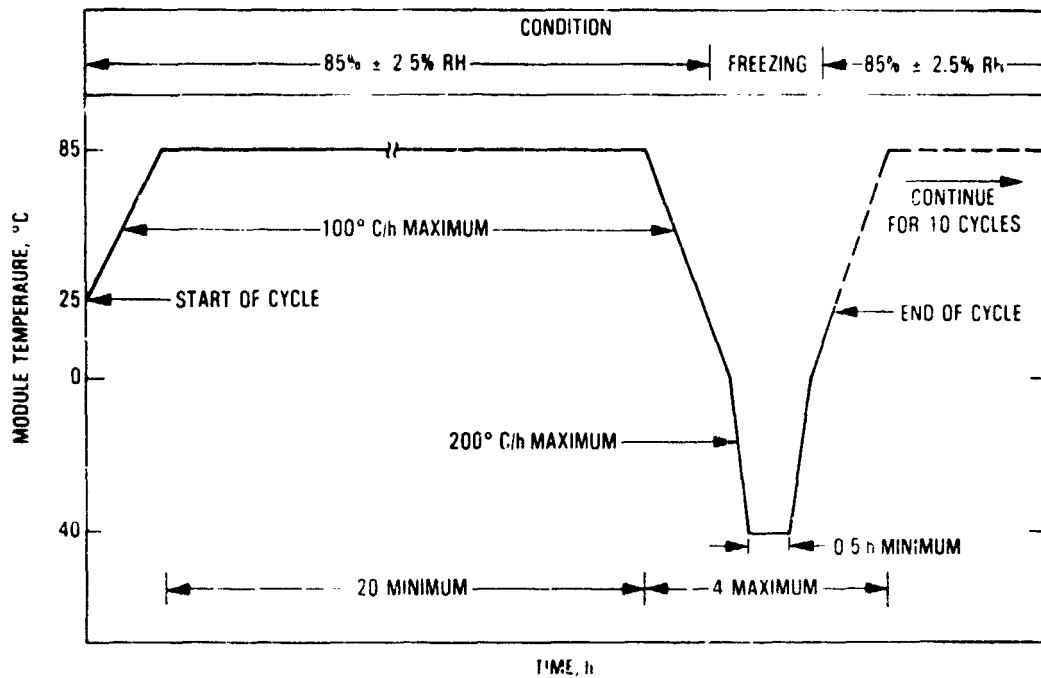
Electrochemical Qualification Test Results: 500 Vdc, 85°C/85% RH for 20 h, −40°C for 4 h, 10 24-h Cycles

Sample	Polarity	Metallization	Encapsulation	Metal Substrate Foil?	Q200, C/cm	P/P₀	I/I₀	Equivalent 500-V Field Exposure Miami, yr*
MO 5107	P	Pd/Ni-solder	PVB	Y	1.17	0.95	0.91	1.8
PW 5222	P	Ni-solder	PVB	Y	1.53	0.97	0.96	1.8
AS 200307	P	Print Ag	PVB	Y	3.61	0.96	0.96	1.8
AS 107461	P	Print Ag	PVB	N	2.91	0.17	0.32	84.0
MO 5117	N	Pd/Ni-solder	PVB	Y	0.737	0.79	0.97	1.8
PW 5224	N	Ni-solder	PVB	Y	0.0034	1.0	1.0	1.8
AS 200303	N	Print Ag	PVB	Y	0.181	0.99	1.01	1.8
AS 107449	N	Print Ag	PVB	N	1.41	0.88	0.94	84.0
MS 4887	P	Ni-Cu-Sn	EVA	Y	0.031	0.98	0.99	1.0
SP 58494	P	Ni-Sn	EVA	Y	0.072	0.93	0.98	1.0
SO 009	P	Print Ag	EVA	N	0.202	0.9	0.8	4.3
AS 022	P	Print Ag	EVA	N	0.534	0.96	0.97	4.3
MS 4954	N	Ni-Cu-Sn	EVA	Y	0.052	0.53	1.0	1.0
SP 58487	N	Ni-Sn	EVA	Y	0.006	1.06	0.98	1.0
SO 011	N	Print Ag	EVA	N	0.346	0.73	0.9	4.3
AS 021	N	Print Ag	EVA	N	0.205	0.94	0.96	4.3

* 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

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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
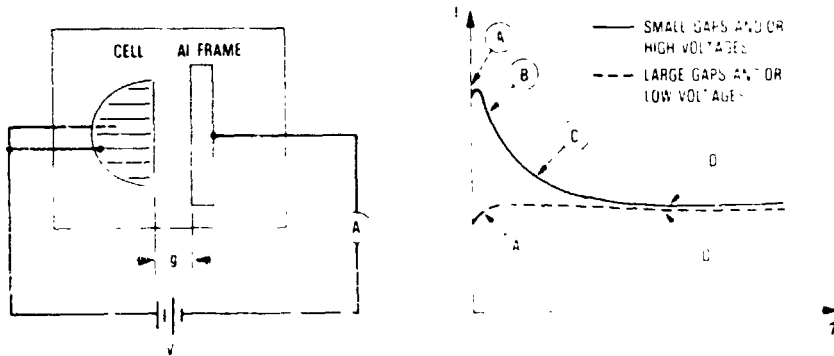
Current response characteristics

(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)