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MODULE VOLTAGE ISOLATION AND CORROSION RESEARCH

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This paper presents a summary of recent research at JPL on two topics related to achieving long-term reliability of photovoltaic modules: voltage isolation and electrochemical corrosion. Special emphasis is given to similarities and differences in performance between crystalline-silicon modules and amorphous-silicon modules.

VOLTAGE ISOLATION

The problem of voltage isolation is to confine the generated energy to the module circuitry. Energy may dissipate from the module slowly in the form of low-level leakage current, or rapidly as in insulation breakdown (Figure 1). If leakage-current levels in a photovoltaic array are excessive, proper operation of ground-fault detection equipment may be disrupted. A conventional solution to this problem is to use very-high-resistivity polymer insulations as module encapsulants.

The rapid dissipation of energy known as module breakdown, or more generally as voltage breakdown, can have several causes (Figure 2). It has been observed that, for a fixed applied voltage stress, the breakdown probability of polymer substrate films such as Tedlar and Mylar increases with increasing environmental exposure. Thus, regions within the insulation--here referred to as flaws--become more susceptible in time to puncture by applied voltage stresses. Voids in insulation are thought to be one type of flaw: gaseous microbubbles in the insulation that may be "manufactured in" or that may have evolved from defects at the molecular level. Normal cell-frame electrode stresses may discharge these voids, causing internal erosion. These measurable internal discharges provide information on insulation breakdown tendencies.

These insulation flaws may be further stressed by stress concentration centers on electrified parts, such as sharp points on solar cells. It is expected that in amorphous-silicon modules, sharp points with sub-micrometer radii, resulting from laser-scribing operations, may result in voltage breakdown of the amorphous silicon.

The performance of edge seals and gaskets must not be overlooked in considering the problem of voltage breakdown. In crystalline-silicon modules, such devices share the voltage stress load with the encapsulation, but in amorphous-silicon modules, the devices may bear all of the applied voltage stress.

A list of practical design techniques to reduce the likelihood of module voltage breakdown is presented in Figure 3: Use relatively few layers of

relatively thick, high-resistivity, flaw-free insulating films; use rounded, burr-free, and adequately spaced cell-frame electrodes; and use low-conductivity gaskets and edge seals (Reference 1).

### ELECTROCHEMICAL CORROSION

The fundamental principles of photovoltaic module electrochemical corrosion can be understood with the aid of Figure 4. Leakage current is composed of charge carriers that move under the influence of voltage and concentration gradients through the insulation, reacting with it and with the cell-frame electrodes to produce corrosion products. Leakage current levels are determined in part by the electrical conductivity of the insulation, which varies with changing environmental conditions of temperature, and the relative humidity to which the module is exposed, as indicated for two popular photovoltaic insulations in Figure 5. Note that for the same conditions of temperature and humidity, the conductivity of polyvinyl butyral (PVB) is about three orders of magnitude larger than that of ethylene vinyl acetate (EVA). This will explain in part the higher equilibrium leakage current levels observed in amorphous-silicon modules encapsulated in PVB (Figure 6).

Leakage current integrated over time yields charge transferred between the cell-frame electrodes. The quantity of charge transferred is an important measure of the degree of electrochemical corrosion. The cell maximum power output is an important measure of device performance. As environmental exposure continues, the cell power output decreases (Figure 7), as the quantity of charge transferred increases. Quantifying this relationship between total charge transferred and reduction of maximum cell power output for crystalline-silicon modules (Figure 8) and amorphous-silicon modules (Figure 9) reveals similar aging characteristics: 1 to 10 C/cm of charge transferred between cell and frame are required to produce a significant level, say 50%, of cell failures. This observation of a quantitative electrochemical failure threshold enables the prediction of module field life (Reference 2).

Assuming that equal quantities of charge transferred in laboratory and field environments produce equivalent electrochemical damage enables the determination of equivalent laboratory and field exposure times. This equivalence may form the basis of a qualification test for photovoltaic modules (Reference 3).

The important fundamentals of photovoltaics module electrochemical corrosion are summarized in Figure 10.

### PHYSICAL OBSERVATIONS

Typical corrosion observed in crystalline-silicon modules is depicted in Figures 11 through 13. Typical corrosion in positive polarity is characterized by missing cell metallization and the formation of cathodic dendrites; the dissolved metallization ions have migrated to the frame, where they deposit as dendritic crystallites. Typical corrosion in negative polarity exhibits less obvious characteristics to the naked eye, but microscopic examination reveals the formation of anodic corrosion salts and

the evolution of gas bubbles at the metallization-silicon interface, resulting in metallization delamination. Although the corrosion mechanisms in the two polarities differ, the corrosion rates are comparable.

At this stage in amorphous-silicon module research, nothing observed can be said to be typical. This notwithstanding, results of one set of corrosion tests on amorphous-silicon modules are presented here.

Two amorphous-silicon configurations tested are shown in Figure 14. The parallel modules consist of 16 separate amorphous-silicon cells, all of which share a common electrode--the SnO<sub>2</sub> layer deposited on the underside of the glass superstrate. The series modules consist of eight amorphous-silicon cells interconnected in a series-circuit configuration. The individual module units are encapsulated, together with aluminum bars serving as frames, in either PVB or EVA and are then exposed for more than 300 hours in an environmental chamber held at 85°C and 85% RH, with 500 volts applied between cell and frame. Front and rear views of the actual parallel modules are shown in Figures 15 and 16; front and back views of the actual series modules are shown in Figures 17 and 18. Note that wire attachments to individual cells in Figures 16 and 18 were accomplished with the use of Cho-bond silver epoxy. Note also that the series modules in Figure 18 arrived from the manufacturer with a layer of protective black paint on their rear surfaces; this paint layer was removed from all modules save No. 3 before testing. This negative-polarity series module encapsulated in EVA underwent a chemical reaction at the paint-metallization interface: the metallization extending beyond the paint edge began to disappear after 40 hours of exposure (Figure 19), and had completely disappeared after 130 hours (Figure 20).

Figures 21 through 23 show a front-face view of progressive corrosion of series module No. 6 (negative polarity, PVB) at 40, 130, and 300 hours, respectively. Note the progressive pinhole-like loss of metallization and amorphous silicon. Note also the squiggly, worm-like configurations generated by the loss of metallization. Figures 24 through 26 show front views of progressive corrosion of the same module. Clearly, some type of ion is moving from the frame toward the center of the module, perhaps an impurity in the PVD.

Figure 27 depicts series module No. 7 at 300 hours of exposure. Note the extensive loss of metallization and the worm-like patterns. Also note the voltage breakdown pit at the cell-frame interface, a result of internal discharge pulse counting at 5 kV. Figures 28 and 29 show a close-up of this region at 130 and 300 hours, respectively. The series modules exhibited a greater propensity for voltage breakdown than did the parallel modules, due no doubt to differences in materials and fabrication processes.

Corrosion of parallel modules, with one exception, was considerably less severe. Parallel module No. 688F (positive polarity, EVA) exhibited an unidentified discoloration of the rear metallization (Figure 30) after 300 hours. Parallel module No. A690E (negative polarity, PVB) exhibited some interesting effects. Figures 31 and 32 present a front view at 130 and 300 hours, respectively. Note again the worm-like metallization loss patterns and their growth with time of exposure. Figures 33 and 34 show the corresponding rear views. Figures 35 and 36 show close-ups of one cell at 40 and 300 hours, respectively. Note, in addition to the worm-like patterns, the pinhole-like losses of both metallization and silicon.

These observed degradations have yet to be subjected to surface analysis techniques such as EDX, SIMS, etc., so much remains to be learned about amorphous-silicon module corrosion at the mechanism level. Additional testing is required to categorize the long-term corrosion behavior of amorphous-silicon modules with non-metallic frames.

It should be emphasized that, although amorphous-silicon module corrosion appears to involve extensive loss of silicon material, the quantitative data of Figures 8 and 9 indicate that corrosion rates are comparable.



## REFERENCES

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2. Mon, G., Orenotsky, J., Ross, R., and Whitla, G., "Predicting Electrochemical Breakdown in Terrestrial Photovoltaic Modules," Proceedings of the 17th IEEE Photovoltaic Specialists Conference, pp. 682-692, Institute of Electrical and Electronics Engineers, Inc., New York, 1984.
3. Mon, G., Whitla, G., Neff, M., and Ross, R., "The Role of Electrical Insulation in Electrochemical Degradation of Terrestrial Photovoltaic Modules," IEEE Transactions on Electrical Insulation, Institute of Electrical and Electronics Engineers, Inc., New York, June 1985 (in press).

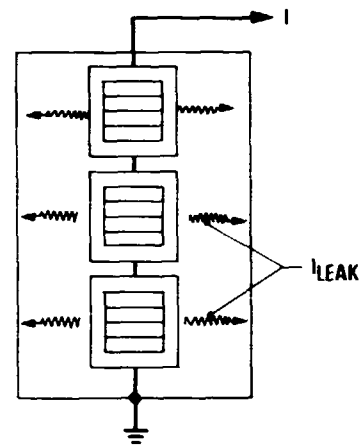
# LABORATORY EXPERIENCE WITH VOLTAGE BREAKDOWN

JET PROPULSION LABORATORY

G.R. Mon

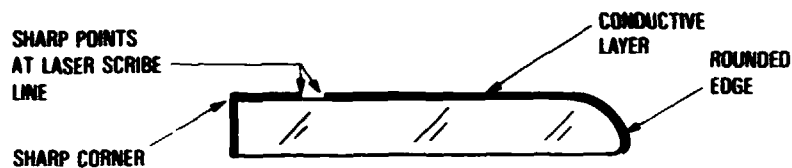
Figure 1. Voltage Isolation Overview

- **Two problems associated with photovoltaic module insulations:**
  - **Applied voltage may stress the insulation to breakdown**
  - **Excessive leakage current levels may wreak havoc with proper operation of ground-fault detection equipment and may contribute to catastrophic breakdown of the insulation**
- **High-resistivity encapsulations assure low leakage-current levels**
  - **Encapsulation resistivity generally decreases as temperature and moisture content increase**
  - **Encapsulation resistivity decreases with time of exposure**



## Figure 2. Topics in Voltage Isolation Research

- **Voltage stress vs breakdown probability of pristine and environmentally exposed substrate (polymer) films**
- **Stress enhancement factors for geometrically sharp electrodes (such as solar cells)**

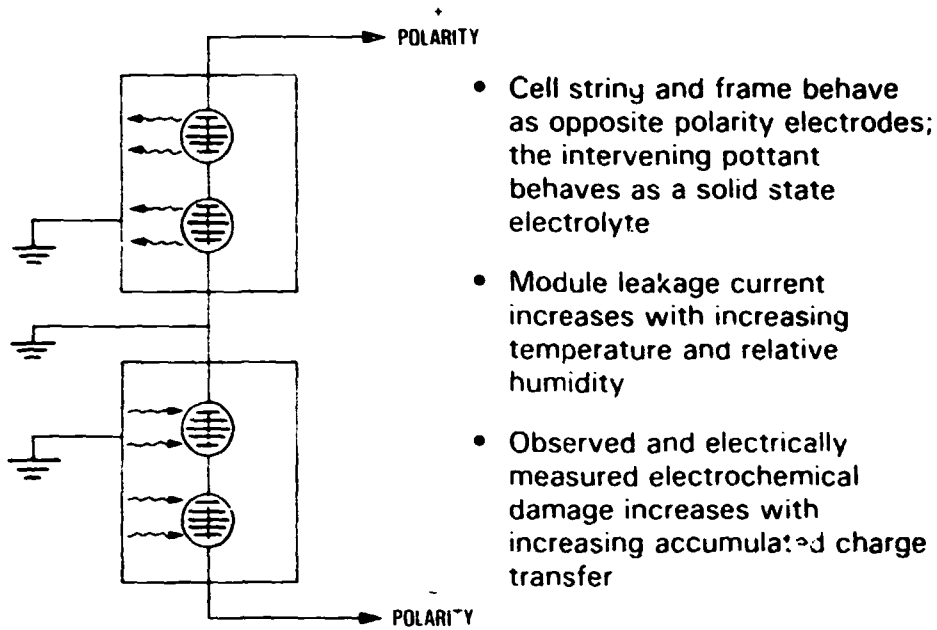


- **Internal discharge characterization of photovoltaic modules**
- **Performance of edge seals, gaskets, etc.**

## Figure 3. Voltage Isolation Research Results and Effective Design Practices

- **At a fixed voltage, the breakdown probability of polymer films increases with environmental exposure**
  - **Use high resistivity, pinhole-free insulating films**
  - **Use multiple layers of insulating films to reduce the probability of breakdown**
  - **Economics dictates the use of fewer layers of thick films rather than many layers of thin films**
- **Design for low module breakdown probability**
  - **Use rounded, burr-free cell and frame electrodes**
  - **Maintain adequate clearance between cell-frame electrodes**
  - **Use low-conductivity gaskets and edge seals**

**Figure 4. Relationship Between Leakage Current and Electrochemical Damage**



**Figure 5. Electrical Conductivity of PVB and EVA**

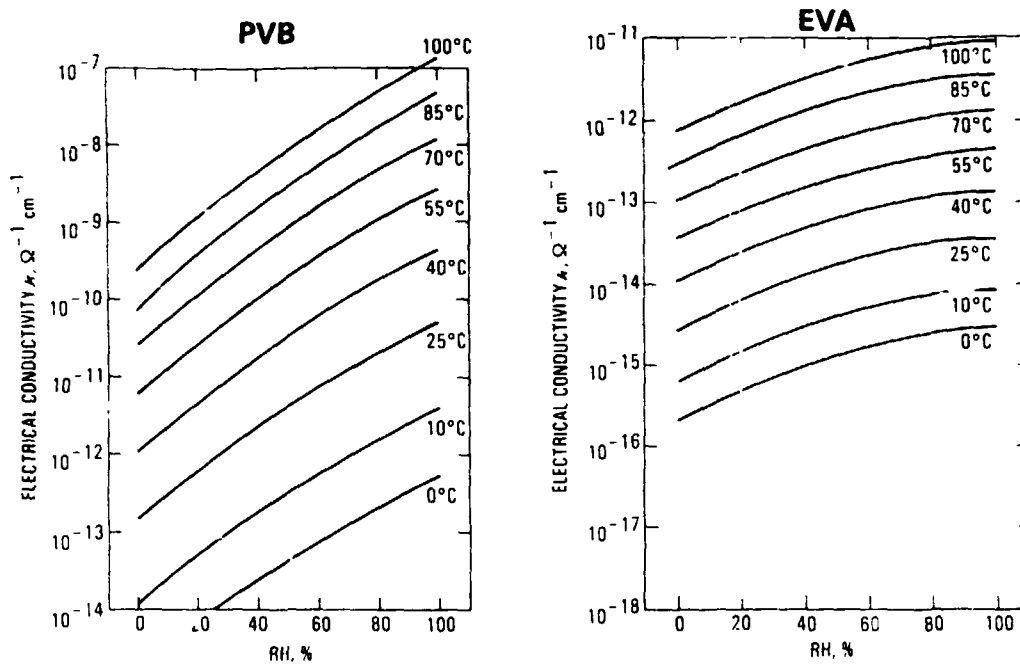


Figure 6. Amorphous Modules: Leakage Current vs Time of Exposure at 85°C/85% RH/500 Volts

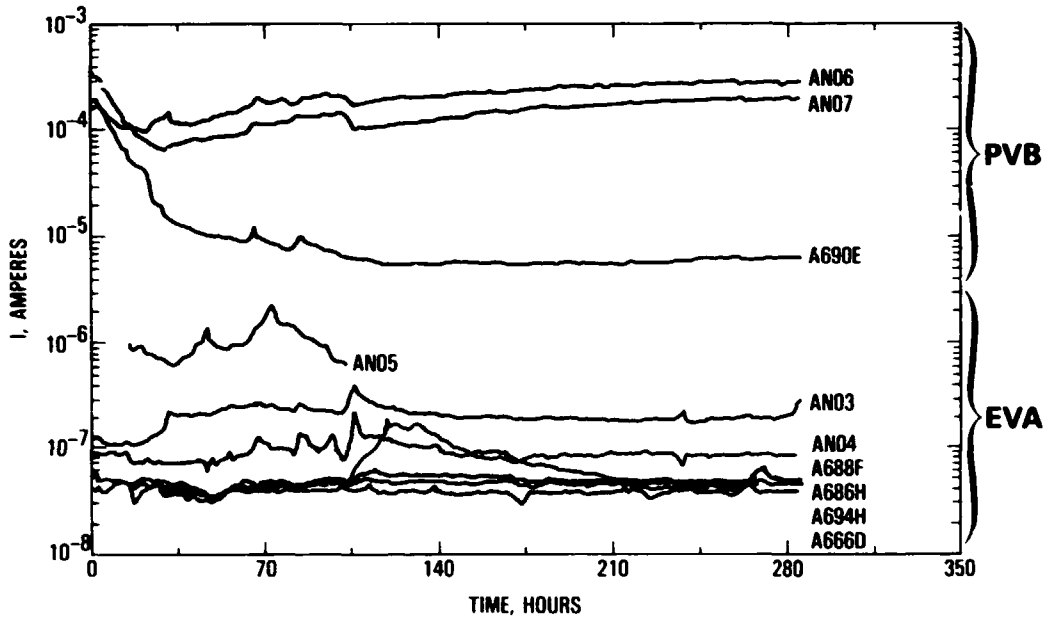


Figure 7. I-V Curves for Cell No. 6, Parallel Module A690E: 85°C/85% RH/500 Volts

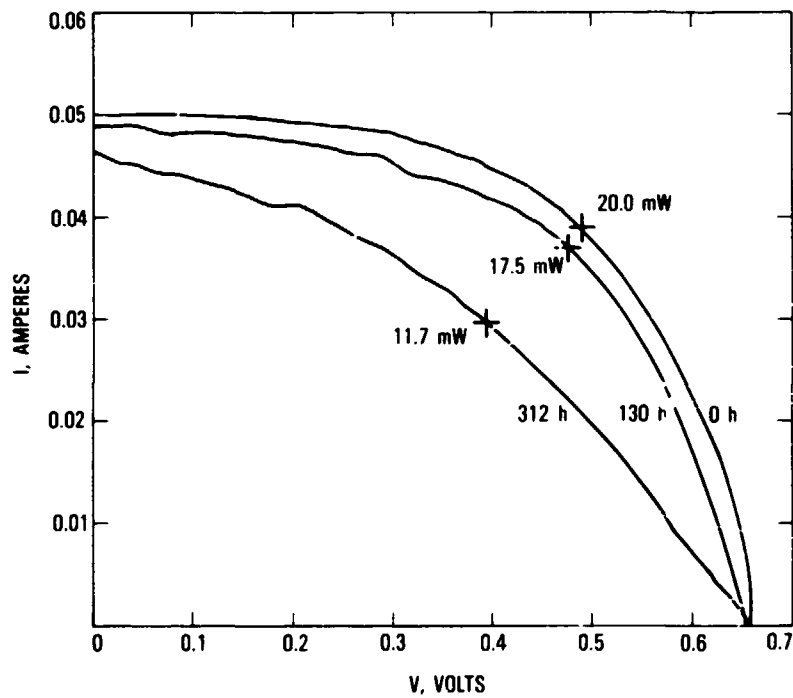


Figure 8. Power Output Reduction vs Accumulated Unit Charge Transfer

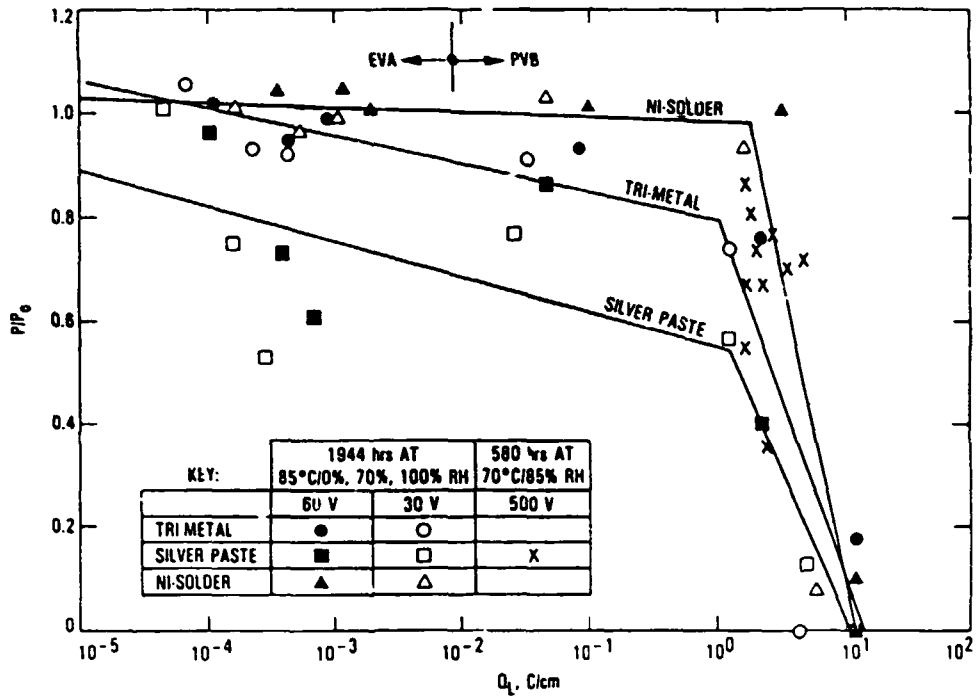


Figure 9. Amorphous Modules: Maximum Cell Power Output vs Charge Transfer per Unit Cell-Frame Length

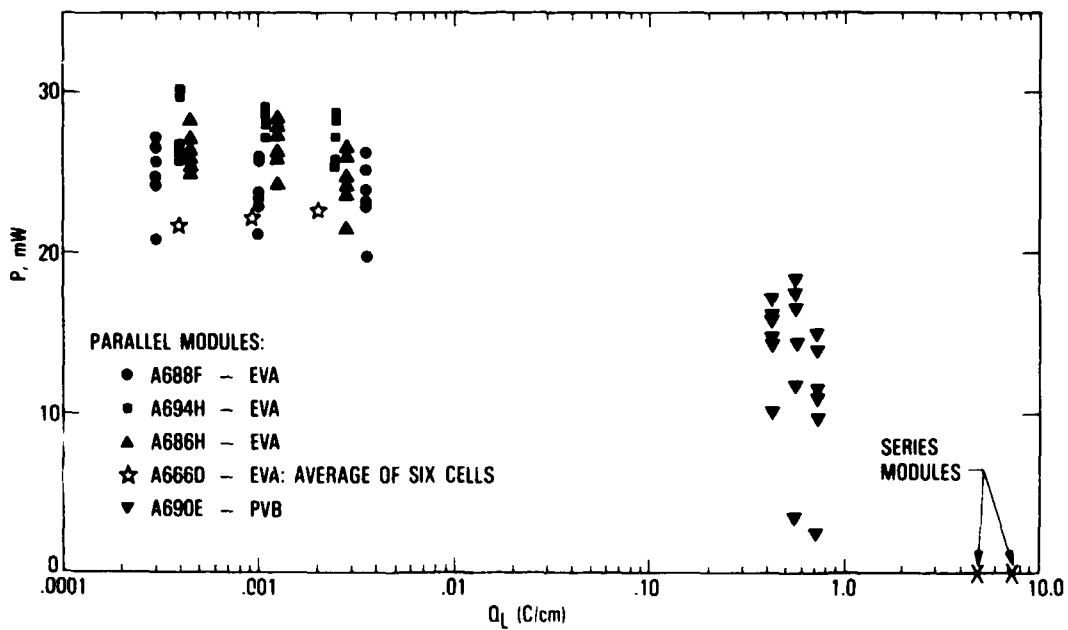
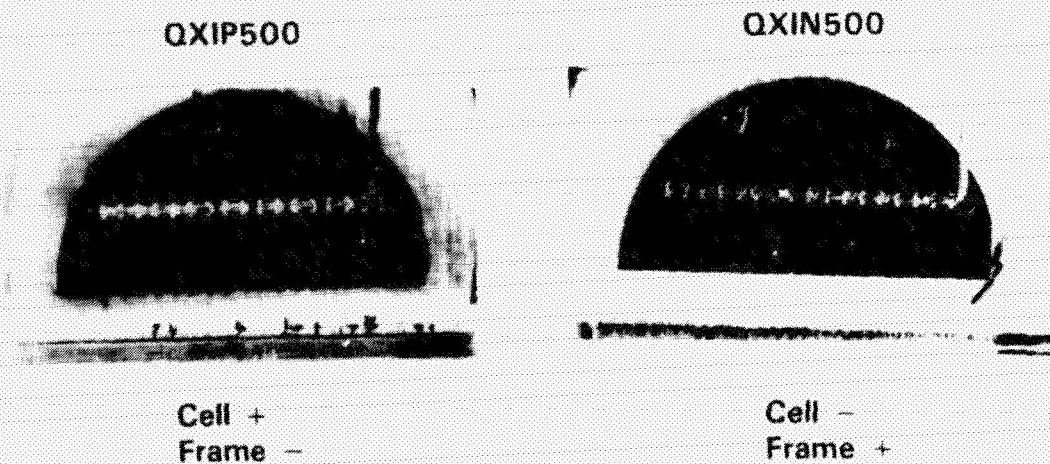


Figure 10. Electrochemical Corrosion Overview

- Total charge transferred between cell and frame is an important measure of the degree of corrosion
  - Leakage current is a manifestation of the movement between cell and frame of mobile ions in response to voltage and concentration gradients
  - Ions interact with the encapsulant and the cell-frame electrodes to produce corrosion products
  - Assuming that equal quantities of charge transferred in lab and field environments produce equivalent electrochemical damage enables the determination of equivalent lab/field exposure times
- Maximum cell power output is an important measure of cell performance
  - Cell power output degrades as corrosion progresses
  - Quantifying the relationship between cell power output reduction and total charge transferred enables module field-life prediction

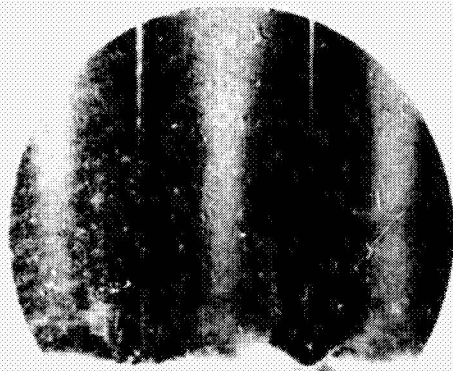
Figure 11. PV Cell Electrochemical Degradation in Two Polarities: 500 V, 580 h at 70°C/85% RH



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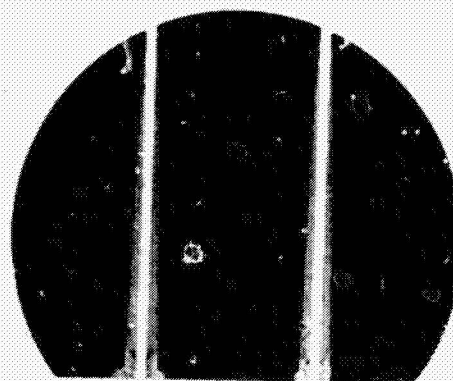
Figure 12. PV Cell Electrochemical Degradation in Two Polarities: 500 V, 580 h at 70°C/85% RH (Cont'd)

QXIP500



Cell +  
showing  
metallization  
dissolution  
and migration

QXIN500



Cell -  
showing  
metallization  
delamination



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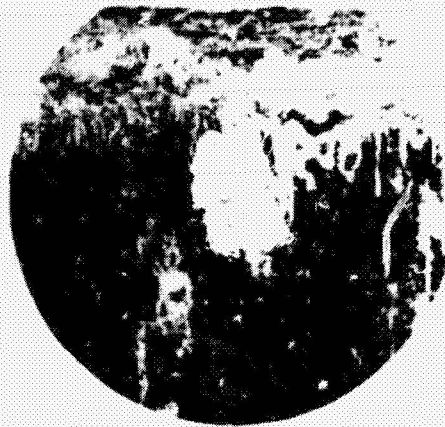
Figure 13. PV Cell Electrochemical Degradation in Two  
Polarities: 500 V, 580 h at 70°C/85% RH  
(Cont'd)

QXIP500



Frame -  
showing  
dendrite  
formation

QXIN500



Frame +  
showing  
white "fuzzball"  
corrosion salts

Figure 14. Amorphous Modules: Series and Parallel Configurations

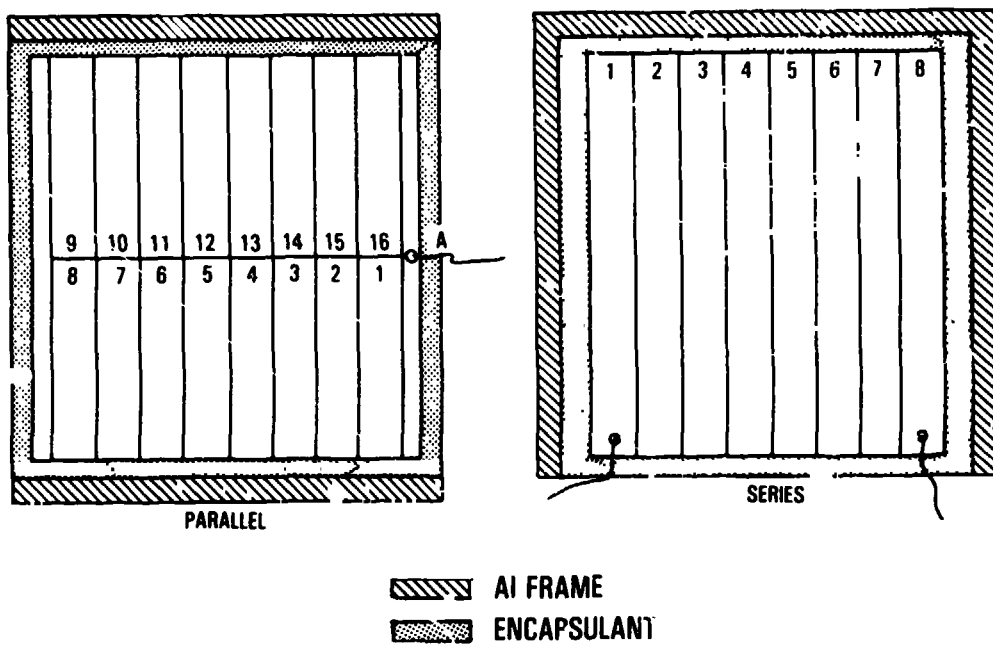


Figure 15

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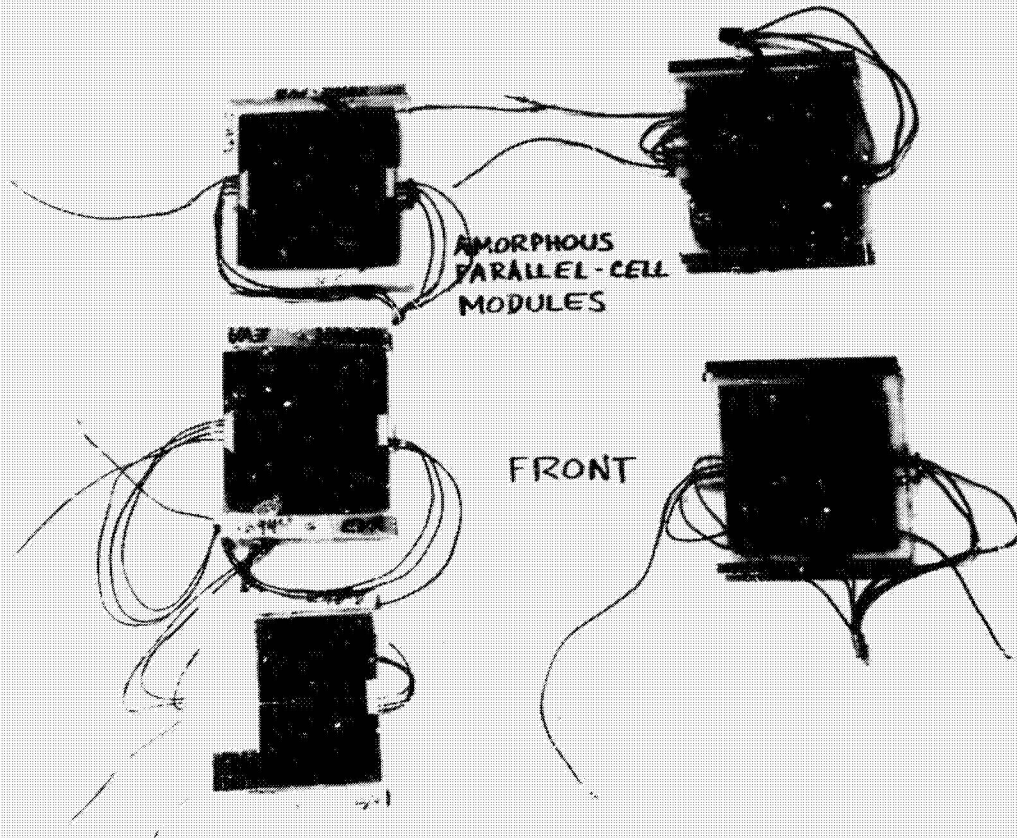




Figure 16

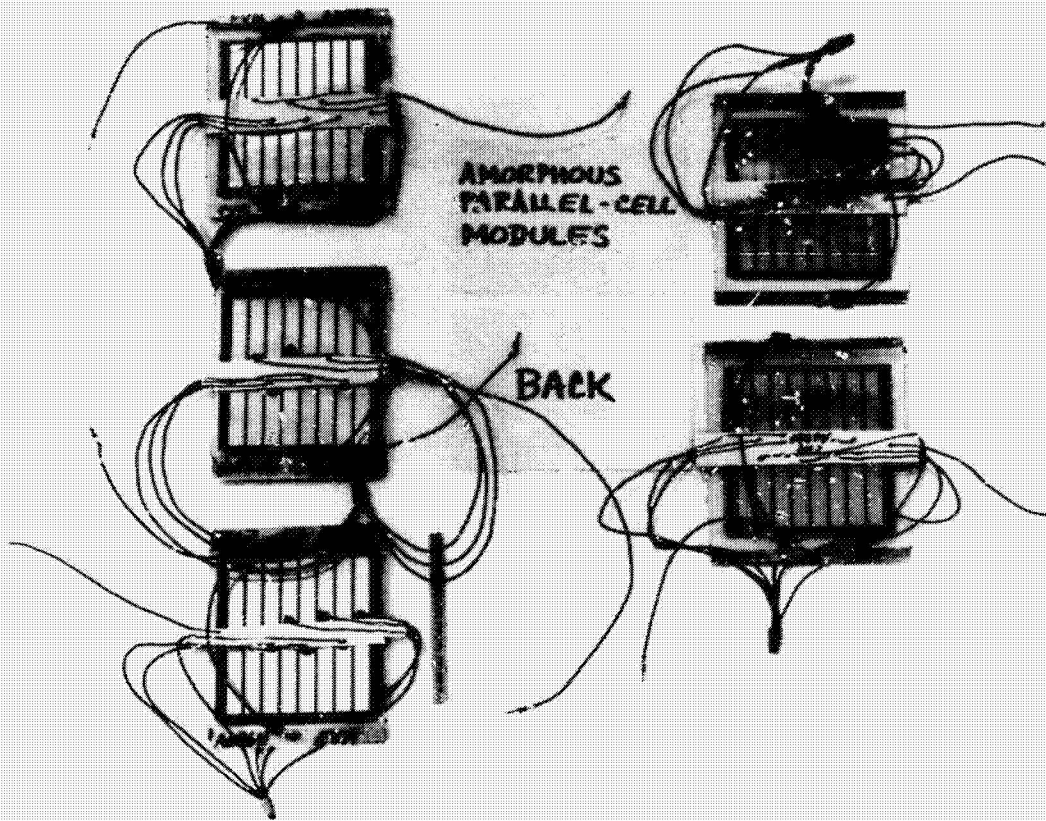


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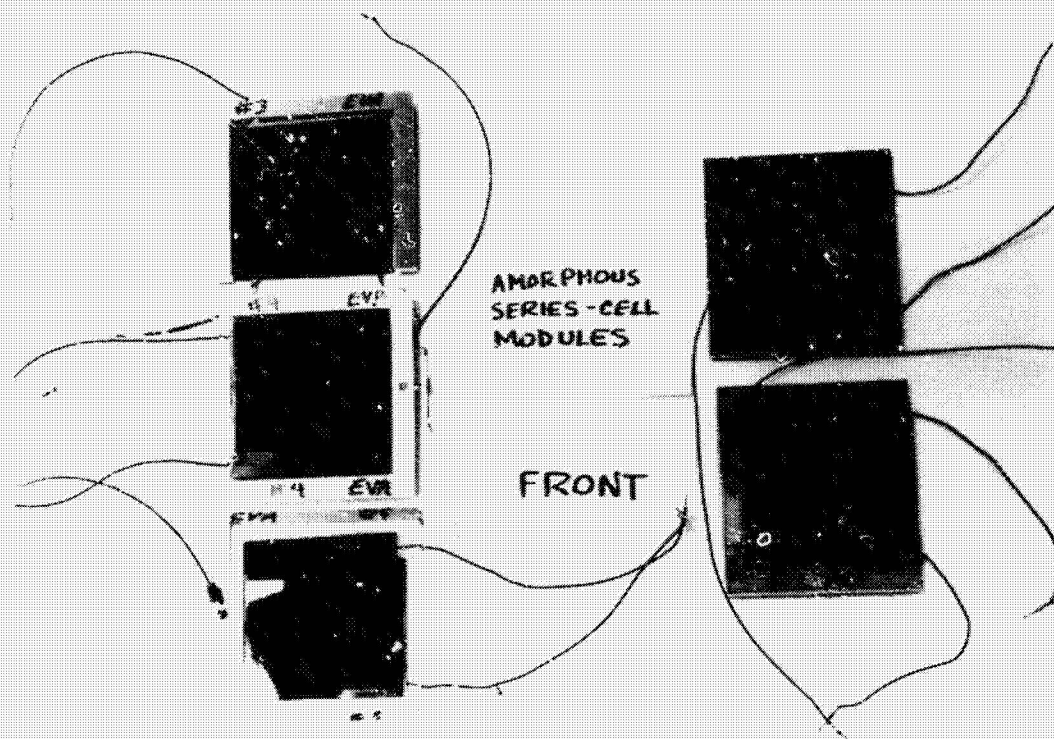


Figure 18

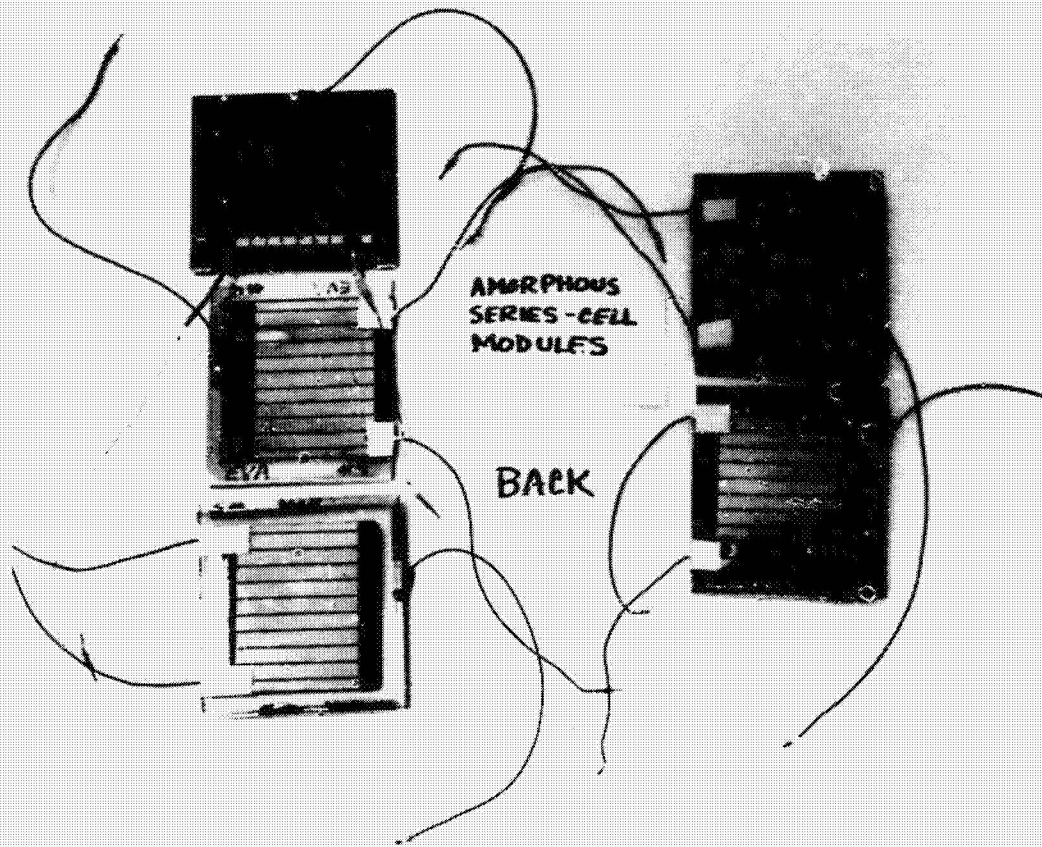




Figure 19

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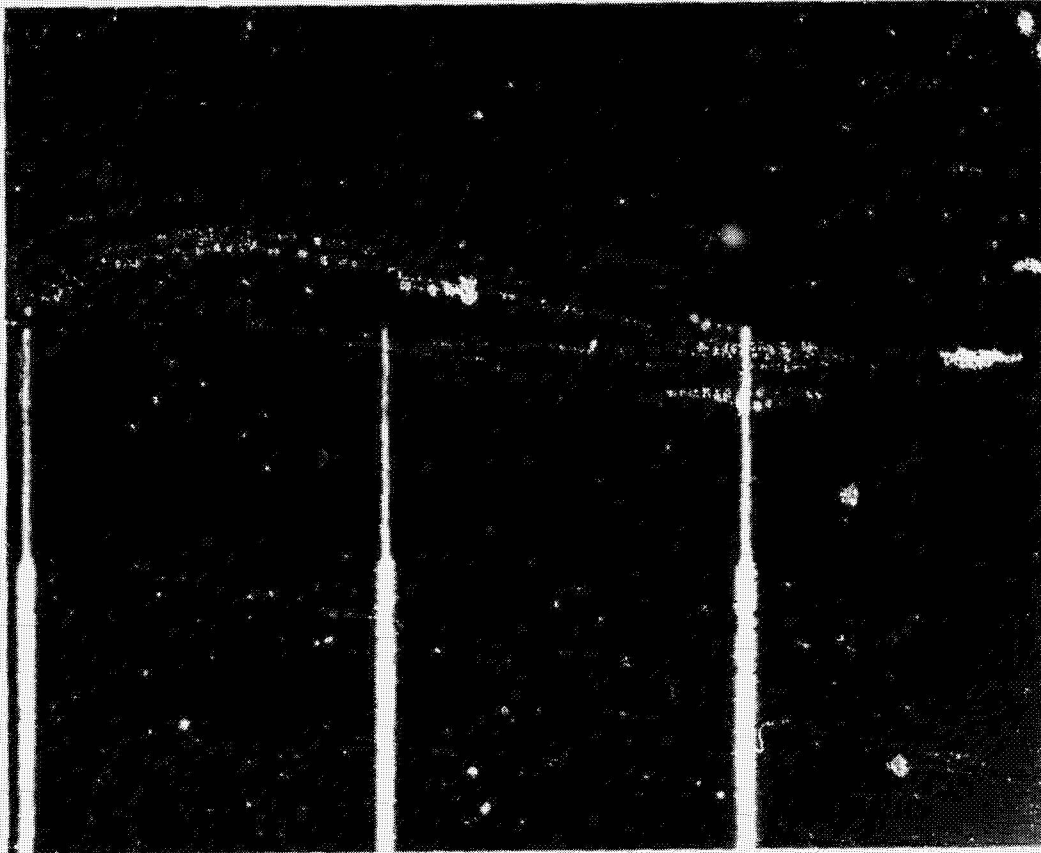


Figure 20

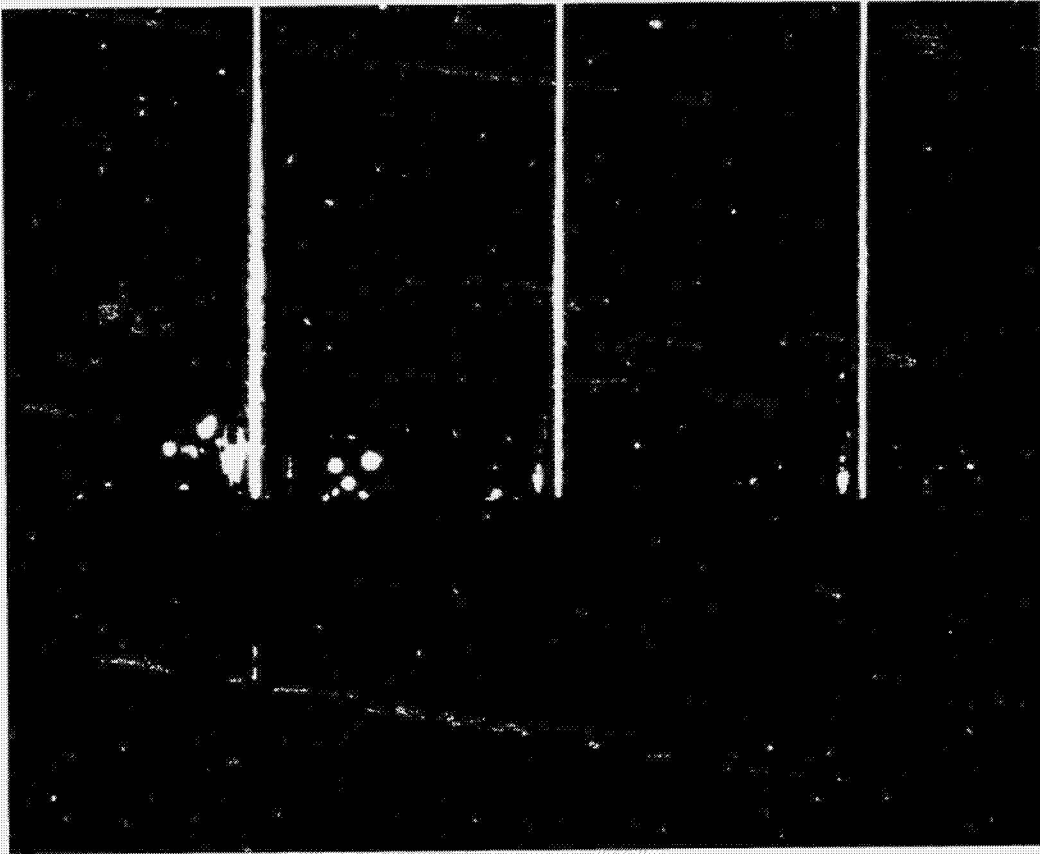




Figure 21

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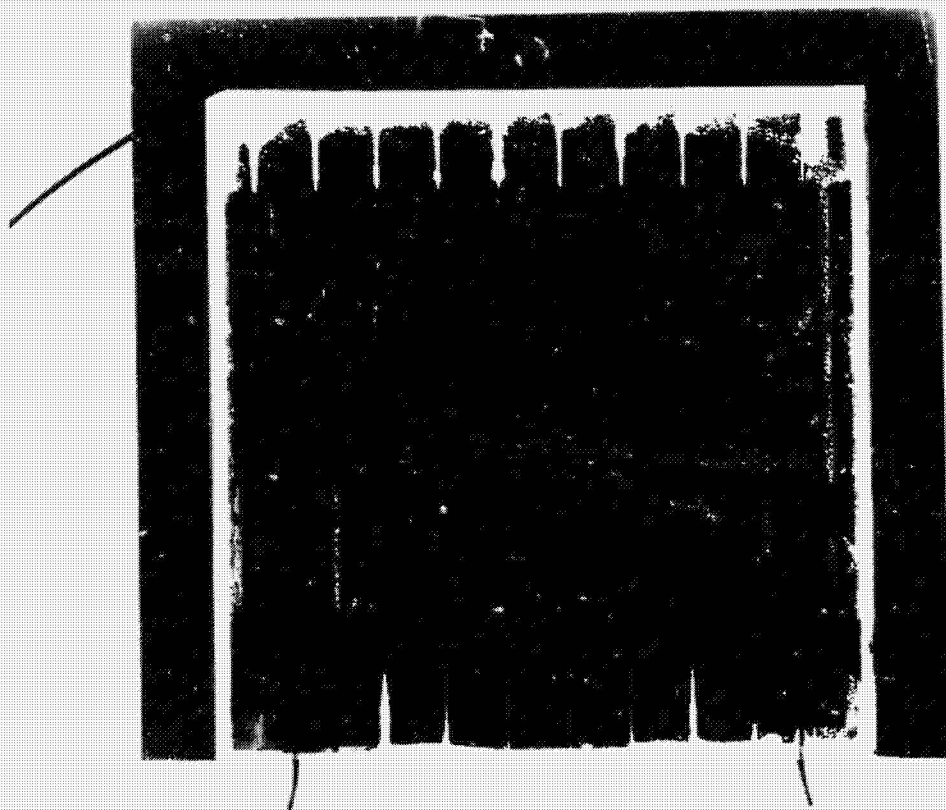


Figure 22



Figure 23

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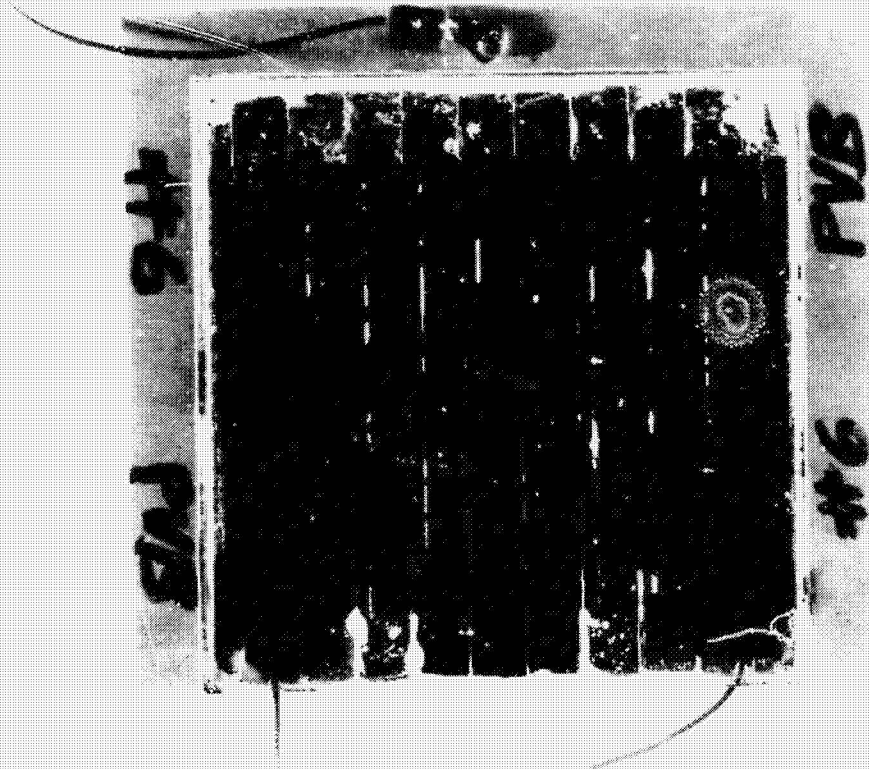




Figure 24

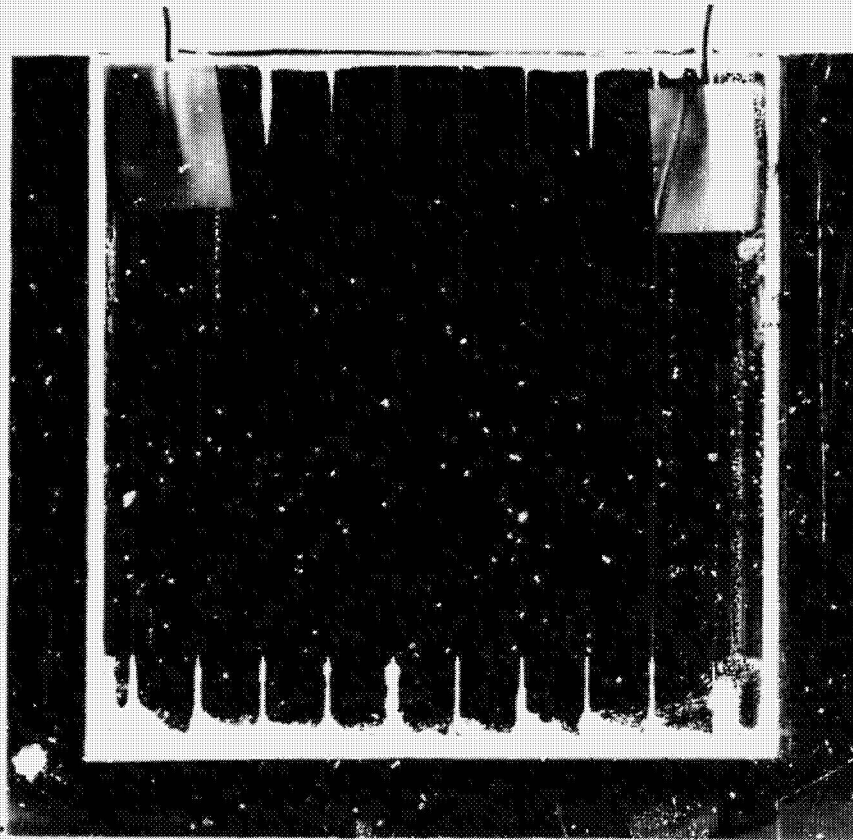


Figure 25

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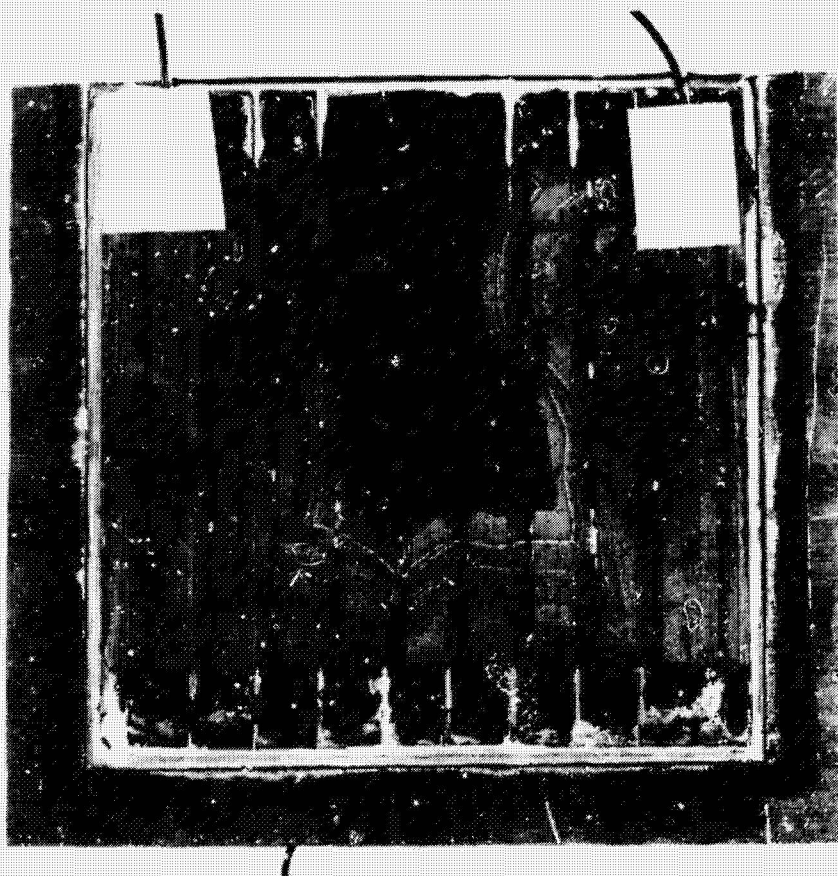




Figure 26

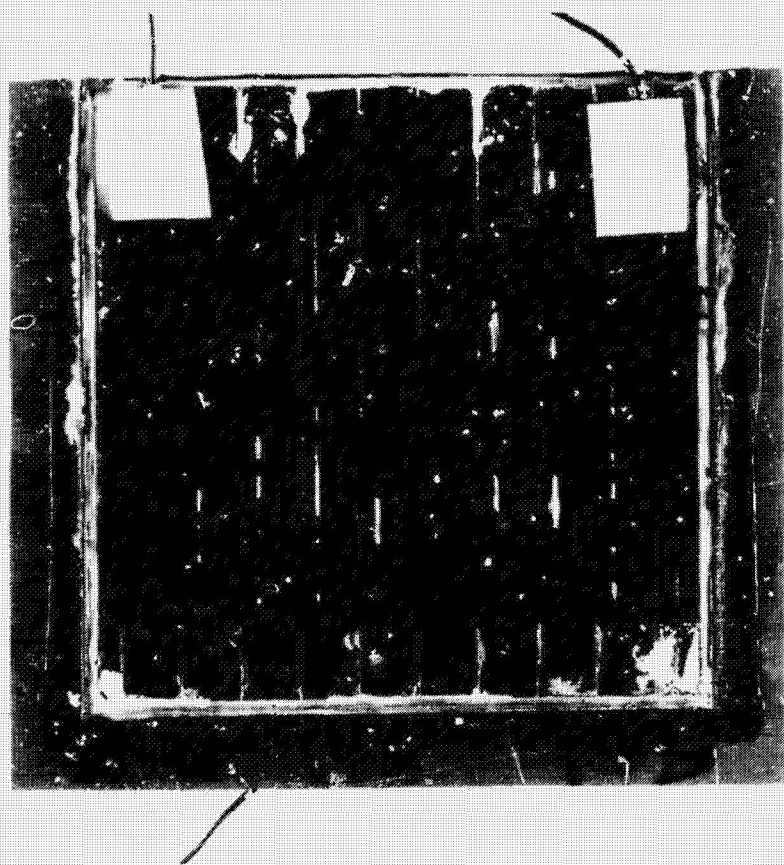


Figure 27

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Figure 28

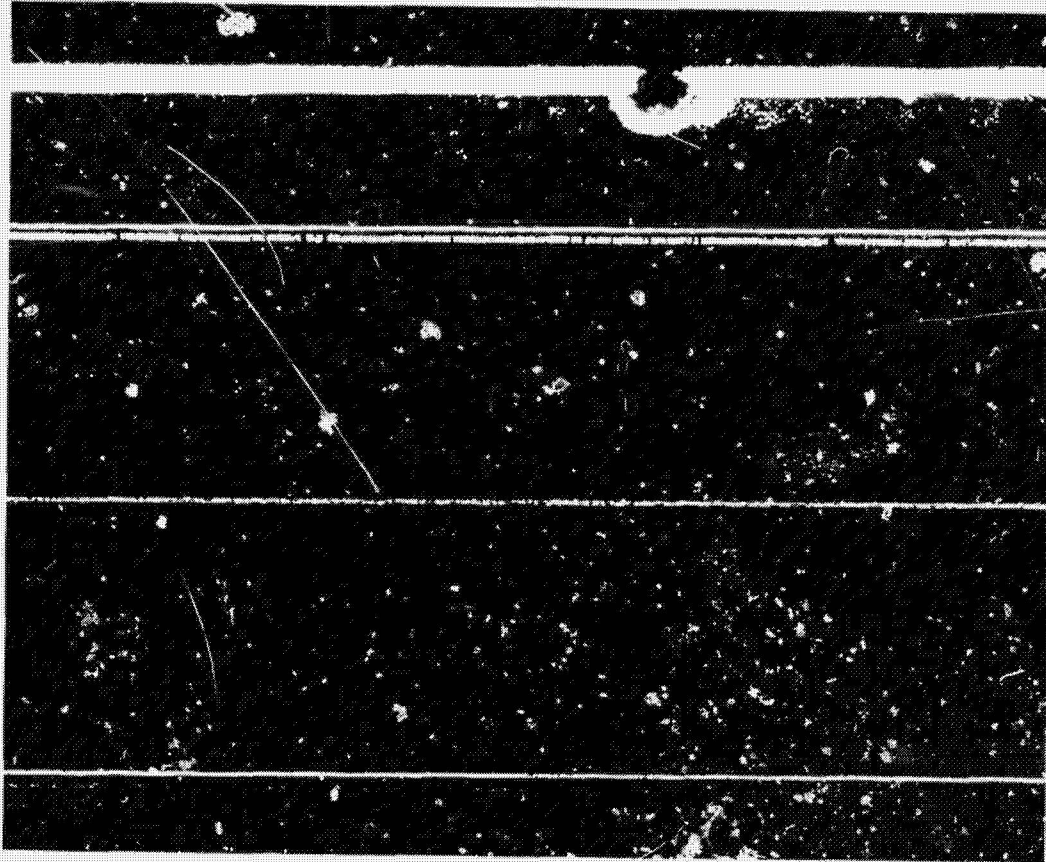




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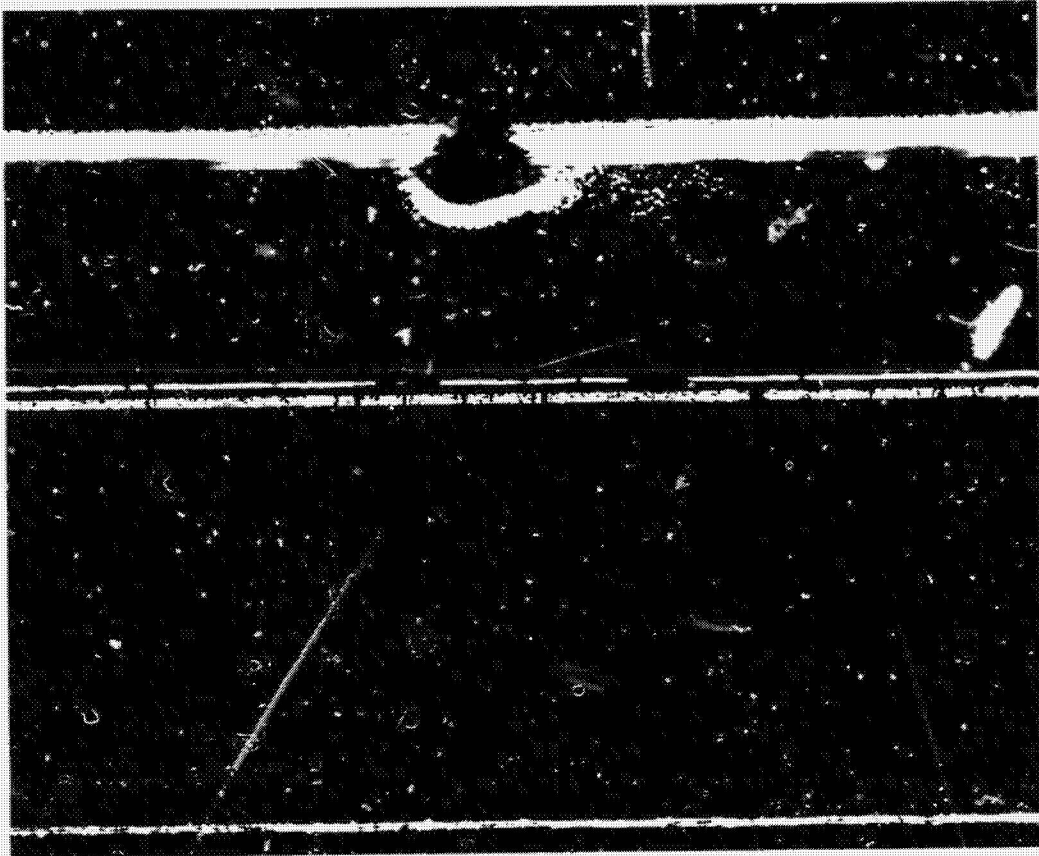


Figure 30

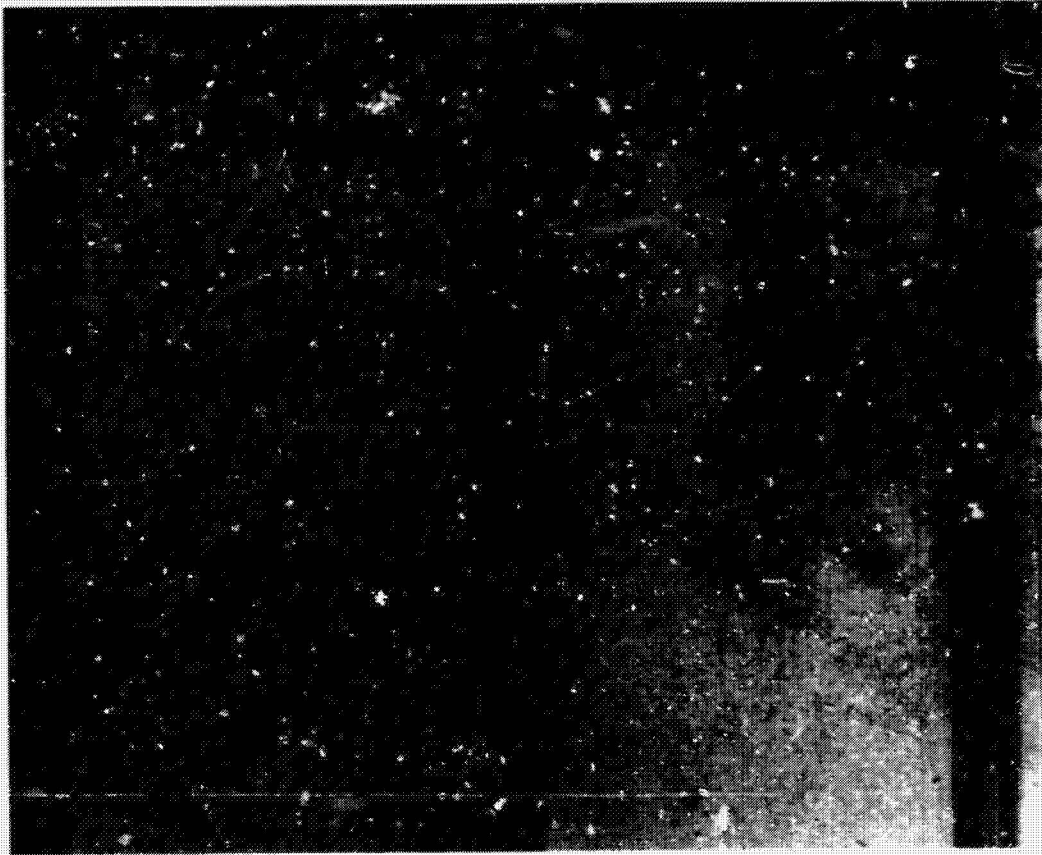


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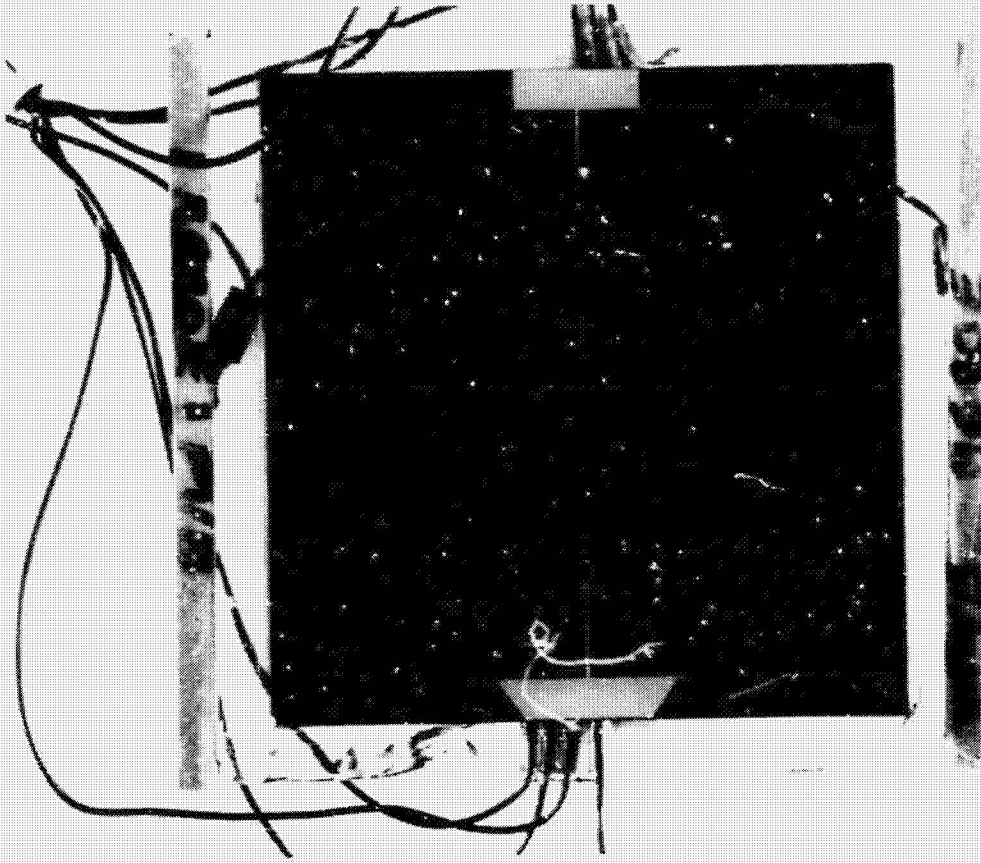




Figure 33

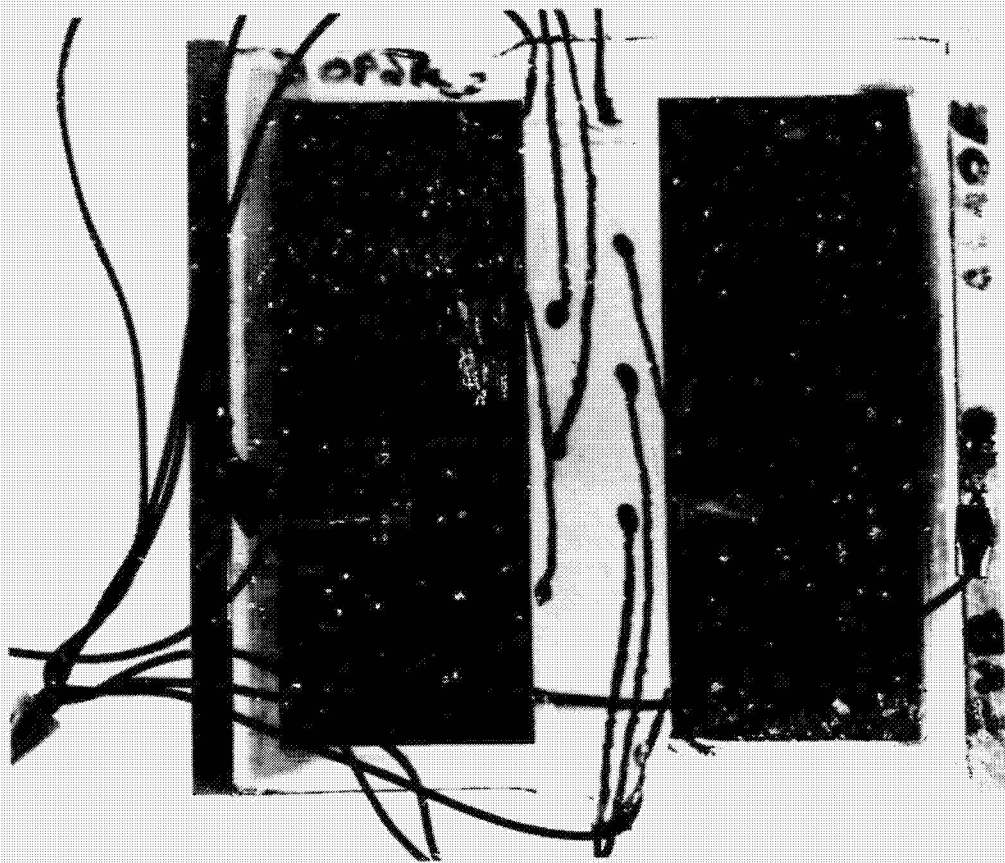


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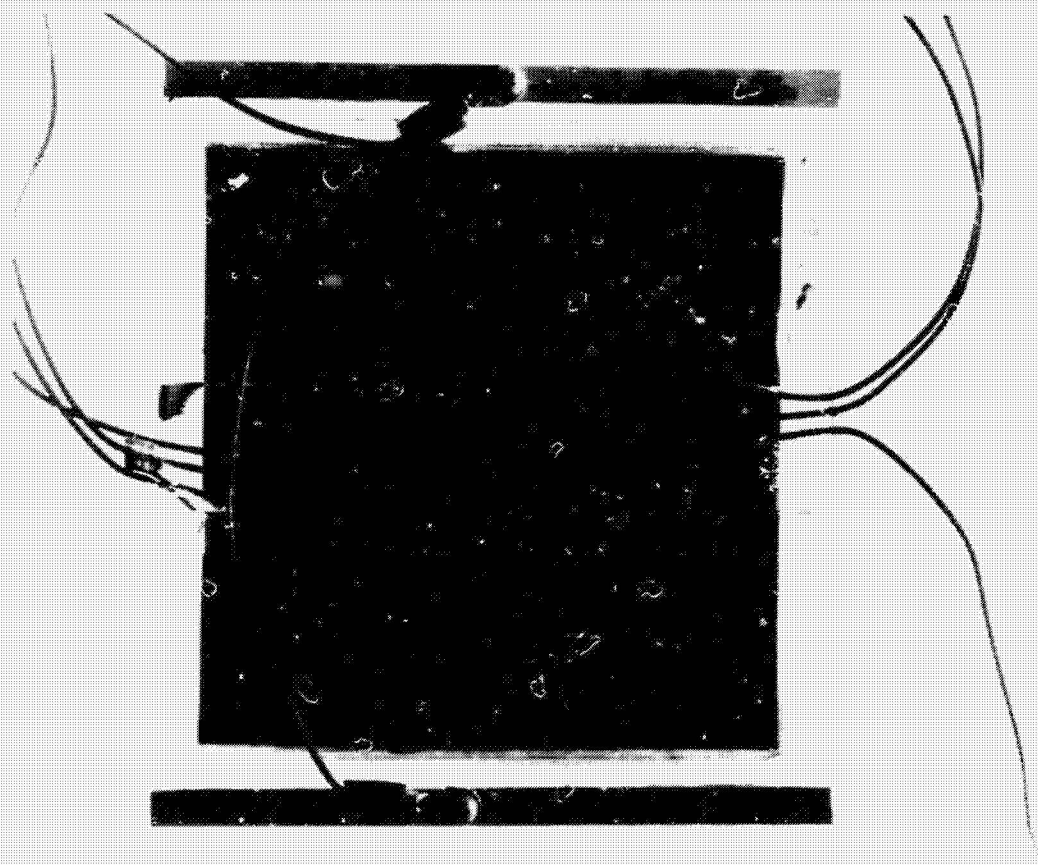


Figure 35

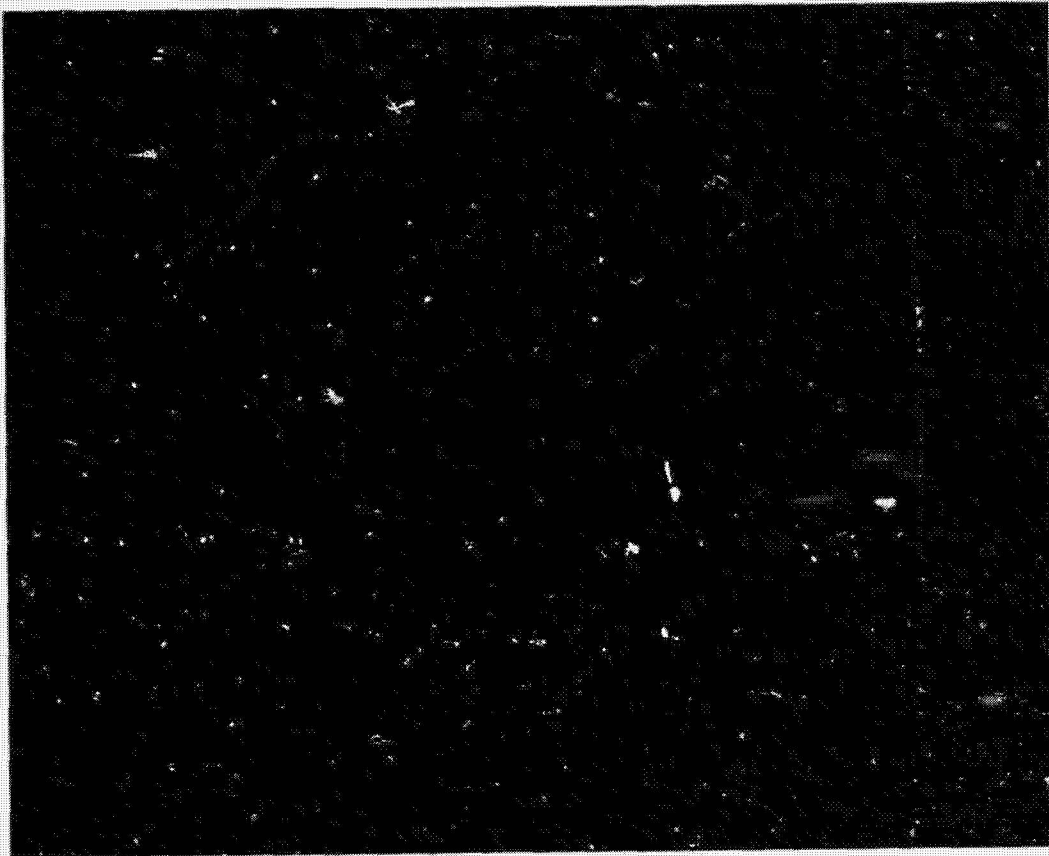
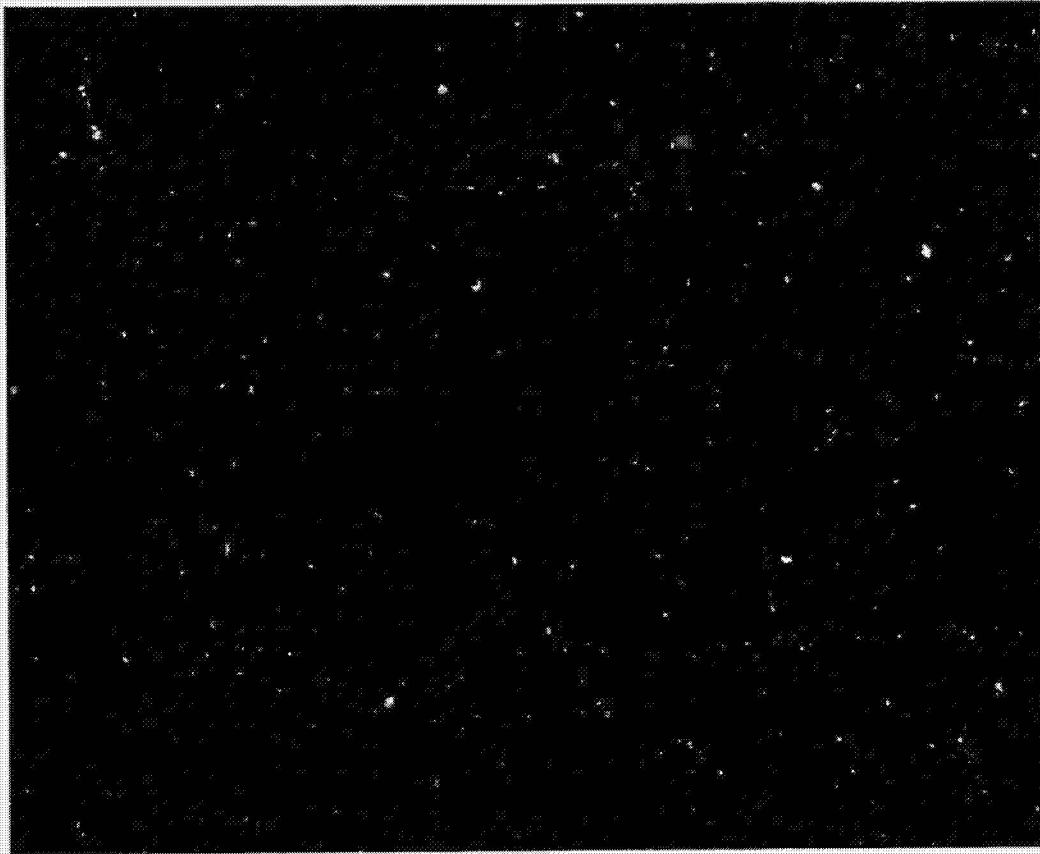




Figure 36

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## DISCUSSION

ROSS: Let me start out with just a comment to second what Gordon said at the very beginning. Even though these things look horrible, in fact the total amount of charge transfer to destroy an amorphous module is very comparable to what it is for the crystalline-silicon module. What is interesting here is that this particular mechanism is causing a form of degradation that we don't really understand, in terms of these little wormy looking erosions that don't follow the normal patterns. In crystalline we always erode the part of the cell that's next to the electrode. With amorphous we don't see erosion next to the electrode; we see this very selective strange-looking erosion out in the middle of the cell at some seemingly random spot.

JESTER: Did you measure the I-V curves of any of those cells before and after? I mean obviously they looked terrible, but did it show up as series resistance, as you might expect?

MON: We had a weirdness happen when we were attempting to measure pre-test I-V curves, so we got hardly any, but we did get I-V curves at 40 hours, 130 hours and 300 hours. The basic degradation occurred in series resistance, although there was some short circuit current reduction, probably due to encapsulation obscuration. I must say that we have had a crash program to gather data, but we haven't had much time to analyze, to go deeply into what's really happening.

JESTER: I was wondering if they all do it, or was there one cell on one module, or many of them?

MON: No. Four parallel modules survived unscathed -- the four modules encapsulated in EVA -- except for that one picture I showed, where it looked like there were watermarks. And then the fifth parallel module was PVB, and that was the one that gave us all these wormholes. So, it's something to do with the PVB, probably with the plasticizer and all the alien ions in the plasticizer. All the series modules showed extensive degradation.

JESTER: Are these modules all from one company?

MON: We got these modules from two companies. If you want to know the names of them, see me later. The parallel modules were basically test modules. They certainly had no pedigree, we just got them and tested them. The series modules were made for the purpose, I guess, of producing power.

MARSHALL: We have seen similar mysterious corrosion in aluminum layers on space cells. Primarily contamination by borides or bromides. Polarities have a second-order effect; you may be looking at something that would have occurred without voltage. If you had some kind of contaminant in there at those humidities -- there is



some literature on it. Primarily in painted metal surfaces on ships and things. We have seen it on the back-surface reflector of a cell, usually in greater than 70% relative humidity.

LESK: For central-power generation your first curve showed that no matter what the metallization system, after 1 C/cm they all died. Are you saying there is a finite calculable lifetime for central power where your voltage will be above 500 volts?

MON: I'm saying it seems to be that between 1 and 10 C of charge per cm of frame edge length is necessary to produce, say, 50% failures. We don't have this down solid. It was surprising that the amorphous gave a very similar result. So I think I can say with some justification that somewhere between 1 and 10 C/cm you are going to get about 50% cell failure. We have taken that number and run with it. We developed a life-prediction algorithm; the question is, how much faith do you have in that algorithm? The answer is, I have a lot of faith in it. Even though I could not say it is precisely 4.2 C/cm, it is somewhere between 1 and 10, an order of magnitude. That is basically all you are interested in, in life prediction anyway, at this point.

ARNETT: Was it dangerous for us to bid on the SMUD program, then?

ROSS: First of all, with EVA-encapsulated modules we have done some life prediction, and it appears you have the equivalent of almost 30 years of life with conventional crystalline or amorphous modules. It is a non-problem. Now that I have said that, let me withdraw all of that and say, with respect to a lot of amorphous modules, there is not any EVA between the module and the frame. The conductive oxide layer goes on the amorphous module right out to the edge of the glass. And it turns out that it's your gasket, your lovely gasket that the Hughes person spoke about earlier, that may be, in fact, the determiner of these integrated corrosion currents. This is why it becomes terribly important -- the selection of the edge treatment of these modules, in terms of the isolation of the TO coating away from the edge of the glass, and the very careful treatment of that gasket isolation from the frame. This also obviously includes wet environments, so that even if you have a plastic frame, if the entire surface of the plastic is wet and it's matted on a metal structure, you may have basically an electrically conductive path up to the edge of whatever this gasket is. The PVB here, even though it looks bad, really works for us as a standard of known high-conductivity encapsulant material that allows us to have fairly large numbers of amp-hours in fairly short periods of time, which means you could accelerate it in a testing environment. EVA, with a very high resistivity, is a thousand times less effective in the test of showing degradation, so things come out looking very pretty. The bottom line is to take these data now on total corrosion currents and try to relate them to your module design with your particular edge treatment and your particular gasket. This gives you a feeling that you can measure corrosion currents with your modules; you can relate it back to whether or not you will survive

in the field. If you predict between 1 and 10 C/cm of edge for your module, you will be in trouble. You can show that it is in the order of magnitude below that, then you are probably not in too bad shape.

ARNETT: Just to clarify my thinking on the construction of the test samples that you used, was it only the edge that is exposed, and PVB between?

ROSS: The whole thing is encapsulated in EVA. That in the gap between the frame and the cell is EVA. The submodule has EVA on all sides of it. The whole thing is floating in a blob of material.

MON: The front surface is glass, the back surface is EVA.

ARNETT: So, like in an 85-85 environment, you have the maximum penetration capability. If you had a back sheet on that, or if it was glass, then you would be looking at the edge. At some point would you attempt to repeat these tests with a structure that represents more of a real-world module?

MON: Yes. That is one of our next steps.

ARNETT: Do it!