RELIABILITY CHARACTERIZATION

AND FAILURE ANALYSIS OF AMORPHOUS SILICON MODULES

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INTRODUCTION

After 10 years of extensive research on crystalline-silicon flat-plate photovoltaic modules, the emphasis of recent reliability research at JPL has shifted to the emerging first-generation thin-film amorphous silicon modules. These new modules share much in common with their crystalline precursors, but also include many new materials and processes that demand the development of new reliability technologies. Key research thrusts include light-induced effects, cell corrosion, glass breaking strength, hot-spot heating, and electrical isolation of the cells from the module exterior.

A critical first step toward achieving high-reliability modules is identifying the strengths and weaknesses of the available technologies. To this end JPL has been conducting a systematic test program involving qualification testing, field aging studies, and laboratory investigations using a broad variety of available first-generation a-Si modules.

BLOCK V QUALIFICATION TESTING RESULTS

To assess the reliability attributes of the first-generation a-Si modules and to define priorities for required reliability research, a representative sample of a-Si modules was acquired from the 4 U.S. manufacturers and subjected to the standard JPL Block V qualification test sequence.

In general, the first-generation a-Si modules performed well in the Block V test sequence--comparable to the performance to first-generation crystalline-Si module designs. Such designs rarely pass the test completely, because of minor design deficiencies, but degradation levels are modest (on the order of 10%); a degradation of less than 5% is required to pass the Block V test.

FIELD TESTING OF AMORPHOUS-SI MODULES

Because the Block V test sequence was developed and refined specifically for crystalline-Si modules, another important first step was testing the applicability of the test procedure to amorphous-Si modules. This required careful comparison of real-time and accelerated field-aging results with those obtained in the Block V test sequence. Of specific concern was light-induced degradation, which is known to be important in a-Si modules, and which is <u>not</u> tested for in the Block V tests.

To obtain high quality field data, a representative sample of first-generation and prototype a-Si modules was placed in the field at JPL's main

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Solar Energy Research Institute, Golden, Colorado, 1987, pp. 179-195.

test site. Performance degradation was carefully monitored by periodically removing the modules and making precision I-V measurements using JPL's LAPSS measuring system.

When mounted in the field, each module was electrically loaded to a specific electrical operating point on its I-V curve; some modules were loaded open circuit, some short circuit, and the majority were loaded at their maximum power point via a constant-voltage (zener diode) load.

Light induced effects were prominent in nearly all field-test modules. The degradation is typified by modest short-circuit current loss accompanied with a shunt-like loss in fill factor. However, the initial rapid rate of degradation slows to a stable asymptotic level after a month or so of field exposure. Consistent with device testing experience, the electrical operating point of the module is found to have a significant influence on the level and rate of degradation.

ACCELERATED LABORATORY AGING TESTS

In combination, the Block V qualification testing and the field aging reveal a number of degradation mechanisms important to a-Si modules and highlight the inadequacy of the Block V test procedure to predict the light-induced degradation observed in the field. To further understand the stress parameters influencing these mechanisms and to separate the interrelated effects of light-induced-effects and cell corrosion, JPL is conducting a broad program of laboratory testing on specially prepared test coupons. These investigations are focused in four key areas:

- Corrosion of the cell interconnection regions and back metal
- Electrochemical corrosion between cell string and module frame including "bar graph" delamination of the tin oxide
- Electrical breakdown and leakage currents between the cell string and module frame
- Degradation of large-area a-Si cells due to hot-spot heating

Although not covered in detail in this presentation, results from these laboratory investigations have been reported elsewhere (1, 2, 3, 4, 5).

SUMMARY

As an indication of the evolving nature and continuing growth of photovoltaic technology, thin-film amorphous-Si power modules have made their commercial debut during the past 2 years. Because of the extensive interest in this technology, the majority of recent reliability research has focused on characterizing the reliability of the first-generation a-Si power modules, and on initiating the development of reliability enhancements required to achieve 30-year-life. Extensive field testing and early application experience have highlighted certain failure mechanisms as being the most important to long-term power generation. These include light-induced effects, corrosion of the cell monolithic interconnects, electrochemical corrosion between cells and module frame, electrical breakdown

between cell string and frame, and diffusion of dopants and chemical elements between the thin-film cell layers. Research thrusts in each of these areas are actively underway and are making important contributions to the reliability of this promising technology.

ACKNOWLEDGMENT

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2. Mon, G.R., and Ross, R.G., Jr., "Amorphous-Silicon Module Intercell Corrosion", Proceedings of the American Institute of Physics Conference on Stability of Amorphous Silicon Allow Materials and Devices, Palo Alto, CA, January 28-30, 1987.

3. Mon, G.R., Wen, L., and Ross, R.G. Jr., "Corrosion of a-Si Cells and Modules", Proceedings of the 19th IEEE PV Specialists Conference, New Orleans, Louisiana, May 4-8, 1987.

4. Mon, G., Wen, ., and Ross, R.G., Jr., "Encapsulant Free Surfaces and Interfaces: Critical Parameters in Controlling Cell Corrosion", Proceedings of the 19th IEEE PV Specialists Conference, New Orleans, Louisiana, May 4-8, 1987.

5. Gonzalez, C., and Ross, R.G., Jr., "Response of Amorphous Silicon Cells to Reverse Biasing", Proceedings of the American Institute of Physics Conference on Stability of Amorphous Silicon Alloy Materials and Devices, Palo Alto, CA, January 28-30, 1987.

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AMORPHOUS SILICON MODULE TEST PROGRAM OBJECTIVES

Objective

- Assess reliability characteristics of amorphous silicon modules
- Assess attributes of various test methods
- Establish research priorities

Approach

- Test a number of first-generation amorphous silicon modules using a wide variety of tests
  - Block V qualification tests
  - Field aging (various electrical loading points)
  - Field aging (at elevated temperatures)
  - Dark oven aging (various electrical biases)
  - Photothermal oven aging
  - Hot-spot endurance

BLOCK V QUALIFICATION TESTS

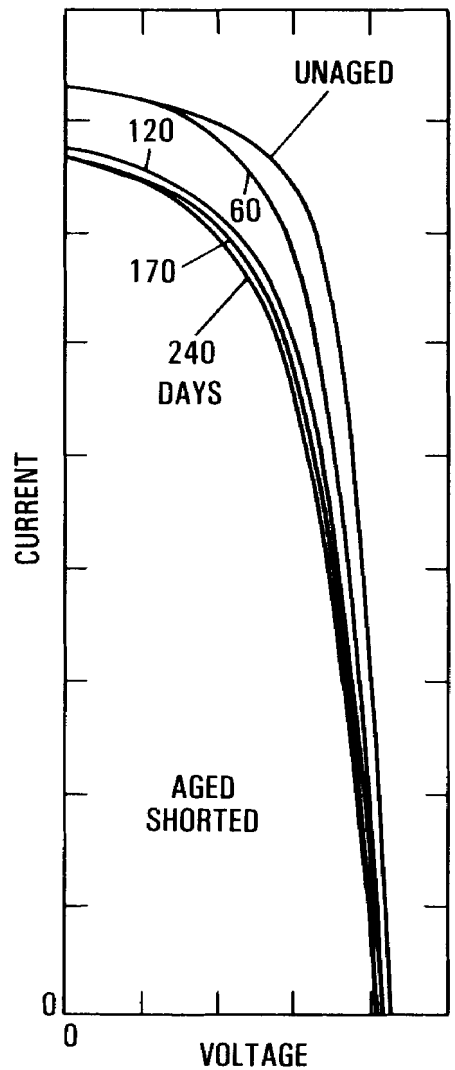
Test	Level and Duration
Temperature cycling	200 cycles; each cycle: 4 h, −40°C to +90°C
Humidity-freeze	10 cycles; each cycle: 20 h at 85°C, 85% RH followed by 4 h excursion to −40°C
Cyclic pressure loading	10000 cycles, ± 2400 Pa (± 50 lb/ft^2)
Wind resistance (shingles only)	Underwriters Lab Standard UL 997 1.7 k Pa (35 lb/ft^2)
Hail impact	10 impacts at most sensitive locations using 25.4 mm (1 in.) iceball at 23.2 m/sec (52 mph)
Electrical isolation	Leakage current ≤50 μA at twice worst-case system open circuit voltage plus 1000 V
Hot-spot endurance	3 cells back-biased to maximum bypass-diode voltage and cell-string current for 100 h of on-time

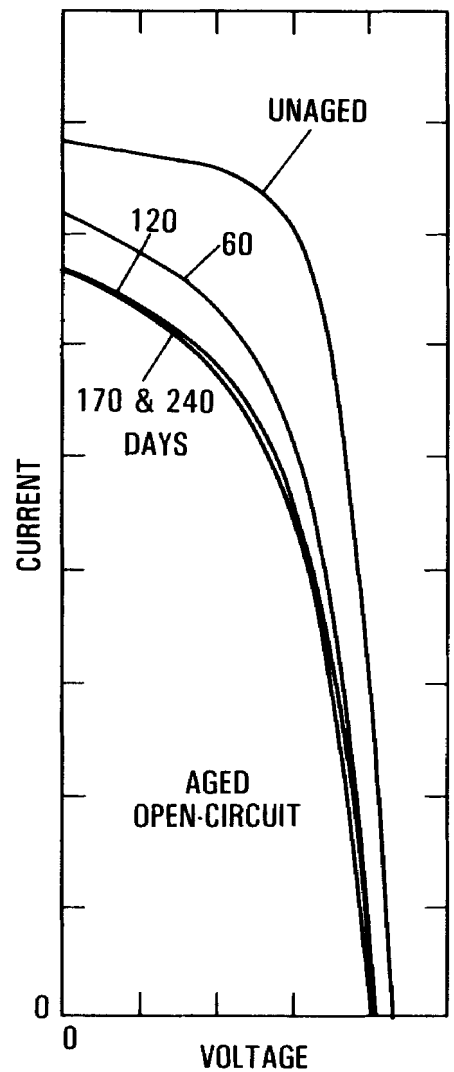
BLOCK-V QUAL TESTING OF AMORPHOUS SILICON MODULES

SUMMARY

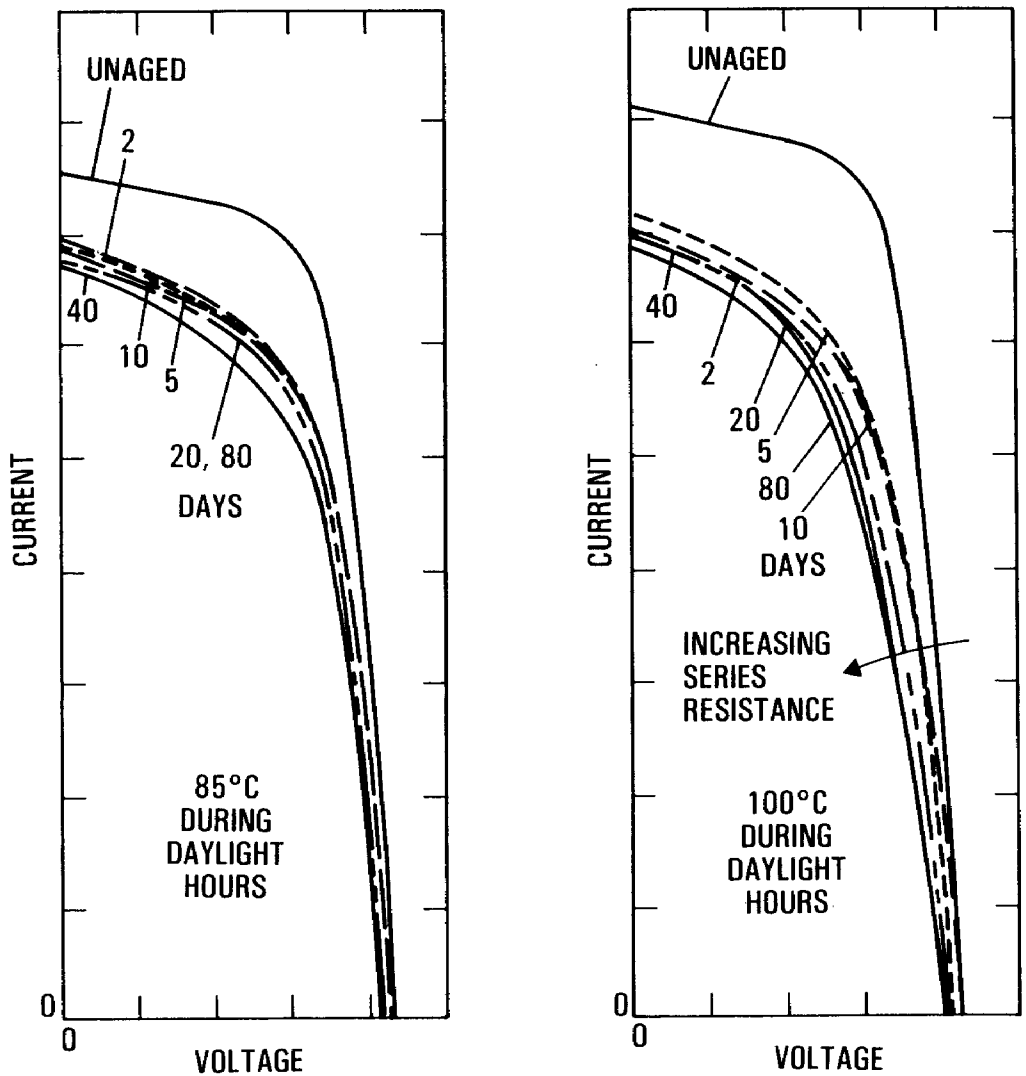
- Good performance in mechanical loading tests
  - Mechanical cycling at 50 psf
  - Hail impact with 1 in. ice balls
- Slight degradation (10%) in thermal cycle and humidity tests
  - Corrosion of monolithic interconnects
  - Some open-circuiting of monolithic interconnects
- Good performance in hot-spot test
- Mixed performance with encapsulant system
  - Frame softening
  - Some delamination of non-EVA systems

α-Si MODULE FIELD PERFORMANCE
(AMBIENT-TEMPERATURE AGING)



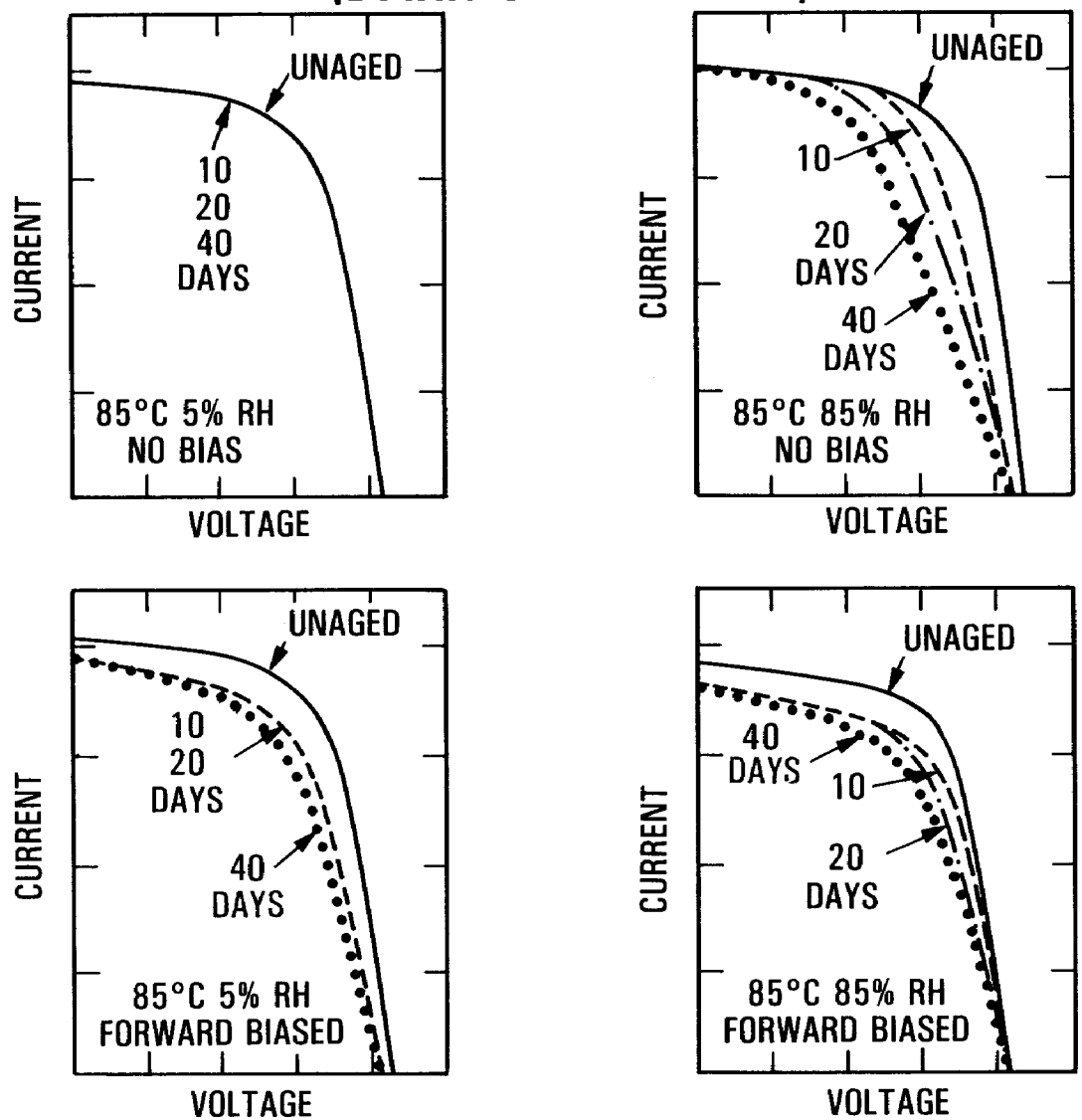


α-Si MODULE FIELD PERFORMANCE
(ELEVATED-TEMPERATURE AGING)

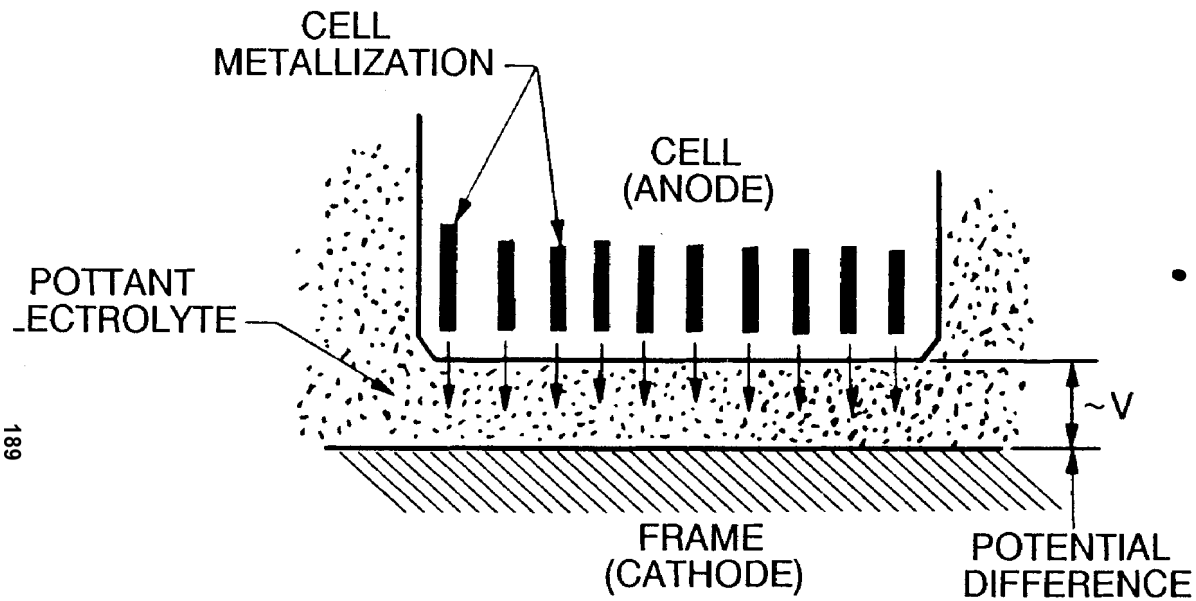


AMORPHOUS SILICON MODULE I-V PERFORMANCE

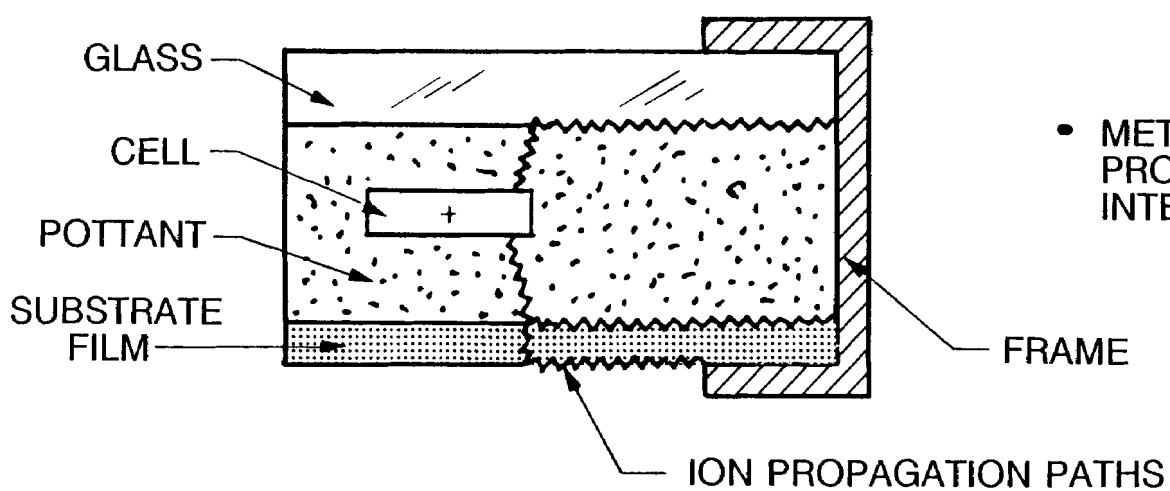
(DARK OVEN AGING)



SCHEMATIC REPRESENTATION OF ELECTROCHEMICAL CORROSION

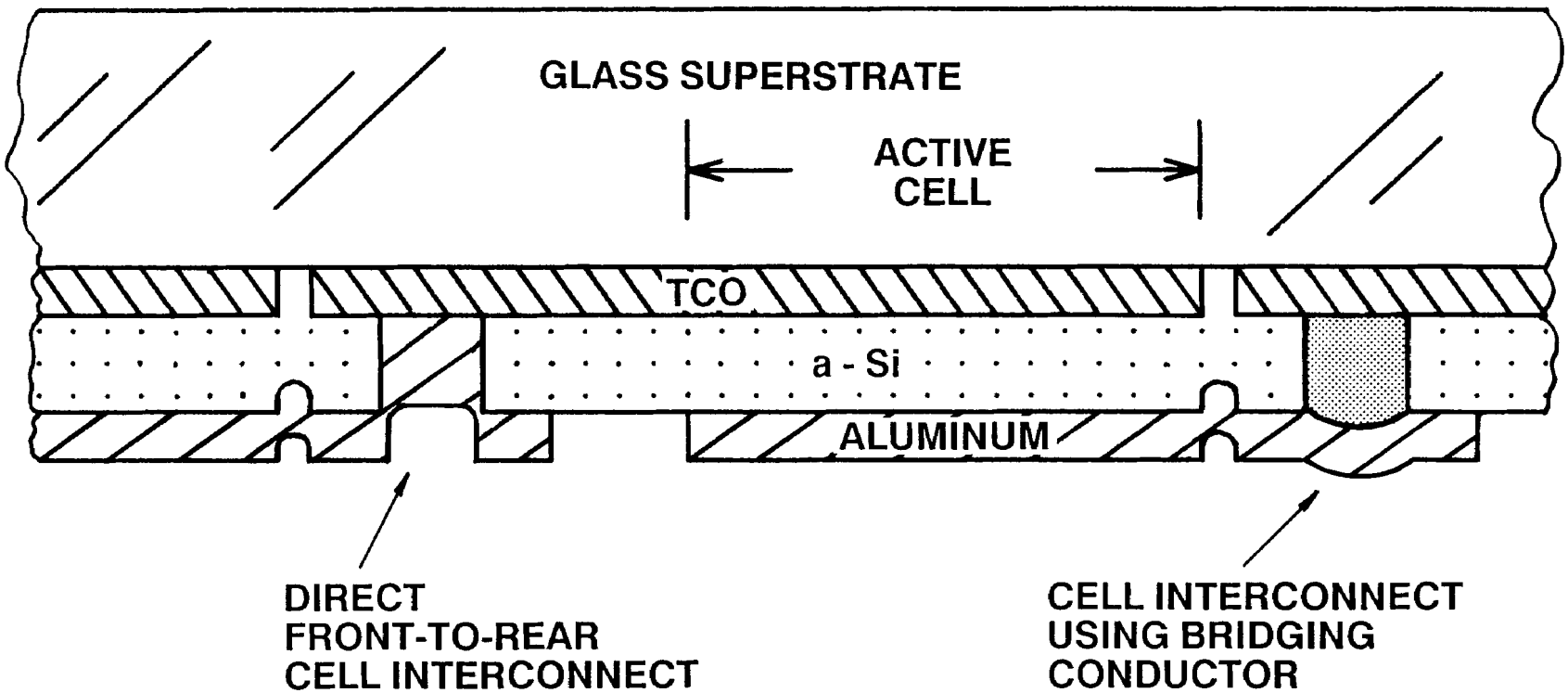


- METALLIZATION IONS FOLLOW ELECTRIC FIELD LINES BETWEEN CELL AND FRAME

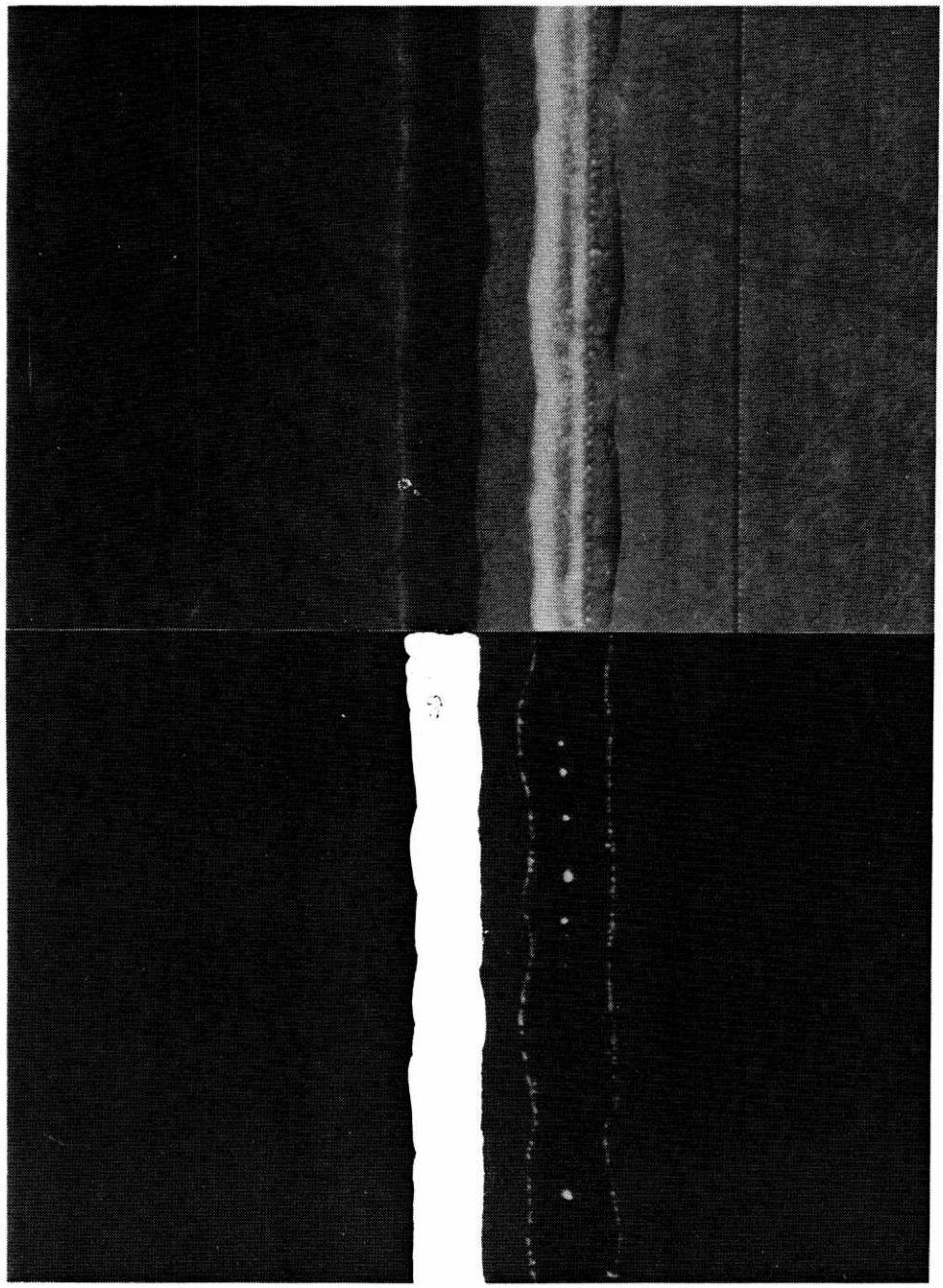


- METALLIZATION IONS OFTEN PROCEED TO, AND THEN ALONG, INTERFACIAL SURFACES

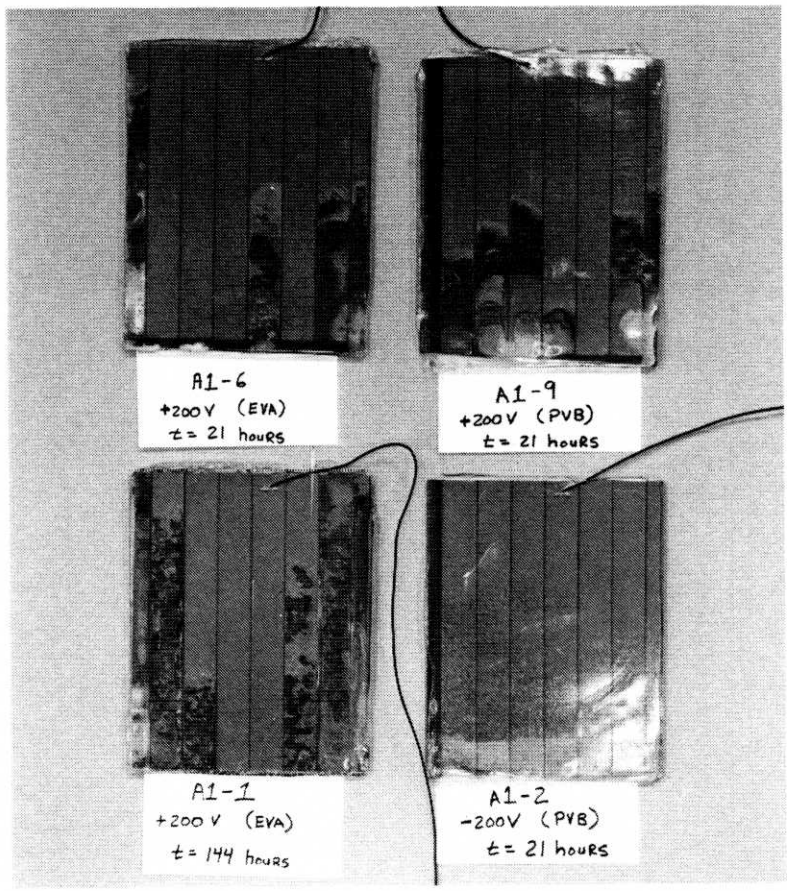
CROSS-SECTION OF MONOLITHIC a - Si MODULE



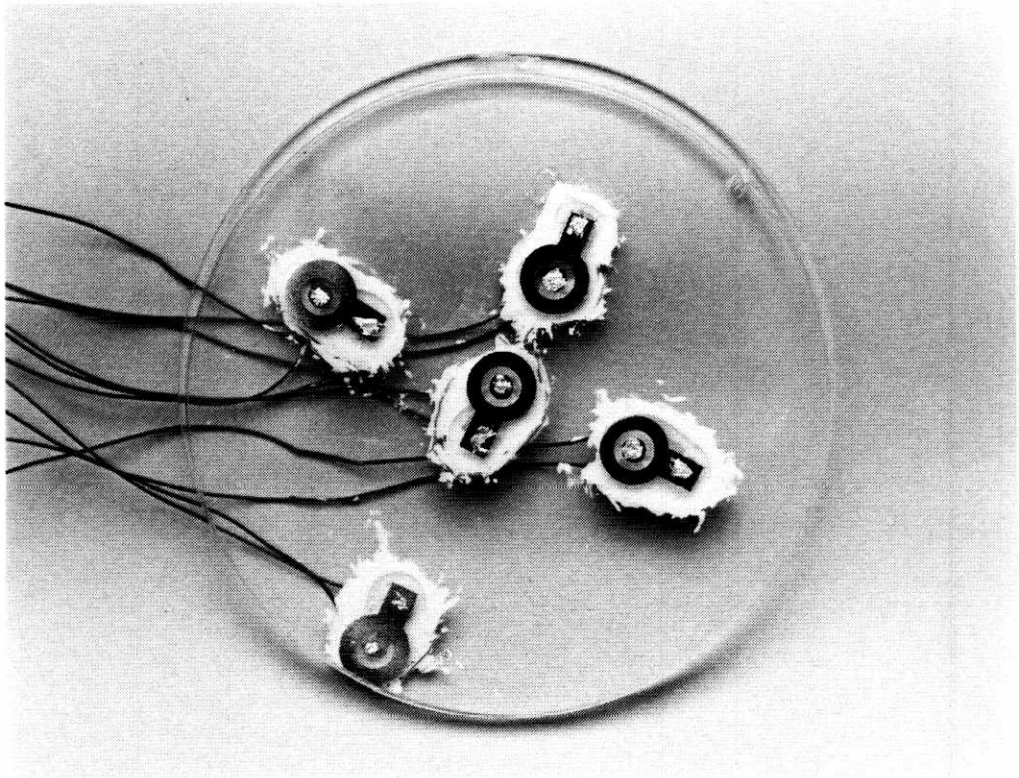
METAL VOIDS ALONG CELL INTERCONNECT

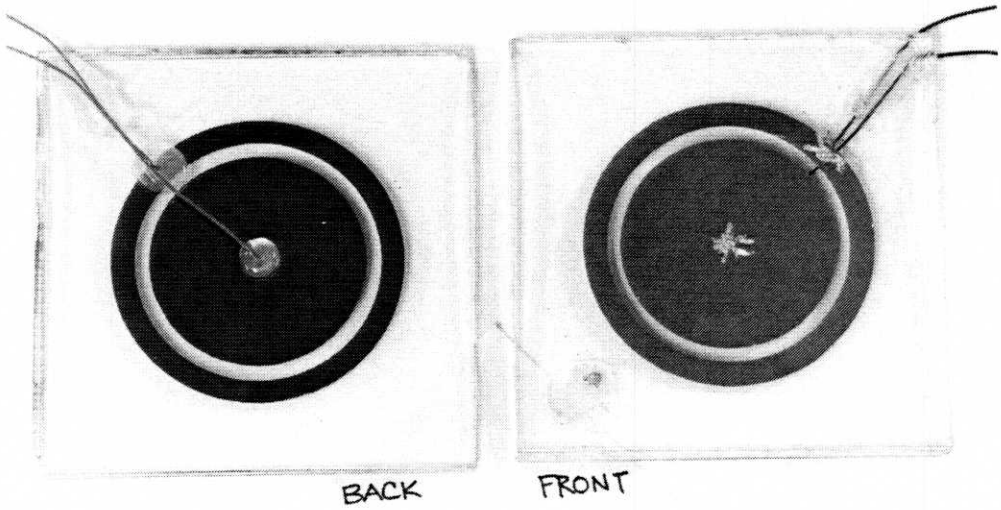


BAR-GRAPH CORROSION TESTING



MOISTURE SORPTION AND IONIC CONDUCTIVITY INSTRUMENTATION





INTERFACE SAMPLE

SUMMARY

- The majority of reliability research over the past year has focused on the emerging first generation power modules fabricated of amorphous-silicon
- Extensive laboratory testing, field testing and application experience have been successful in identifying areas of technology improvement required to achieve 30-year operational life
- Block V crystalline-silicon qualification test is insufficient for amorphous silicon modules
    - Good indicator of mechanical and hot-spot endurance
    - Poor indicator of electrical stability of amophous silicon
- Tests appropriate for amophous silicon procurement specifications do not exist at this time

SUMMARY (CON'T)

- Numerous solution-oriented research thrusts are ongoing and are making important contributions in understanding the underlying physics and in developing the needed technologies. These areas include:
  - Light-induced effects
  - Corrosion of intercell regions
  - Electrochemical Corrosion
  - Hot-spot Heating
  - Thermal Diffusion
  - Voltage Isolation
- Electrical stability of amorphous silicon modules is very complex
  - Light induced effects
    - Sensitive to electrical loading point (Voc, Isc, Pmp)
    - Complex temperature dependency
  - Corrosion induced effects
    - Strong (Arrhenius) temperature dependency
    - Strong humidity dependency
- Accelerated laboratory and field testing must address the complex parameter dependencies