ELECTROCHEMICAL AGING EFFECTS IN PHOTOVOLTAIC MODULES

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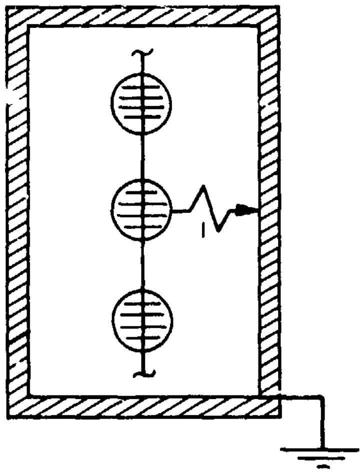
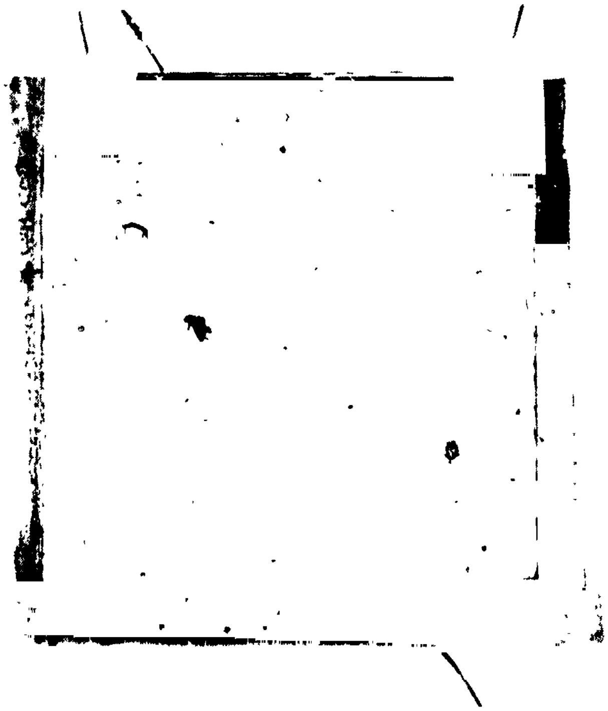
Electrochemical Corrosion of Photovoltaic Modules: A Review

- Cause of corrosion
  - Spurious ionic currents ("leakage currents") between cells and frame
- Corrosion damage
  - Crystalline Silicon
    - Dissolution and migration of metallization
    - Metallization delamination
    - Dendritic growths
    - Encloudment of encapsulation
- Amorphous silicon
  - Worming and pinholing of metallization and amorphous silicon layers



Typical Electrochemical Damage in Crystalline Silicon Modules

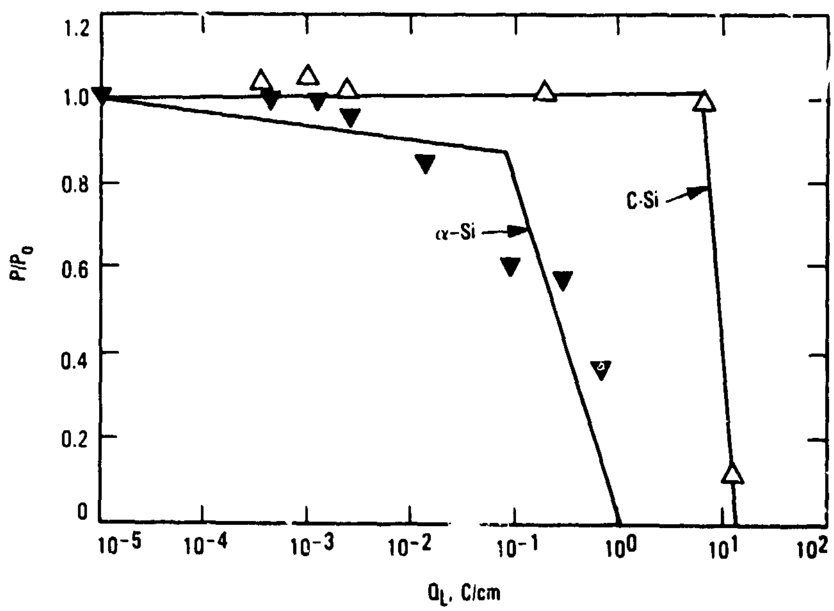
Typical Electrochemical Damage in Amorphous Silicon Modules



Quantifying Electrochemical Corrosion

- **Experimentally, it has been determined that 50% cell failures (>25% reduction in cell power output) occur after the passage between cell and frame of:**
  - **C-Si: 1.0 - 10.0 C/cm of cell-frame edge**
  - **A-Si: 0.1 - 1.0 C/cm of cell-frame edge**

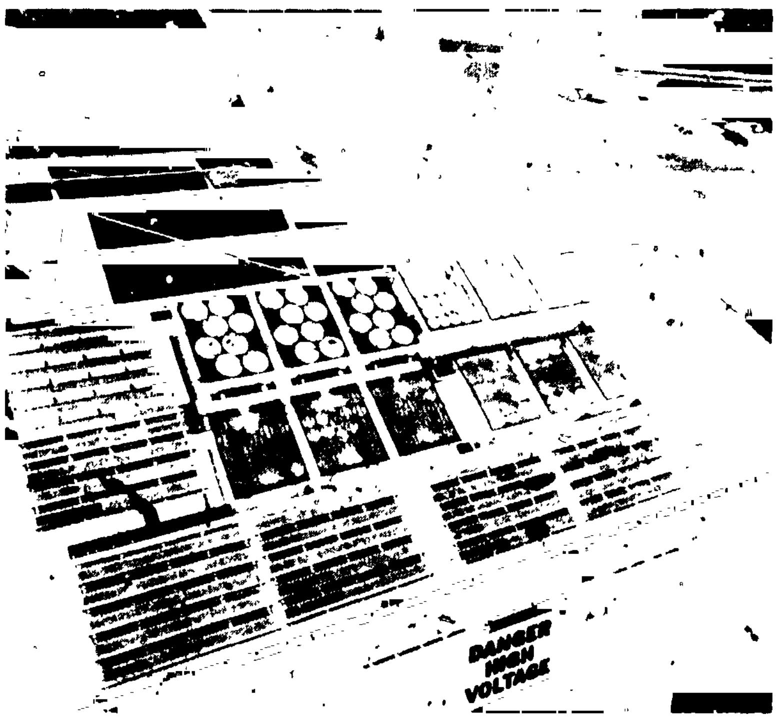
Comparison of Amorphous and Crystalline Silicon Cells for Power Output Versus Accumulated Unit Charge Transfer



Electrochemical Corrosion of Photovoltaic Modules: Present Research Focus

- **Quantify factors that determine module leakage current levels**
- **Determine dominant conduction paths in PV modules**
- **Create realistic analytical PV module conduction models**
- **Establish methods to:**
  - **Predict module life**
  - **Develop correlations between module behavior in controlled laboratory environments and field environments (acceleration factors)**

PVB-Encapsulated Modules Arranged on Outdoor Test Stand



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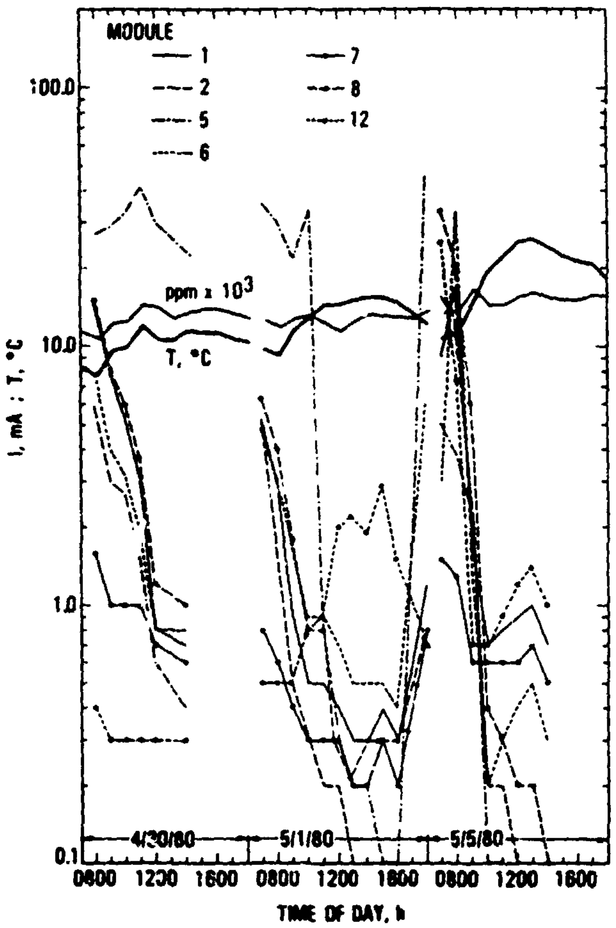
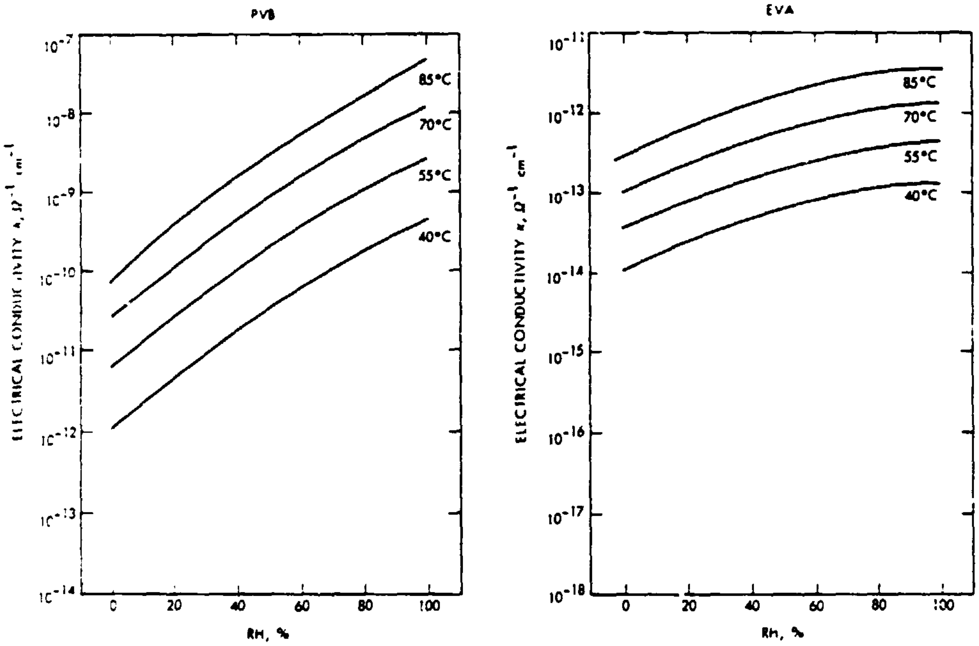
Outdoor Test Stand Data (Minimodules)



Observations on Outdoor Test Stand PVB-Minimodules

- Very high leakage current levels observed during periods of dew and precipitation
- Large current reductions observed as the modules "dried out"
- Sensitivities
  - Temperature: modest
  - Moisture: very large

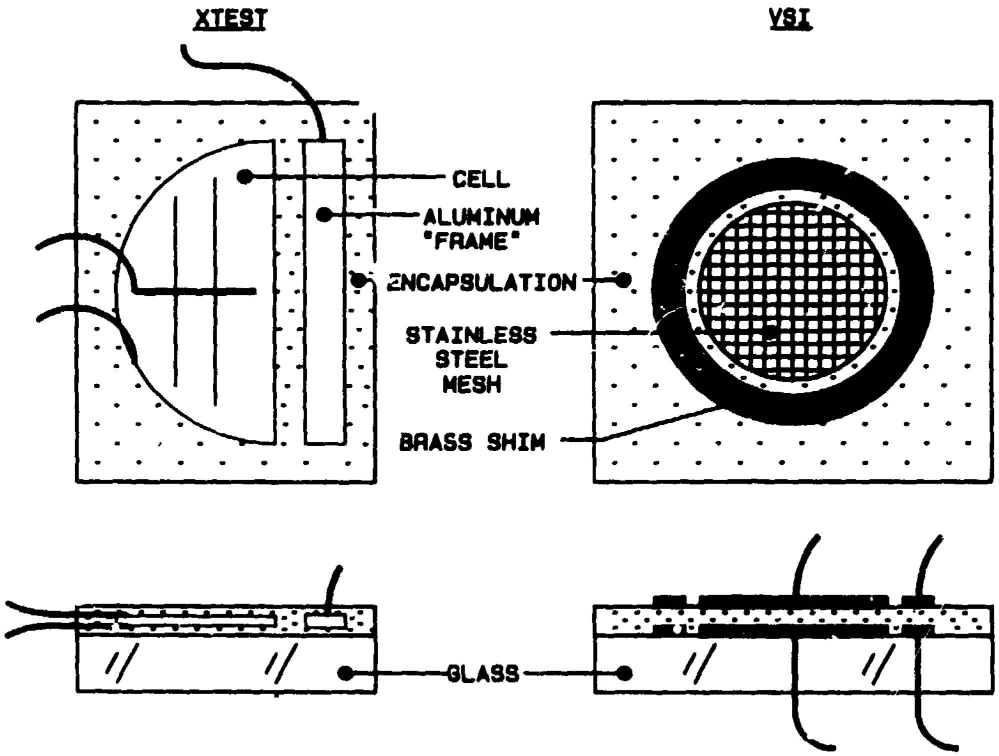
Bulk Conductivity of PVB and EVA



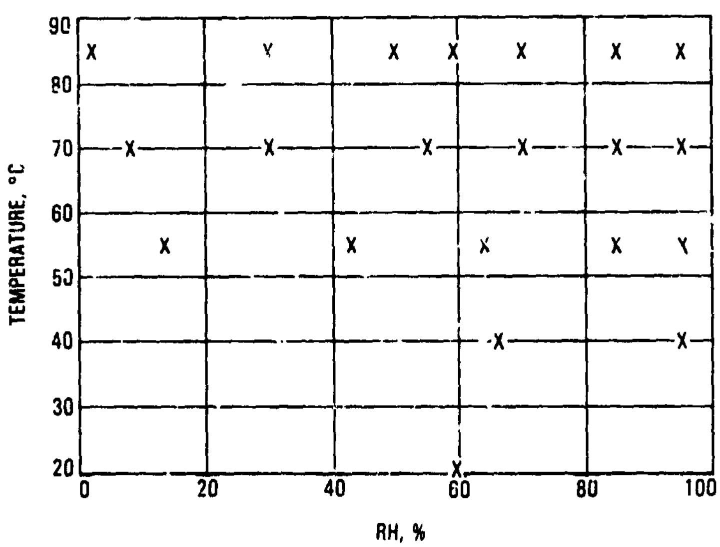
Experimental Program

- Controlled environment tests (equilibrium leakage current measurements over a broad range of constant T/RH-values)
  - VSI (encapsulated symmetric-electrode coupons)
    - Measure fundamental volume, surface, and interfacial electrical conductivities
  - XTEST (encapsulated cell-frame coupons)
    - Establish overall module leakage current levels
    - Determine charge transfer required to induce failure
- Field tests
  - Measure leakage current of VSI and XTEST samples previously characterized in T/RH chambers

Sample Configurations in Leakage-Current Test

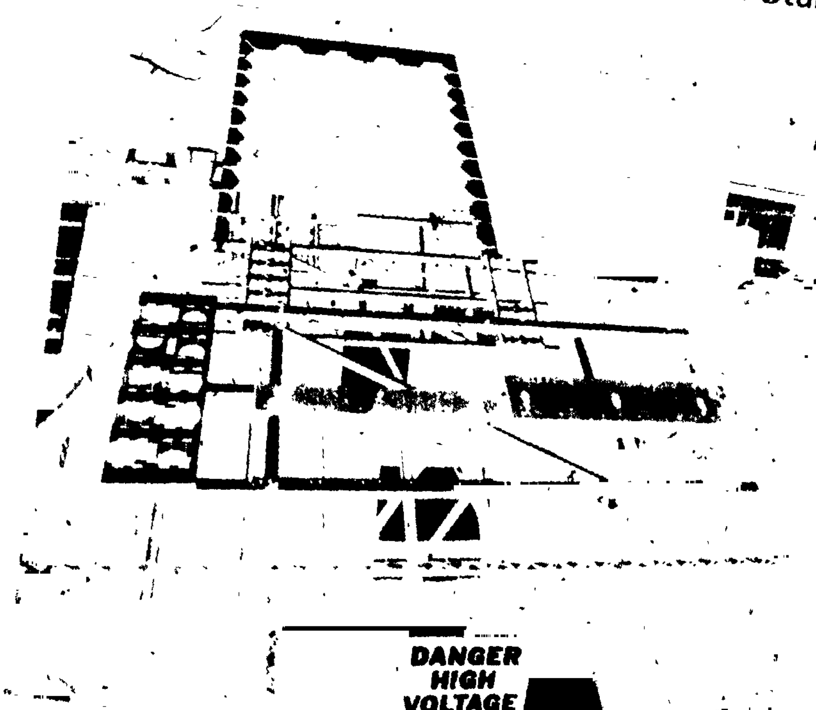


Temperature/Humidity Chamber Test Matrix



Samples Mounted in Laboratory Environmental Chamber

Overview of Outdoor High Voltage Test Stand



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XTEST Samples Mounted on Outdoor High Voltage Test Stand

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VSI Samples Mounted on Outdoor High Voltage Test Stand

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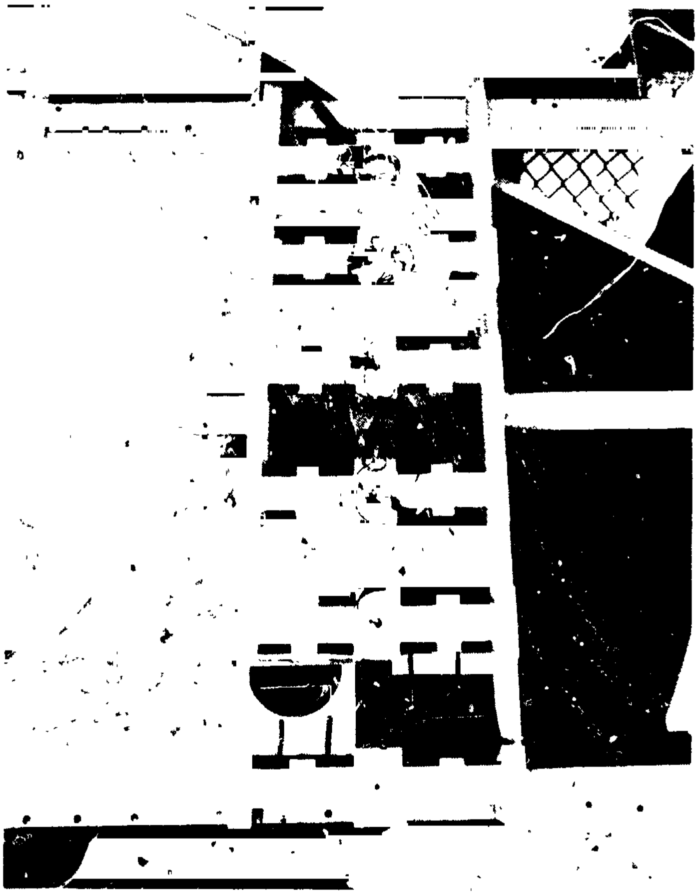
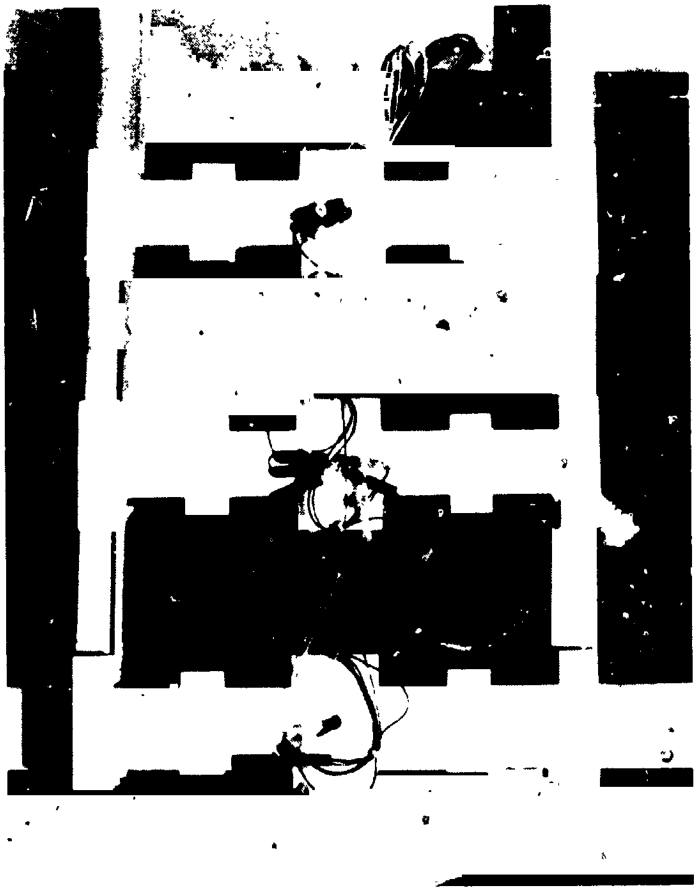
VSI Samples Mounted on Outdoor High Voltage Test Stand
(Note Delamination)



VSI Samples Mounted on Outdoor High Voltage Test Stand



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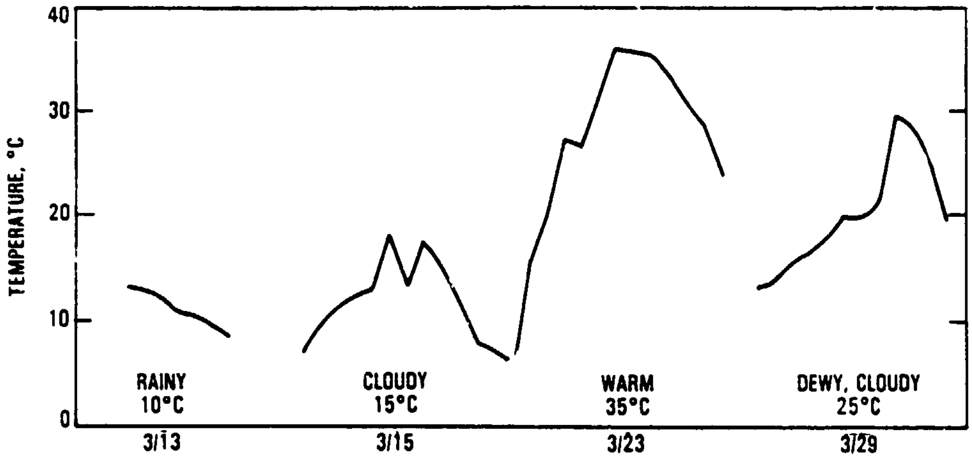
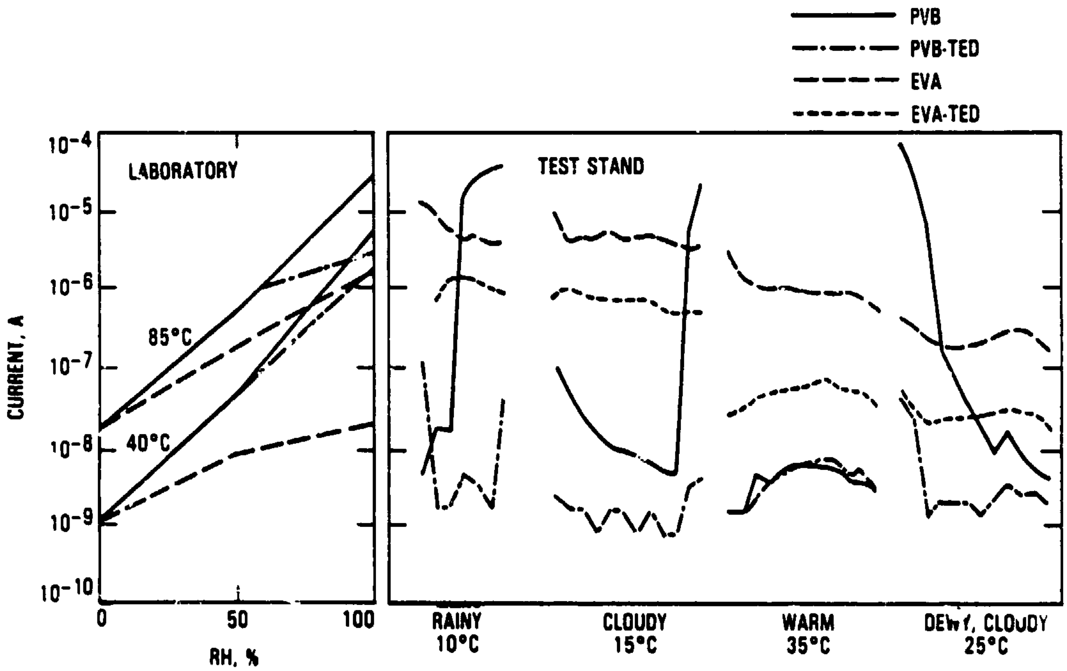
Test Stand Module Temperatures



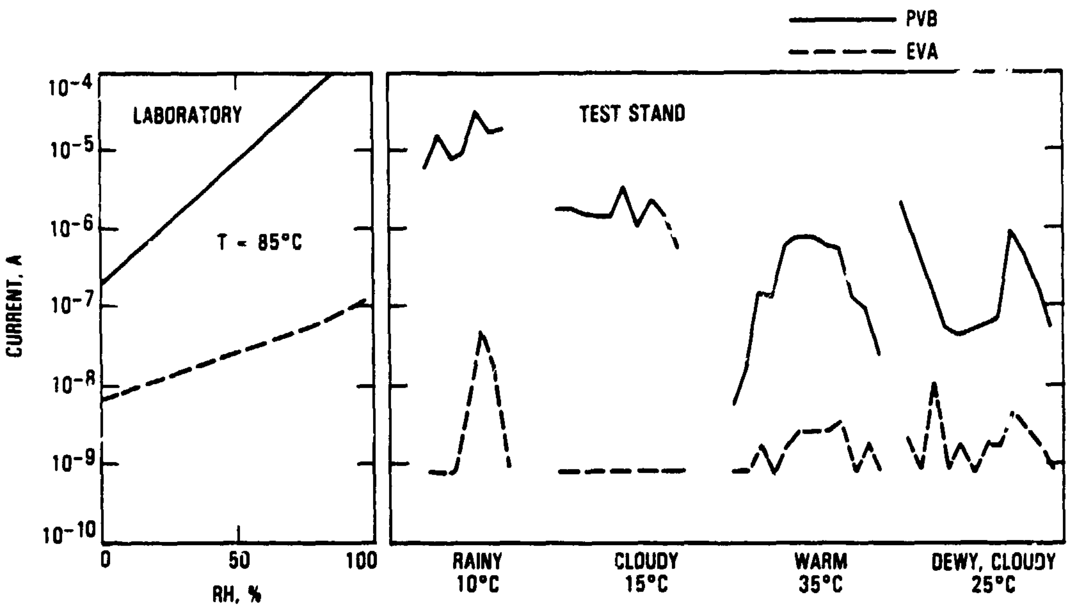
Module Leakage-Current Levels (XTEST Data)



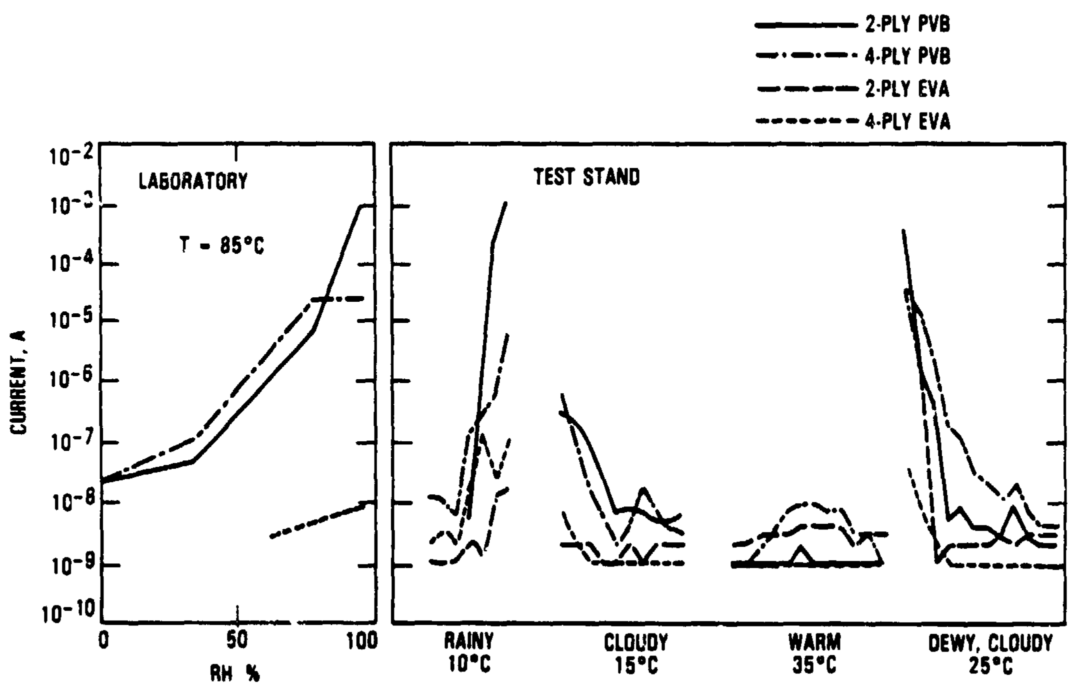
XTEST Observations

- Laboratory
  - PVB sensitivity to temperature variations decreases as relative humidity increases
  - EVA sensitivity to temperature variations increases as relative humidity increases
  - At high relative humidities, Tedlar reduces leakage currents in PVB coupons, but not in EVA coupons
  - For PVB coupons, total leakage current sensitivity to temperature variations is considerably less than that of bulk PVB, although sensitivity to humidity variations is somewhat greater than that of bulk PVB
  - For EVA coupons, total leakage current sensitivity to temperature and humidity variations is about the same as that of bulk EVA
- Test stand
  - For PVB (but not EVA) coupons, large current excursions were observed during periods of rain and dew, just as had been observed for PVB minimodules
  - Higher leakage current levels were observed in EVA coupons than in PVB coupons
- Laboratory versus test stand
  - For both PVB and EVA coupons, sensitivity to temperature variations was about the same at the test stand as in the laboratory
  - For PVB coupons, sensitivity to moisture variations in the field was greater than sensitivity to relative humidity variations in the test chambers

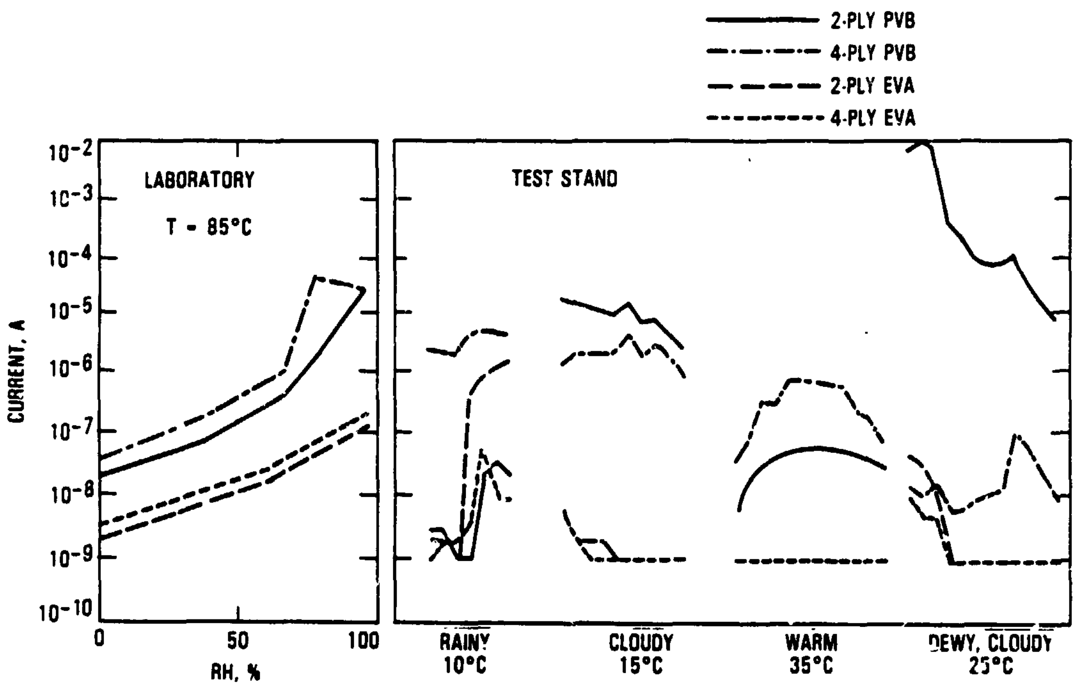
Bulk Leakage-Current Levels (VSI Data)



Surface Leakage-Current Levels (VSI Data)



Interface Leakage-Current Levels (VSI Data)



VSI Observations

- Laboratory
  - For PVB, surface and interface currents were observed to be about equal
  - For EVA, interface currents were greater than surface currents
  - Leakage currents in PVB always exceeded those in EVA
- Test Stand
  - For PVB, large surface and interface current excursions were observed during periods of dew and rain. Relatively smaller volume current excursions were noted
  - Interface currents generally exceeded surface currents
  - In dry conditions, PVB and EVA surface currents were both very low
  - Currents in PVB generally exceeded currents in EVA
  - Moisture pockets were observed at sample interfaces after extended periods of rain

Inferences

- For PVB, the largest electrochemical corrosion currents occur during periods of dew and after periods of precipitation
- In EVA modules, leakage current is dominated by bulk conduction effects
- In PVB modules, leakage current is governed by bulk conduction effects at high relative humidities and by surface/interface conduction effects at low relative humidities
- Conditions can exist in the field that don't exist in equilibrium T/RH-chambers (liquid water, moisture pockets, environmental transients, etc.). Field leakage currents can even exceed those in 85°C/85% RH laboratory environments. Such tests are inadequate for modeling field conditions
- Water, clustering at module interfaces, can vaporize resulting in blistering and delaminations

Conclusions

- Realistic life prediction and/or lab-field correlations (acceleration factors) require:
    - Consideration of short- and long-term environmental transients
    - Understanding of the relative contributions of volume, surface, and interfacial conduction to overall module conduction
    - Understanding of the roles of temperature, water vapor (RH), and liquid water in establishing module leakage current levels