tttps://ntrs.nasa.gov/search.jsp?R=19860015574 2020-03-20T15:31:17+00:00Z

19P

5101-280 Flat-Plate Solar Array Project

DOE/JPL-1012-113 Distribution Category UC-63b

2610

# Environmental Tests of Metallization Systems for Terrestrial Photovoltaic Cells

Paul Alexander, Jr.

(JPL-Publ-85-86)ENVIRONMENTAL TESTS OFN86-25045METALLIZATION SYSTEMS FOR TERRESTRIAL<br/>PHOTOVOLTAIC CELLS (Jet Propulsion Lab.)N86-2504579 p HC A05/MF A01CSCL 10AUnclasG3/44G3/4443381

December 31, 1985

Prepared for U.S. Department of Energy Through an Agreement with National Aeronautics and Space Administration by

Jet Propulsion Laboratory California Institute of Technology Pasadena, California

JPL Publication 85-86

5101-280 Flat-Plate Solar Array Project DOE/JPL-1012-113 Distribution Category UC-63b

# Environmental Tests of Metallization Systems for Terrestrial Photovoltaic Cells

### Paul Alexander, Jr.

December 31, 1985

Prepared for U.S. Department of Energy

Through an Agreement with National Aeronautics and Space Administration by

Jet Propulsion Laboratory California Institute of Technology Pasadena, California

JPL Publication 85-86

0

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This publication reports on work done under NASA Task RE-152, Amendment 66, DOE / NASA IAA No. DE-AI01-76ET20356.

٤

#### ABSTRACT

Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were  $-50^{\circ}$ C to  $150^{\circ}$ C per cycle. Humidity conditions were  $70^{\circ}$ C at 98% relative humidity. The seven metallization systems were: (1) Ti/Ag, (2) Ti/Pd/Ag, (3) Ti/Pd/Cu, (4) Ni/Cu, (5) Pd/Ni/Solder, (6) Cr/Pd/Ag, and (7) Thick Film Ag.

All of the seven metallization systems showed slight to moderate decreases in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copper-based systems showed the largest decrease in cell efficiencies after temperature cycling.

All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper-based systems again showed the largest decrease in cell efficiencies after humidity exposure.

Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.

#### ACKNOWLEDGMENTS

Acknowledgments are extended to ASEC Corp. for fabricating the test cells, and to Jerry Stebbins, Lee Midling, and Ken Gray of the JPL Process Research Laboratory who conducted the environmental tests and generated the cell I-V data. Acknowledgments are also extended to Ron Williams for his help in editing this document.

# PRECEDING PAGE BLANK NOT FILMED

v

•

### PAGE IV INTENTIONALLY BLANK

### CONTENTS

I.	INTRODUCTION	1-1
II.	PROCESSING OF SPECIMEN CELLS	2-1
III.	DISCUSSION OF METALLIZATION SYSTEMS	3–1
IV.	TEST EQUIPMENT	4-1
۷.	TEST PROGRAM	5-1
VI.	TEST RESULTS	6-1
	A. I-V CHARACTERISTICS AFTER ENVIRONMENTAL EXPOSURE	6-1
	B. SECONDARY ION MASS SPECTROMETRY EVALUATION	6-27
	C. I-V CURVES OF TEMPERATURE CYCLING AND HUMIDITY EXPOSURE TESTS	6-29
VII.	DISCUSSION OF RESULTS	7-1
	A. OVERVIEW	7-1
	B. TEMPERATURE CYCLING TESTS	7-1
	C. DISCUSSION OF HUMIDITY TESTS	7-3
VIII.	REFERENCES	8-1
IX.	SELECTED BIBLIOGRAPHY	9–1
	APPENDIX	A-1

### Figures

4-1.	Temperature and Humidity Chamber 4-2
4-2.	Temperature Cycling Chamber
4-3.	I-V Test Equipment, Light Source 4-4
4-4.	I-V Test Equipment, Data Printout 4-5
6-1.	Control Cells (No Environmental Exposures) for Ti/Ag, Ti/Pd/Ag, Ti/Pd/Cu, Ni/Cu, Pd/Ni/Solder, Cr/Pd/Ag and Thick Film Ag Paste 6-3
6-2.	Control Cells, After Temperature Cycling, and After Humidity Exposure, Ti/Ag (a, b and c) 6-4

# PRECEDING PAGE BLANK NOT FILMED

6-3.	Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Ti/Pd/Ag (a, b and c) 6	-6
6-4.	Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Ti/Pd/Cu (a, b and c) 6	-8
6-5.	Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Ni/Cu (a, b and c) 6	-10
6-6.	Control Cells, 16x, After Temperature Cycling, and After Humidity Exposure, Pd/Ni/Solder (a, b and c) 6	-12
6-7.	Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Cr/Pd/Ag (a, b and c) 6	-14
6-8.	Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Thick Film Ag Paste (a, b and c)	-16
6-9.	Temperature Cycling: Efficiency Versus Number of Cycles for Seven Metallization Systems 6	-18
6-10.	Temperature Cycling: Percent Change in Efficiency Versus Number of Cycles for Seven Metallization Systems	-18
6-11.	Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ti/Ag	-19
6-12.	Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ti/Pd/Ag 6	-19
6-13.	Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ti/Pd/Cu 6	-20
	Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ni/Cu 6	-20
6-15.	Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Pd/Ni/Solder 6	-21
6-16.	Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Cr/Pd/Ag 6	-21
6-17.	Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Thick Film Ag Paste 6	-22
6-18.	Humidity Tests: Efficiency Versus Number of Days Exposure For All Seven Metallization Systems	-22
6-19.	Humidity Tests: Percent Change in Efficiency Versus Number of Days Exposure For All Seven Metallization Systems	-23

•

6-20.			Series Resistance Ti/Ag		•	•	•	6-23
6-21.			Series Resistance Ti/Pd/Ag	•••	•	•	•	6-24
6-22.			Series Resistance Ti/Pd/Cu		•	•	•	6-24
6-23.			Series Resistance Ni/Cu	•••	•	•	•	6-25
6-24.	-	-	Series Resistance Pd/Ni/Solder		•	•	•	6-25
6-25.			Series Resistance Cr/Pd/Ag		•	•	•	6-26
6-26.	•	•	Series Resistance Thick Film Ag Paste	e.	•	•	•	6-26
6-27.	Sample of the SIN	1S Profile Data	•••••	•••	•	•	•	6-28
6-28.	I-V Curves of Ter Sample, Ti/Pd/Cu		ng Test, Selected	•••	•	•	•	6-31
6-29.	I-V Curves of Ter Sample, Ti/Pd/Ag	•	ng Test, Selected	•••	•	•	•	6-33
6-30.	I-V Curves of Hur Sample, Ti/Pd/Cu		Test, Selected		•	•	•	6-35
6-31.	I-V Curves of Hum Sample, Ti/Pd/Ag		Test, Selected		•	•	•	6-37

## <u>Tables</u>

2-1.	Metallization Processing for Each Metallization System
3-1.	Block IV Metallization Systems
5-1.	Temperature Cycling Tests
5-2.	Humidity Exposure Tests
6-1.	Summary of the Results for Temperature and Humidity Exposure Tests
6-2.	Data for I-V Curves of Temperature Cycling Test, Selected Sample, Ti/Pd/Cu

6-3.	Data for I-V Curves of Temperature Cyc Selected Sample, Ti/Pd/Ag		. 6-32
6-4.	Data for I-V Curves of Humidity Exposu Selected Sample, Ti/Pd/Cu	-	. 6-34
6-5.	Data for I-V Curves of Humidity Exposu Selected Sample, Ti/Pd/Ag		. 6-36

.

.

- . .

.

.

#### SECTION I

#### INTRODUCTION

The Flat-Plate Solar Array (FSA) Project was formed at the Jet Propulsion Laboratory (JPL) in 1975 under the sponsorship of the U.S. Department of Energy (DOE). The objective of the project was to reduce the cost of making solar cells to the point at which photovoltaic power would be cost-competitive with electrical power generated by fossil fuels. The cost goal for making terrestrial solar cells was established at \$0.70/watt (1980 dollars), a drastic reduction from over \$100/watt for space cell fabrication. This very severe cost reduction goal generated a re-thinking of the entire fabrication process, starting with the manufacture of solar grade silicon material, through silicon sheet formation, through cell processing, and through solar module fabrication. The terrestrial solar cell evolved from this re-thinking and is a slightly different species than the space solar cell. The silicon material, the silicon sheet, the solar cell processing and module fabrication for terrestrial application evolve from different fabrication techniques than space cell fabrication.

In the very important area of contact metallization of terrestrial solar cells, cheaper metals and new ways for applying them were pursued. The expensive vacuum evaporated titanium-palladium-silver metallization system, long (and still) the dominant, almost exclusive metallization system in space solar cells because of its very excellent performance properties, has given way in terrestrial applications to solder-based metallization systems, thick film metallization systems and copper based metallization systems, mostly because of their cheaper costs. Metal deposition by vacuum evaporation has given way to solder dipping, thick film printing and plating. Again, this is because of cheaper costs.

The literature on testing of solar cell metallization systems deals almost entirely with titanium-silver and titanium-palladium-silver metallization systems. This is because the early space cells, going back to the early 1960s, received considerable attention and funding to evaluate these two systems. The Ti/Ag system gave way to the Ti/Pd/Ag when it was determined that the addition of palladium helped the system against moisture ingression and improved cell performance degradation under humidity conditions. The Ti/Pd/Ag metallization system is, and has been for over 20 years, the dominant metallization system for space solar cells, and is also the "standard of comparison" in terrestrial cell work.

In this work seven metallization systems were selected and tested for terrestrial application: (1) Ti/Ag, (2) Ti/Pd/Ag, (3) Ti/Pd/Cu, (4) Ni/Cu, (5) Pd/Ni/Solder, (6) Cr/Pd/Ag, and (7) a Thick Film Ag paste. The tests conducted were very straightforward, similar to those found in the literature on testing. It was the intent of this program to evaluate these different metallization systems (as contrasted with qualifying such systems) and to assess the relative sensitivities of these metallization systems to the two most commonly tested environments, temperature cycling and humidity exposure. It is hoped that the data collected and described in this test program will add to the body of literature on environmental testing of solar cell metallization systems.

#### SECTION II

#### PROCESSING OF SPECIMEN CELLS

All cells used in this test program were from the same lot and processed as one lot through front and back junction formation. The starting material was 3 in. diameter, chemically polished, 12 mils thick, 2 ohm-cm, p-type, Czochralski (Cz) grown silicon with (100) orientation. The wafers were masked with SiO<sub>2</sub> using a low temperature, chemical vapor deposition process. The back P+ layer was first formed by boron nitride diffusion followed by the front N layer (0.3  $\mu$ m deep) which was diffused using a POCl<sub>3</sub> source. The sheet resistance of the N layer surface was approximately 30 ohms/square. The silicon oxide layer, formed during diffusion, was removed by an HF dip. This procedure eliminated process variations in the front and back junctions since the junctions were all formed together for all seven metallization groups.

After the front and back junctions were formed, all of the 3 in. diameter cells were cut into 2 x 2 cm size blanks and equally divided into seven different metallization groups. Again, to eliminate as many process variables as possible, six of the seven metallization groups were metallized by vacuum evaporation through a shadow mask. The seventh group was metallized by screen printing. After completion of each metallization process, all of the cells were coated with Multilayer Antireflective (MLAR) coating and tested at Air Mass 1 (AM1),  $28^{\circ}C$ .

Table 2-1 presents the metallization process information on the seven metallization groups.

Metallization System	Process
Ti/Ag	Evaporate the following: Ti (1000 Å) and Ag (3 $\mu$ m), on both front and back sides, followed by 400°C, 10 min sintering in N <sub>2</sub>
Ti/Pd/Ag	Evaporate the following: Ti (1000 Å), Pd (500 Å) and Ag (3 µm), on both front and back sides, followed by 400°C, 10 min sintering in N <sub>2</sub>
Ti/Pd/Cu	Evaporate the following: Ti (1000 Å), Pd (500 Å) and Cu (2 $\mu$ m), on both front and back sides, followed by 325°C, 10 min sintering in forming gas (10% H <sub>2</sub> and 90% N <sub>2</sub> )
Ni/Cu	Evaporate the following: Ni (5000 Å) and Cu (2 $\mu$ m), on both front and back sides, followed by 325°C, 10 min sintering in forming gas (10% H <sub>2</sub> and 90% N <sub>2</sub> )
Pd/Ni/Solder	Evaporate the following: Pd (500 Å) and Ni (5,000 Å), on both front and back side, followed by $325^{\circ}C$ , 10 min sintering in forming gas (10% H <sub>2</sub> and 90% N <sub>2</sub> ), solder dip
Cr/Pd/Ag	Evaporate the following: Cr (500 Å), Pd (500 Å) and Ag (3 µm), on both front and back side, followed by 400°C, 10 min sintering in N <sub>2</sub>
Thick Film Ag	Screen print back side with silver-aluminum conductor (Thick Film Inc., No. 3398 Ink) and fired at 750°C for 1 min in N <sub>2</sub> , followed by printing silver conductor (Thick Film Inc., No. 3347 Ink) on front side and sintering at $650°C$ for 1 min in N <sub>2</sub>

Table 2-1. Metallization Processing for Each Metallization System

.

#### SECTION III

#### DISCUSSION OF METALLIZATION SYSTEMS

Selection of the metallization systems for this study was determined, for the most part, by consideration of commonly used systems for terrestrial Titanium-palladium-silver is the most familiar metallization system. cells. having been in use for over 20 years, and always used in space cells. Titanium-palladium-silver is also extensively used on terrestrial cells, especially in the earlier designs. Many of the environmental test results found in the cell testing literature is on titanium-palladium-silver. Titanium-silver was a precursor metallization system to titanium-palladiumsilver and is also found in the literature on metallization testing. Palladium was added to the titanium-silver system when it was determined that this addition was beneficial against moisture penetration, especially in humidity testing. The test results, herein, verify this fact. Most of the earlier terrestrial solar cells (1978 to 1982), which were purchased under the FSA-JPL Block buy programs (Block I, Block II, Block III, and Block IV), used solder overlay as the main conducting metal. The metallization systems using solder were typically palladium-nickel-solder, gold-nickel-solder, or nickelsolder. The underlying metals were typically plated by palladium, gold, or nickel solutions and then solder dipped. A palladium-nickel-solder system was tested in this program. The palladium and nickel under-layers were vacuum evaporated rather than plated. In fact, all of the metals used in this program were vacuum evaporated excepting the solder dip operations and the thick film silver metallization system.

Solder based metallization systems have been slowly giving way to copper based systems within the last 3 to 4 years in terrestrial metallization systems. Copper has a much higher electrical conductivity than solder, and on a conductivity per pound basis, is much cheaper than solder. Also copper can be ultrasonically bonded to form a superior cell-to-cell interconnection bond compared to soldered interconnections. Westinghouse, for example, uses a copper based metallization system fabricated by first vacuum evaporating titanium and palladium, and then followed by copper plate-up. The cells are interconnected by ultrasonic bonding. Another terrestrial metallization design is plated nickel followed by copper plate-up. Two copper based metallization systems were tested in this program. One system was nickelcopper (both metals were vacuum evaporated); and the other, titaniumpalladium-copper (again, all three metals were vacuum evaporated).

One thick film system, a commercial silver paste, was tested in this program. Several solar cell manufacturers (Arco Solar, for example) make cells with thick film silver paste metallization systems and they apply the paste by screen printing, the same as done in this test program.

A chromium-palladium-silver system was tested in this program. This metallization system, to this author's knowledge, is not presently being used on any solar cells being commercially manufactured. However, this system has been used for various lab samples for years. The results show that the chromium-palladium-silver system performs as well or better than the titanium-palladium-silver system after humidity tests. Table 3-1 presents data on metallization systems used on the FSA Block IV Solar Module procurement (Reference 1).

The Block IV module, built in the 1980 to 1982 time frame, three generations removed from Block I, II, and III, still shows the use of the Ti/Pd/Ag metallization system, as shown in Table 3-1. Most of the contractors were working on more cost effective metallization systems. However, when cell performance was on the line, there was a tendency to fall back on a proven metallization system such as Ti/Pd/Ag, even though more cost-effective systems were being worked on.

	Metallizatio	on System
Manufacturer	Front Metallization	Back Metallization
Arco Solar	Printed Ag Paste	Printed Al/Printed Ag Paste
Applied Solar Energy Corporation (ASEC)	Vacuum Evaporated Ti/Pd/Ag	Vacuum Evaporated Ti/Pd/Ag
General Electric (GE)	Printed Ag Paste	Printed Al/Printed Ag Paste
Motorola	Plated Pd/Ni/Solder Dip	Plated Pd/Ni/Solder Dip
Photowatt	Plated Ni/Solder Dip	Plated Ni/Solder Dip
Solarex	Vacuum Evaporated Ti/Pd/Ag	Vacuum Evaporated Ti/Pd/Ag
Spire	Vacuum Evaporated Ti/Pd/Ag	Vacuum Evaporated Ti/Pd/Ag

3-2

#### SECTION IV

#### TEST EQUIPMENT

Figure 4-1 is a picture of the humidity chamber used for humidity exposure in this test program. The chamber was manufactured by Blue M Electric Company, Blue Island, Illinois, and is Model No. AC-7502HA-TDA-1(Y). The chamber was developed for long term high temperature/humidity testing that is capable of meeting steady-state requirements such as found in Mil-Std-202C, Method 106B, "continuous operation for 56 days, with low water consumption (less than 1 gallon/24 hours)." Temperature range is  $12^{\circ}$ C above ambient to +93°C ( $\mp$ 1/2°C). The relative humidity range is from 40% to 98% saturation.

Figure 4-2 is a picture of the temperature cycling chamber used for temperature cycling in this test program. The chamber was manufactured by Blue M Electric Company, Blue Island, Illinois, and is Model No. LN-270B-1MP, temperature range -200°C to +300°C. The chamber has a 3kW heater for above ambient heating and is fitted for liquid nitrogen for below ambient cooling. The unit is microprocessor controlled and can be programmed to run various temperature cycling programs.

Figures 4-3 and 4-4 are pictures of the current/voltage (I-V) test equipment. In Figure 4-3, the light source (Solar Simulator, Model No. XT-10) was manufactured by Spectrolab, Sylmar, California. The cell holder equipment beneath the light source is water cooled and set to maintain the cell sample at 28°C. The I-V Plotter and computer equipment are shown in Figure 4-4. The I-V Plotter was manufactured by Tektronix Inc., Model No. 4662. The computer equipment was manufactured by Tektronix Inc., Model No. 4052.

# ORIGINAL PAGE IS OF POOR QUALITY

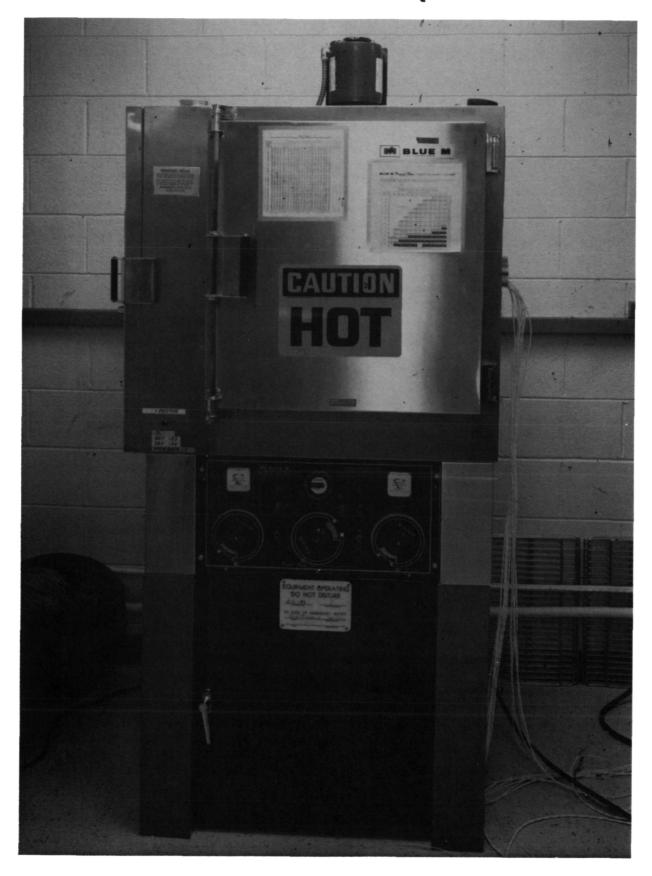


Figure 4-1. Temperature and Humidity Chamber

ORIGINAL PAGE IS OF POOR QUALITY

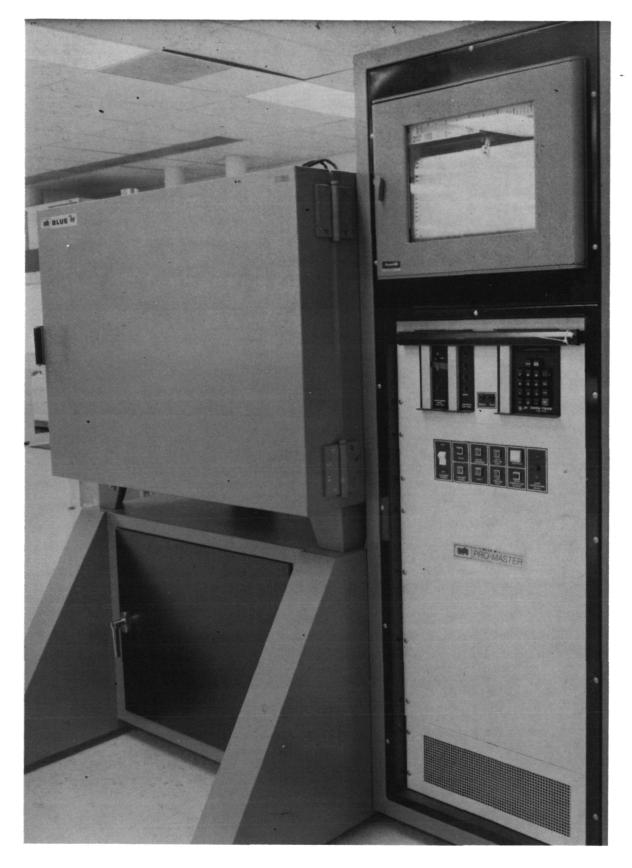


Figure 4-2. Temperature Cycling Chamber

a stat Marine Attraction Marine

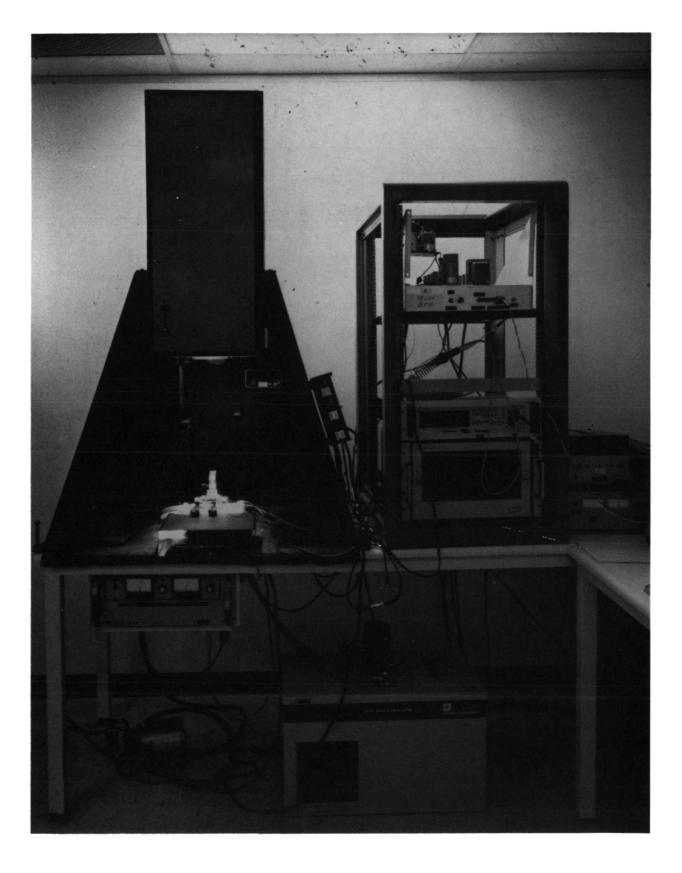


Figure 4-3. I-V Test Equipment, Light Source

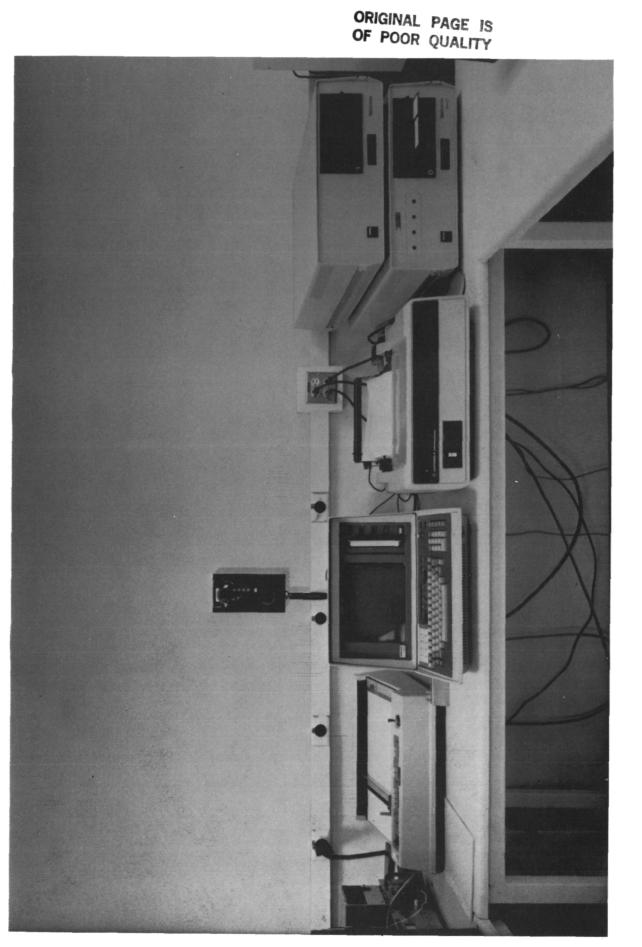


Figure 4-4. I-V Test Equipment, Data Printout

#### SECTION V

#### TEST PROGRAM

Approximately 129 cells were used in the test program. Seven sets of six cells each (43 total) of seven different metallization systems were subjected to temperature cycling tests. Similarly, seven sets of six cells each (43 total) of the seven different metallization systems were subjected to humidity tests. Seven sets of six cells each (43 total) of the seven different metallization systems were used as controls. Tables 5-1 and 5-2 outline the temperature cycling and humidity tests.

Table 5-1. Temperature Cycling Tests <sup>a</sup> , <sup>1</sup>	Table 5-1.	Temperature	Cycling	Tests <sup>a</sup> ,
--	------------	-------------	---------	----------------------

No. of Cells, No. of Cell Types	I-V Test	No. of Temp Cycles	I-V Test	No. of Temp Cycles	I-V Test	No. of Temp Cycles	I-V Test	No. of Temp Cycles	I-V Test	No. of Temp Cycles	I-V Test
6 cells ea of 7 metal types, 43 cells total	43 cells total	10 cycles	43 cells total	30 cycles (40 cycles total)	43 cells total	100 cycles (140 cycles total)	43 cells total	300 cycles (440 cycles total)	43 cells total	560 cycles (1,000 cycles total)	43 cells total 6 ea x 7 sets

<sup>a</sup>Temperature Excursions were:

From  $-65^{\circ}$ C for approximately 6 min dwell at  $-65^{\circ}$ C to  $+150^{\circ}$ C for approximately 6 min dwell at  $150^{\circ}$ C. Approximately 14 min ramp time between temperatures. Total cycle time was approximately 40 min/cycle.

<sup>b</sup> Cell Metal Types:	Bl - Ti/Ag	B3 - Ti/Pd/Cu	B5 - Pd/Ni/Solder	B7 - Thick Film Ag Paste
	B2 - Ti/Pd/Ag	B4 - Ni/Cu	B6 - Cr/Pd/Ag	-

#### Table 5-2. Humidity Exposure Tests<sup>a,b</sup>

No. of Cells, No. of Cell Types	I-V Test	Humidity (No. Days Exposure)			I-V Test	Humidity (No. Days Exposure)	I-V Test	Humidity (No. Days Exposure)	I-V Test	Humidity (No. Days Exposure)	I-V Test
6 cells ea of 7 metal type (43 cells total)		3 days	43 cells total	10 days (13 days total)	43 cells total	20 days (33 days total)	43 cells total	30 days (63 days total)	43 cells total	60 days (123 days total)	43 cells total 6 ea x 7 sets

<sup>a</sup>Humidity conditions were 60°C at 100% saturation for the 3-days and 10 days exposures. Conditions were 70°C at 98% relative humidity for the 20, 30 and 60-day exposures. Differences in humidity conditions were due to testing piggyback with other items which had priority on humidity conditions.

<sup>b</sup> Cell Metal Types:	Bl - Ti/Ag	B3 - Ti/Pd/Cu	B5 - Pd/Ni/Solder	B7 - Thick Film Ag Paste
	B2 - Ti/Pd/Ag	B4 - Ni/Cu	B6 - Cr/Pd/Ag	

#### SECTION VI

#### TEST RESULTS

#### A. I-V CHARACTERISTICS AFTER ENVIRONMENTAL EXPOSURE

Solar cells from each of the seven metallization systems were tested for I-V characteristics after each environmental exposure (see the description of the Test Program). Nine parameters were measured on each I-V test which included: short circuit current, mA ( $I_{sc}$ ); open circuit voltage, mV ( $V_{oc}$ ); maximum power, mW ( $P_{mp}$ ); current at maximum power, mA ( $I_{mp}$ ); voltage at maximum power, mV ( $V_{mp}$ ); cell efficiency ( $\eta$ ); fill factor (FF); cell series resistance, ohms ( $R_s$ ); and cell shunt resistance, ohms ( $R_{sh}$ ).\* A very condensed summary of results is shown in Table 6-1. Extensive light I-V test data are tabulated and presented in the Appendix.

I-V data for each of the seven metallization cell types were generated. The data include: efficiency and fill factor versus temperature cycling; and efficiency and series resistance versus number of days of humidity exposure. The I-V curves are presented in the figures herein.

Pictures at 40 times magnification were taken of selected cell specimens before and after testing. The pictures are presented in the figures herein.

<sup>\*</sup>The shunt resistance values in this work are to be taken as a range or trend as opposed to the absolute values. This is because the algorithms used in the computer program to calculate shunt resistance values, although measured in accordance with one of the ASTM standards, tends to generate numbers that are overly responsive to normal test variations.

Metal System (2x2 cm Cells)	% Change in Cell Efficiency After 1,000 Temperature Cycles <sup>1</sup> ,2	Ranking (Least Degradation)	% Change in Cell Efficiency After 123 Days Humidity Exposure <sup>2</sup> ,3	Ranking (Least Degradation)
Ti/Ag	-4.19	2	-30.15	4
Ti/Pd/Ag	-3.69	1	-11.35	2
Pd/Ni/Cu	-20.7	7	-54.43	6
Ni/Cu	-17.10	6	-71.14	7
Pd/Ni/ Solder	-6.99	4	-12.97	3
Cr/Pd/Ag	-4.6	3	-9.33	1
Thick Film Ag	-14.32	5	-44.40	5

#### Table 6-1. Summary of the Results for Temperature and Humidity Exposure Tests

<sup>1</sup>Temperature excursions were: from -65°C for approximately 6 min dwell at -65°C to +150°C for approximately 6-min dwell at 150°C. Approximately 14 min ramp time between temperatures. Total cycle time was approximately 40 min/cycle.

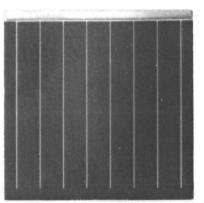
<sup>2</sup>Humidity conditions were: 60°C at 100% saturation for first 13 days and 70°C at 98% relative humidity for 14 through 123 days.

 $^{3}$ I-V test conditions for all tests were: AM1 at  $28^{\circ}$ C.

ORIGINAL PAGE IS OF POOR QUALITY



(a) Ti/Ag



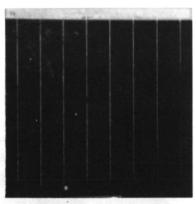
(c) Ti/Pd/Cu



(d) Ni/Cu



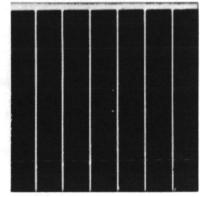
(b) Ti/Pd/Ag



(e) Pd/Ni/SOLDER



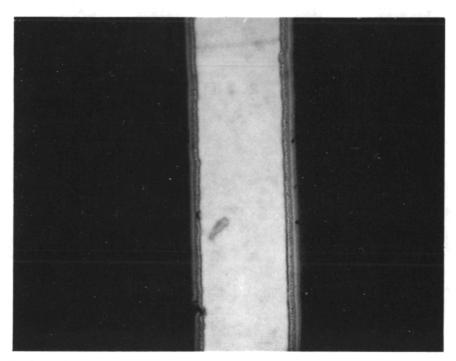
(f) Cr/Pd/Ag



(g) THICK FILM Ag PASTE

Figure 6-1. Control Cells (No Environmental Exposures) for Ti/Ag, Ti/Pd/Ag, Ti/Pd/Cu, Ni/Cu, Pd/Ni/Solder, Cr/Pd/Ag, and Thick Film Ag Paste Figure 6-2 shows a grid line on each of three cells of the Ti/Ag metallization system as follows:

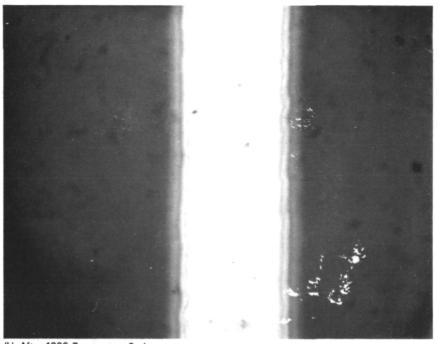
- (a) Cell 19, control cell, 40x magnification.
- (b) Cell 34, after 1000 temperature cycles (-65°C to 150°C), 40x magnification.
- (c) Cell 18, after 123 days humidity exposure (70°C at 98% relative humidity), 16x magnification.



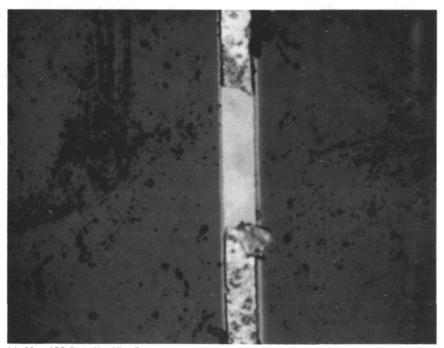
(a) Control Cell

Figure 6-2. Control Cells, After Temperature Cycling, and After Humidity Exposure, Ti/Ag (a, b and c)

ORIGINAL PAGE IS OF POOR QUALITY



(b) After 1000 Temperature Cycles

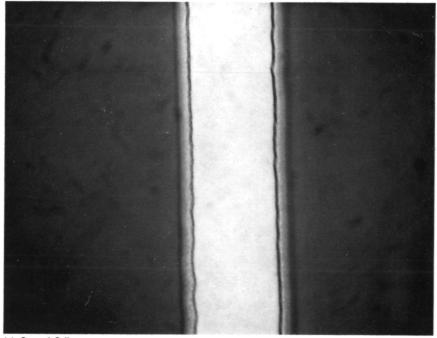


(c) After 123 Days Humidity Exposure

Figure 6-2. (Cont'd)

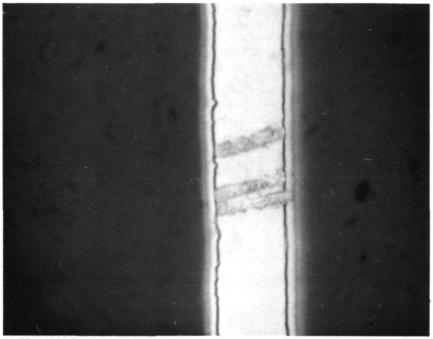
Figure 6-3 shows a grid line on each of the three cells of the Ti/Pd/Ag metallization system as follows:

- (a) Cell 42, control cell, 40x magnification.
- (b) Cell 37, after 1000 temperature cycles (-65°C to 150°C), 40x magnification.
- (c) Cell 19, after 123 days humidity exposure (70°C at 98% relative humidity), 40x magnification.

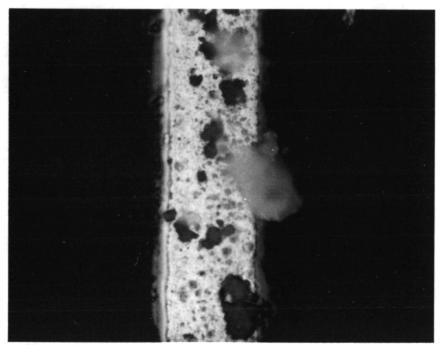


(a) Control Cell

Figure 6-3. Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Ti/Pd/Ag (a, b and c)



(b) After 1000 Temperature Cycles

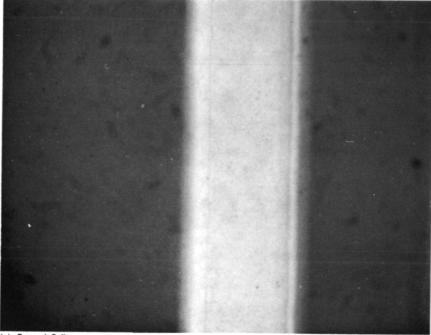


(c) After 123 Days Humidity Exposure

Figure 6-3. (Cont'd)

Figure 6-4 shows a grid line on each of the three cells of the Ti/Pd/Cu metallization system as follows:

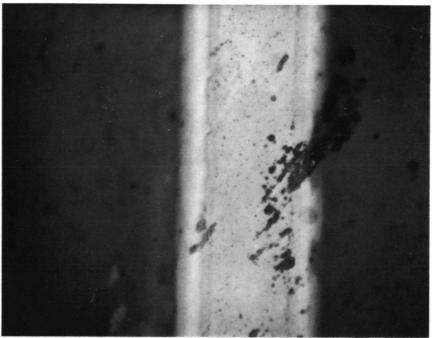
- (a) Cell 25, control cell, 40x magnification.
- (b) Cell 45, after 1000 temperature cycles (-65°C to 150°C), 40x magnification.
- (c) Cell 28, after 123 days humidity exposure (70°C to 98% relative humidity), 40x magnification.



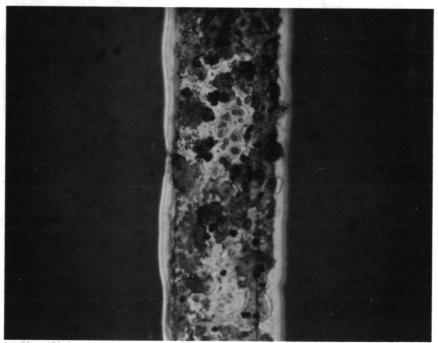
(a) Control Cell

Figure 6-4. Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Ti/Pd/Cu (a, b and c)

ORIGINAL PAGE IS OF POOR QUALITY



(b) After 1000 Temperature Cycles

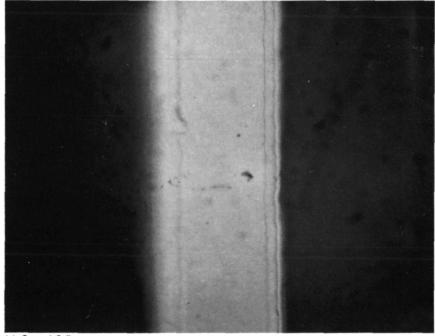


(c) After 123 Days Humidity Exposure

Figure 6-4. (Cont'd)

Figure 6-5 shows a grid line on each of the three cells of the Ni/Cu metallization system as follows:

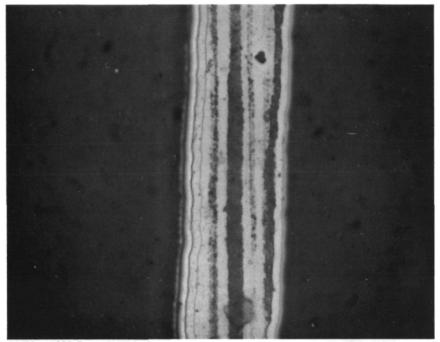
- (a) Cell 30, control cell, 40x magnification.
- (b) Cell 30, after 1000 temperature cycles (-65°C to 150°C), 40x magnification.
- (c) Cell 37, after 123 days humidity exposure (70°C at 98% relative humidity), 40x magnification.



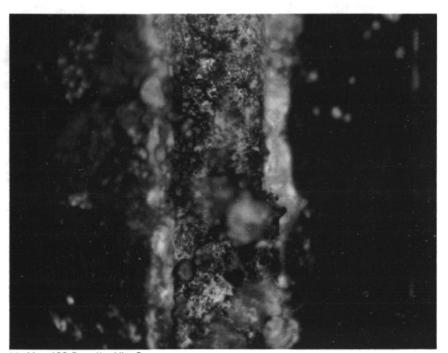
(a) Control Cell

Figure 6-5. Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Ni/Cu (a, b and c)

ORIGINAL PAGE IS OF POOR QUALITY



(b) After 1000 Temperature Cycles

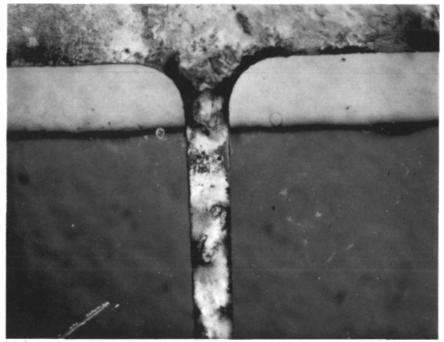


(c) After 123 Days Humidity Exposure

Figure 6-5. (Cont'd)

Figure 6-6 shows a grid line on each of the three cells of the Pd/Ni/Solder metallization system as follows:

- (a) Cell 22, control cell, 16x magnification.
- (b) Cell 30, after 1000 temperature cycles (-65°C to 150°C), 16x magnification.
- (c) Cell 24, after 123 days humidity exposure (70°C at 98% relative humidity), 16x magnification.



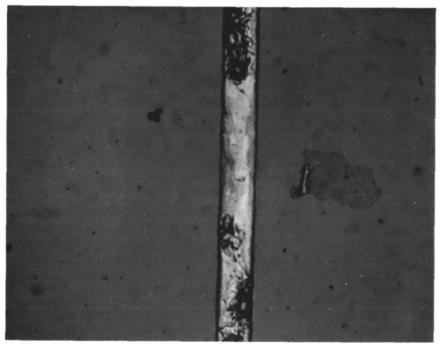
(a) Control Cell

Figure 6-6. Control Cells, 16x, After Temperature Cycling, and After Humidity Exposure, Pd/Ni/Solder (a, b and c)

ORIGINAL PAGE IS OF POOR QUALITY



(b) After 1000 Temperature Cycles

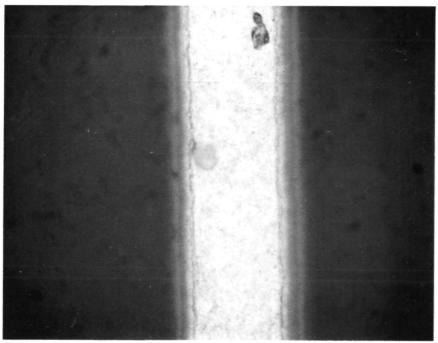


(c) After 123 Days Humidity Exposure

Figure 6-6. (Cont'd)

Figure 6-7 shows a grid line on each of the three cells of the Cr/Pd/Ag metallization system as follows:

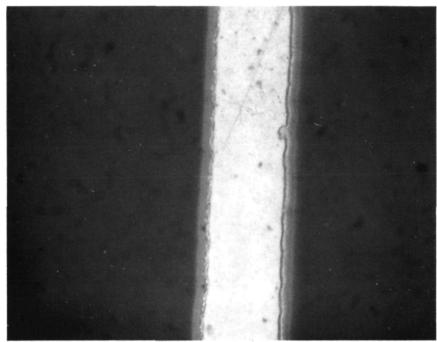
- (a) Cell 26, control cell, 40x magnification.
- (b) Cell 21, after 1000 temperature cycles (-65°C to 150°C), 40x magnification.
- (c) Cell 29, after 123 days humidity exposure (70°C at 98% relative humidity), 40x magnification.



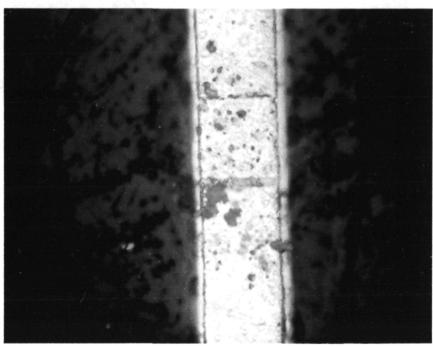
(a) Control Cell

Figure 6-7. Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Cr/Pd/Ag (a, b and c)

## ORIGINAL PAGE IS OF POOR QUALITY



(b) After 1000 Temperature Cycles

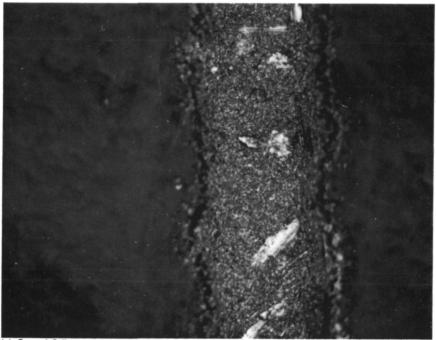


(c) After 123 Days Humidity Exposure

Figure 6-7. (Cont'd)

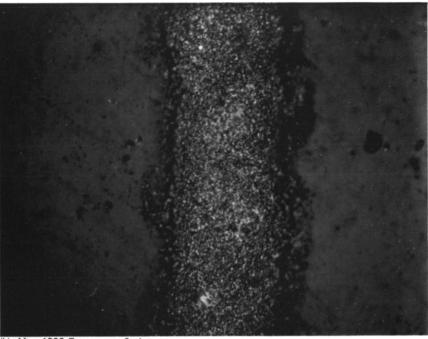
Figure 6-8 shows a grid line on each of the three cells of the Thick Film Ag Paste metallization system as follows:

- (a) Cell 24, control cell, 40x magnification.
- (b) Cell 44, after 1000 temperature cycles (-65°C to 150°C), 40x magnification.
- (c) Cell 61, after 123 days humidity exposure (70°C at 98% relative humidity), 40x magnification.

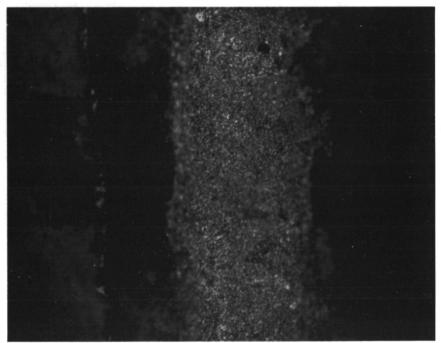


(a) Control Cell

Figure 6-8. Control Cells, 40x, After Temperature Cycling, and After Humidity Exposure, Thick Film Ag Paste (a, b and c)



(b) After 1000 Temperature Cycles



(c) After 123 Days Humidity Exposure

Figure 6-8. (Cont'd)

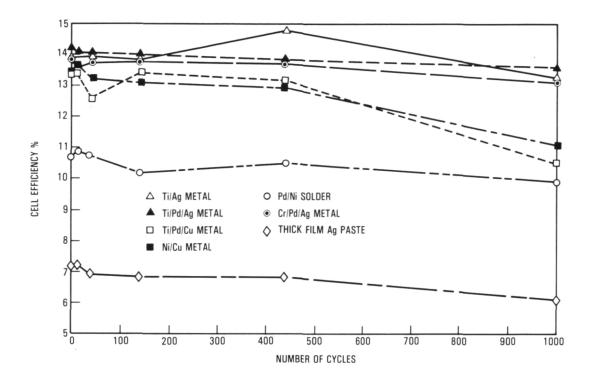


Figure 6-9. Temperature Cycling: Efficiency Versus Number of Cycles for Seven Metallization Systems

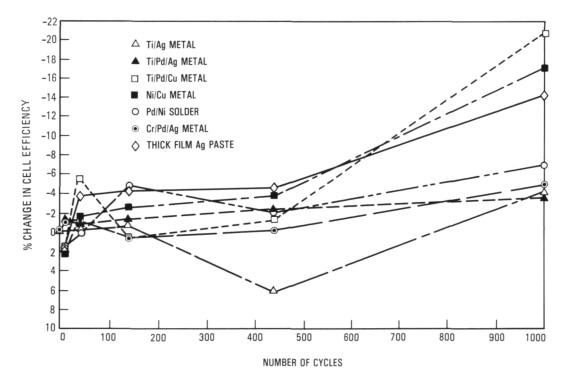


Figure 6-10. Temperature Cycling: Percent Change in Efficiency Versus Number of Cycles for Seven Metallization Systems

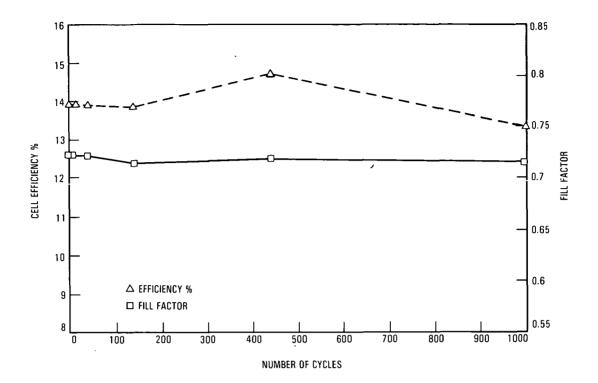


Figure 6-11. Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ti/Ag

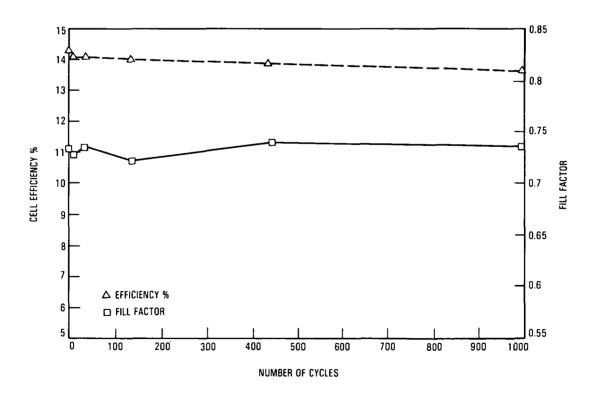


Figure 6-12. Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ti/Pd/Ag

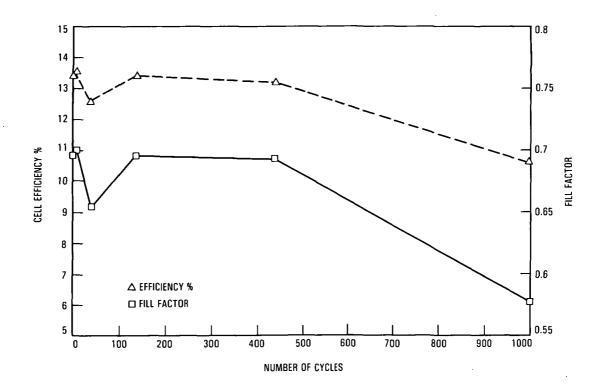


Figure 6-13. Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ti/Pd/Cu

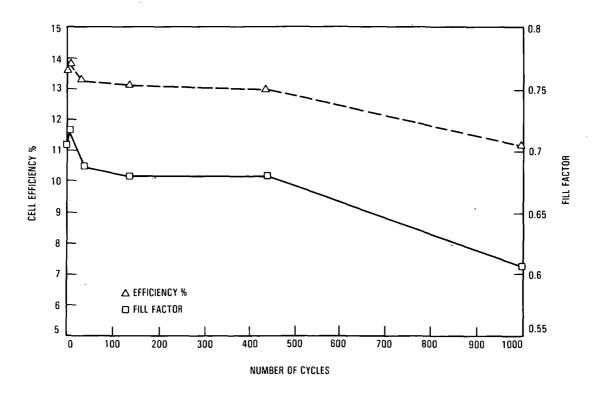


Figure 6-14. Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Ni/Cu

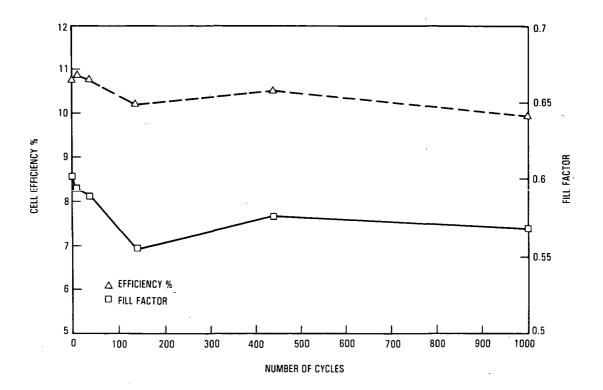


Figure 6-15. Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Pd/Ni/Solder

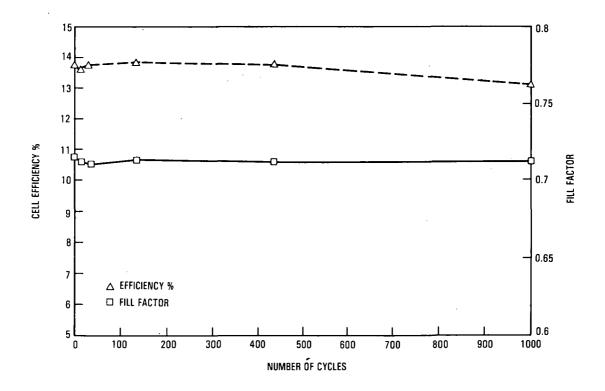


Figure 6-16. Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Cr/Pd/Ag

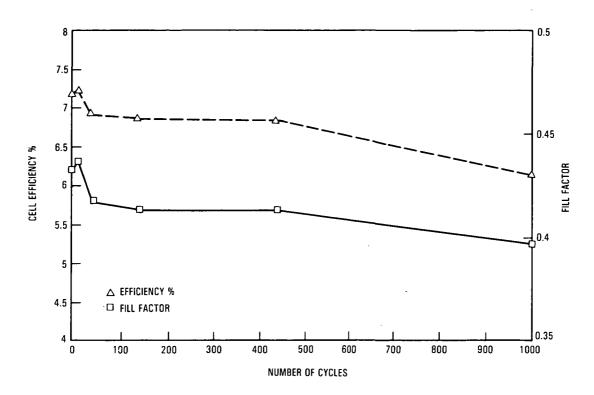


Figure 6-17. Temperature Cycling: Efficiency and Fill Factor Versus Number of Cycles, Thick Film Ag Paste

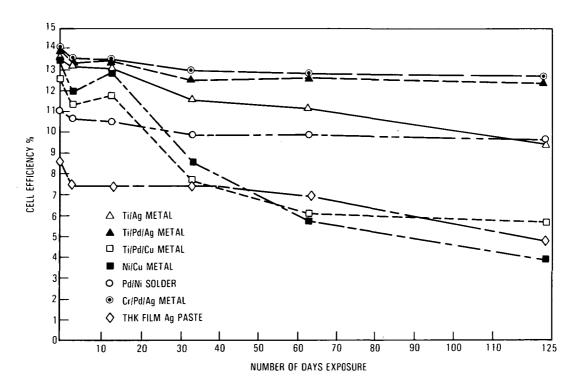


Figure 6-18. Humidity Tests: Efficiency Versus Number of Days Exposure For All Seven Metallization Systems

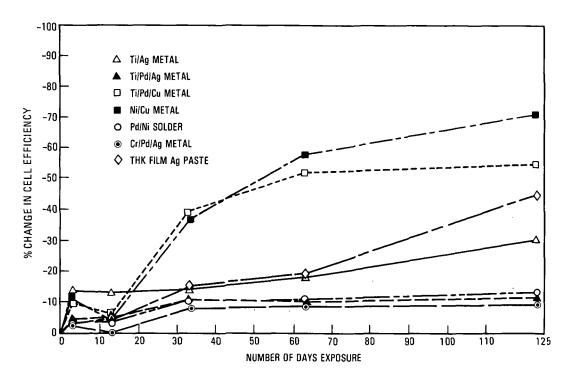


Figure 6-19. Humidity Tests: Percent Change in Efficiency Versus Number of Days Exposure For All Seven Metallization Systems

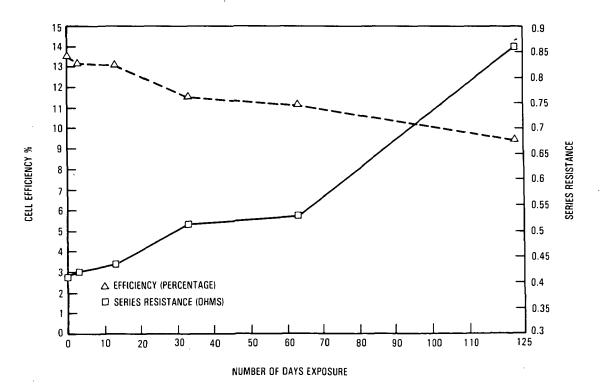


Figure 6-20. Humidity Tests: Efficiency and Series Resistance Versus Number of Days Exposure, Ti/Ag

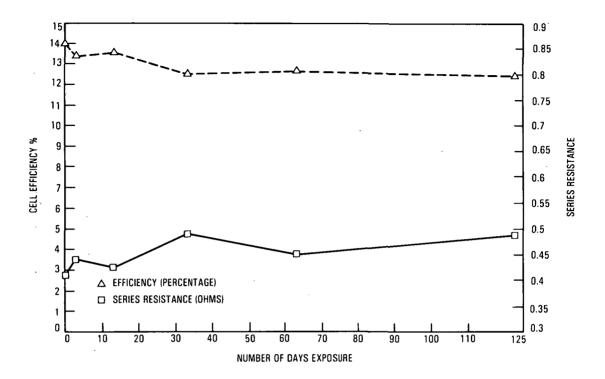


Figure 6-21. Humidity Tests: Efficiency and Series Resistance Versus Number of Days Exposure, Ti/Pd/Ag

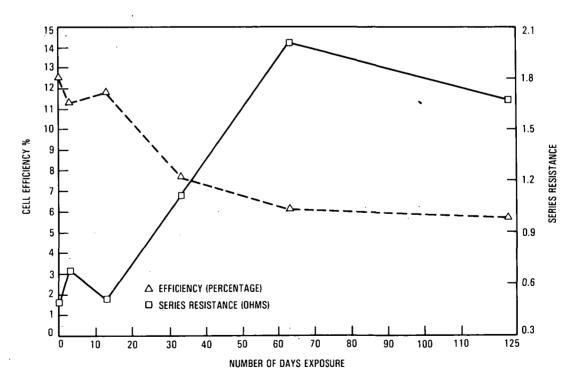


Figure 6-22. Humidity Tests: Efficiency and Series Resistance Versus Number of Days Exposure, Ti/Pd/Cu

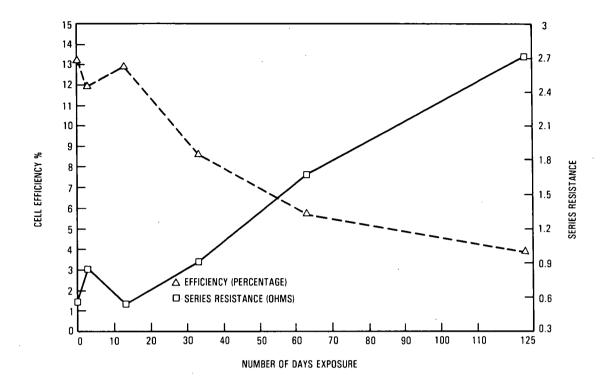


Figure 6-23. Humidity Tests: Efficiency and Series Resistance Versus Number of Days Exposure, Ni/Cu

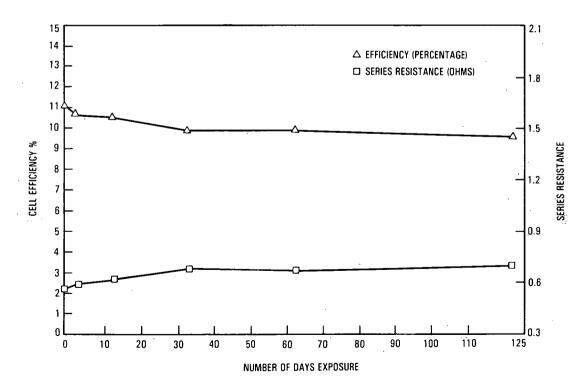


Figure 6-24. Humidity Tests: Efficiency and Series Resistance Versus Number of Days Exposure, Pd/Ni/Solder

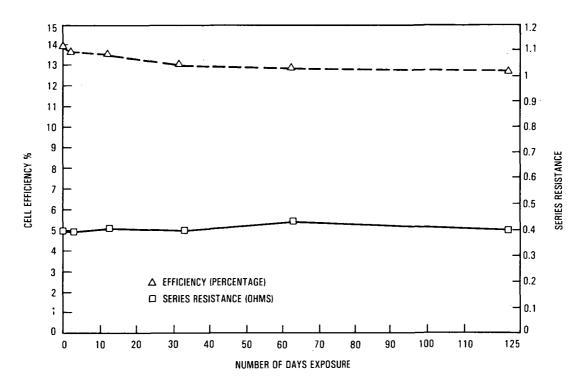


Figure 6-25. Humidity Tests: Efficiency and Series Resistance Versus Number of Days Exposure, Cr/Pd/Ag

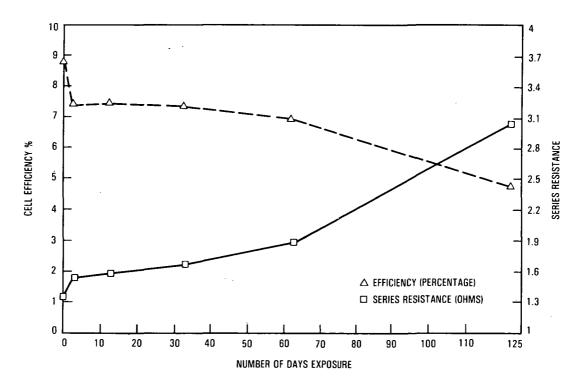


Figure 6-26. Humidity Tests: Efficiency and Series Resistance Versus Number of Days Exposure, Thick Film Ag Paste

### B. SECONDARY ION MASS SPECTROMETRY EVALUATION

Three samples, one a control, one after 1000 temperature cycles, and one after 123 days humidity exposure, were taken from three metallization systems which were Ti/Ag, Ti/Pd/Ag, and Ti/Pd/Cu for a total of nine samples for oxygen content evaluation. The thinking was that if the moisture (water) from the humidity tests were absorbed into the metallization system, and if they reacted to form metal oxides, then an increase in oxygen content of the metallization system should be noted after exposure to humidity tests. A Secondary Ion Mass Spectrometer (SIMS) was used to determine oxygen content. The SIMS operates by boring small holes, 3 to 500  $\mu$ m in diameter, down to a depth of 1 mil or less with a depth resolution of 100 to 200 Å. The holes are bored by a beam of high-energy ions (5 to 20 keV) which erodes the material away, a small fraction of the eroded material being in the ionic form. The ionized material is then accelerated and passed through a mass spectrometer where it is analyzed for element identification and count.

Analysis of the SIMS depth profiles showed significant counts of H and O in the AR coatings on all three cell types, in all the environments, and in roughly the same concentrations. The H and O counts were assumed to be water. Similarly, no evidence of elevated oxygen concentration in the metallic layers were found after either temperature cycling or humidity exposures. The oxygen count was roughly the same for the control cells, the temperature-cycled cells, and the humidity-exposed cells. Figure 6-27 is a sample of the SIMS profile data that were generated.

The SIMS instrument cannot discern between bound oxygen (as in the case of metal oxides) or unbound oxygen (as in the case of trapped oxygen or oxygen agglomerates). It was surmised, however, that the unbound oxygen count in the metal layers were orders of magnitude larger and more variable than any bound oxygen, and swamped (or masked) any subtle changes in oxygen count due to metal oxide formation. It was concluded that the SIMS was not the proper instrument to determine metal oxide formation due to environmental exposures. No more measurements of the oxygen content of the metallization systems were pursued, because this type of effort was not a major thrust of the program.

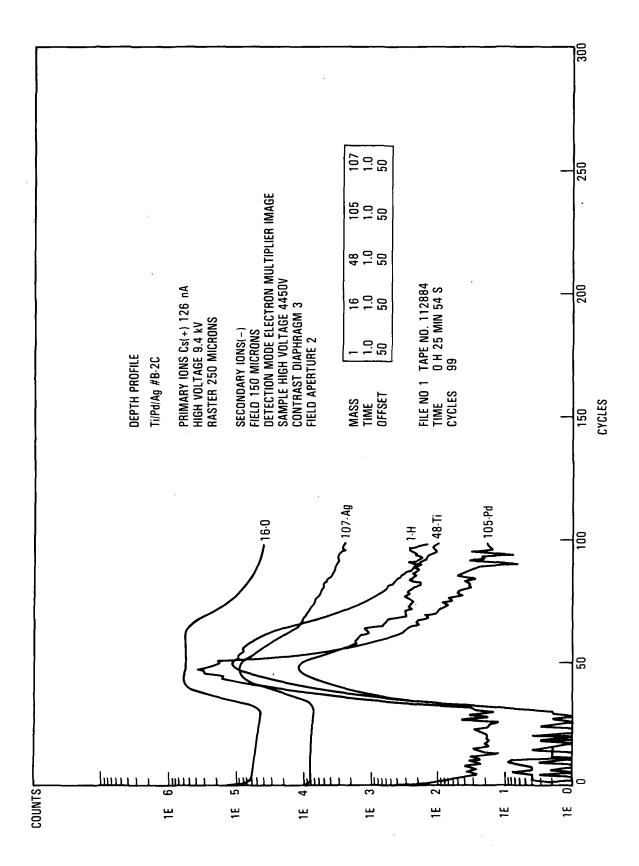


Figure 6-27. Sample of the SIMS Profile Data

## C. I-V CURVES OF TEMPERATURE CYCLING AND HUMIDITY EXPOSURE TESTS

Tables 6-2 through 6-5 show the temperature cycling and humidity exposure test data that correspond to each of the three curves in each of the following figures. For example, the data in Table 6-2, under "A/Before Testing," correspond to Curve "A" in Figure 6-28; "B/After 440 Cycles," to Curve "B"; "C/After 1000 Cycles," to Curve "C."

Figures 6-28 through 6-31 show typical I-V curves of Ti/Pd/Ag and Ti/Pd/Cu metallization systems after subjection to temperature cycling tests and humidity exposure tests. As the I-V curves demonstrate, the Ti/Pd/Ag system held up well under the temperature cycling and humidity tests; the Ti/Pd/Cu did not perform well on either test.

Ti/Pd/Cu	Before	After	After
Cell	Testing	440 Cycles	1000 Cycles
ID	B3-32	B3-32	B3-32
I <sub>sc</sub>	127.9 mA	128.1 mA	123.4 mA
V <sub>oc</sub>	585.0 mV	585.7 mV	587.0 mV
P <sub>mp</sub>	46.6 mW	47.1 mW	36.5 mW
I <sub>mp</sub>	110.8 mA	106.8 mA	94.0 mA
V <sub>mp</sub>	420.4 mV	441.4 mV	389.0 mV
Efficiency	11.6%	11.8%	9.1%
Cell Area	4 sq cm	4 sq cm	4 sq cm
Fill Factor	0.622	0.627	0.504
Rs	0.551 ohms	0.469 ohms	1.318 ohms
Rsh	486.9 ohms	1315.5 ohms	315.3 ohms
I <sub>sc</sub> = Short Ci	rcuit Current	V <sub>mp</sub> = Voltage a	at Maximum Power
J <sub>oc</sub> = Open Cir		R <sub>s</sub> = Series Res	sistance
2 <sub>mp</sub> = Maximum		R <sub>sh</sub> = Shunt Res	
	at Maximum Power	511	

Table 6-2. Data for I-V Curves of Temperature Cycling Test, Selected Sample, Ti/Pd/Cu

Table 6-2 corresponds with Figure 6-28 on the following page.

·

.

n

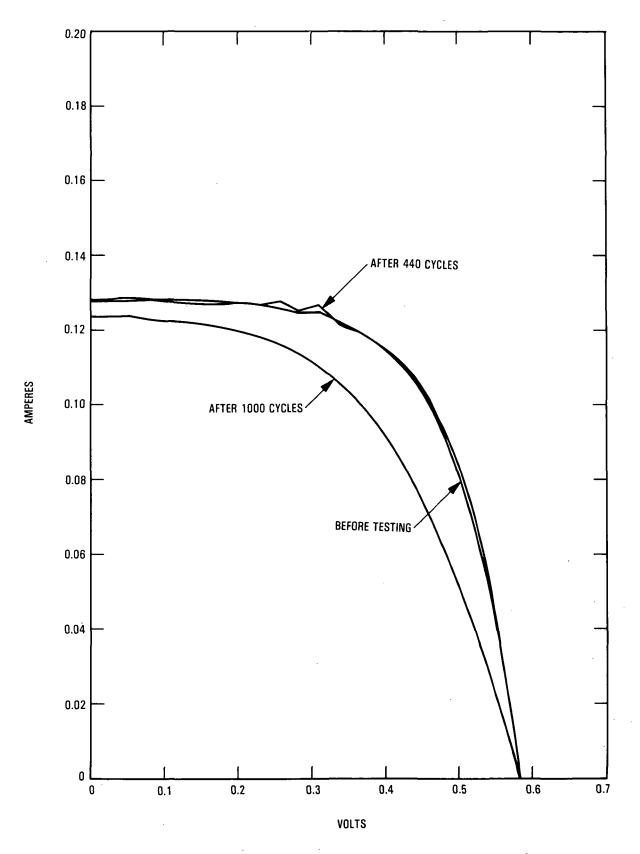


Figure 6-28. I-V Curves of Temperature Cycling Test, Selected Sample, Ti/Pd/Cu

Ti/Pd/Ag Cell	Before Testing	After 440 Cycles	After 1000 Cycles
ID	B2-22	B2-22	B2-22
Isc	130.2 mA	128.5 mA	124.8 mA
V <sub>oc</sub>	593.8 mV	583.0 mV	587.0 mV
P <sub>mp</sub>	56.8 mW	50.7 mW	50.0 mW
Imp	118.3 mA	108.1 mA	105.5 mA
V <sub>mp</sub>	480.0 mV	469.1 mV	473.6 mV
Efficiency	14.2%	12.7%	12.5%
Cell Area	4 sq cm	4 sq cm	4 sq cm
Fill Factor	0.734	0.677	0.682
Rs	0.413 ohms	0.422 ohms	0.416 ohms
R <sub>sh</sub>	275.1 ohms	498.4 ohms	967.2 ohms
$I_{sc} = Short Ci$ $V_{oc} = Open Cir$ $P_{mp} = Maximum$ $I_{mp} = Current$	cuit Voltage	V <sub>mp</sub> = Voltage R <sub>s</sub> = Series Re R <sub>sh</sub> = Shunt Re	

Table 6-3. Data for I-V Curves of Temperature Cycling Test, Selected Sample, Ti/Pd/Ag

Table 6-3 corresponds with Figure 6-29 on the following page.

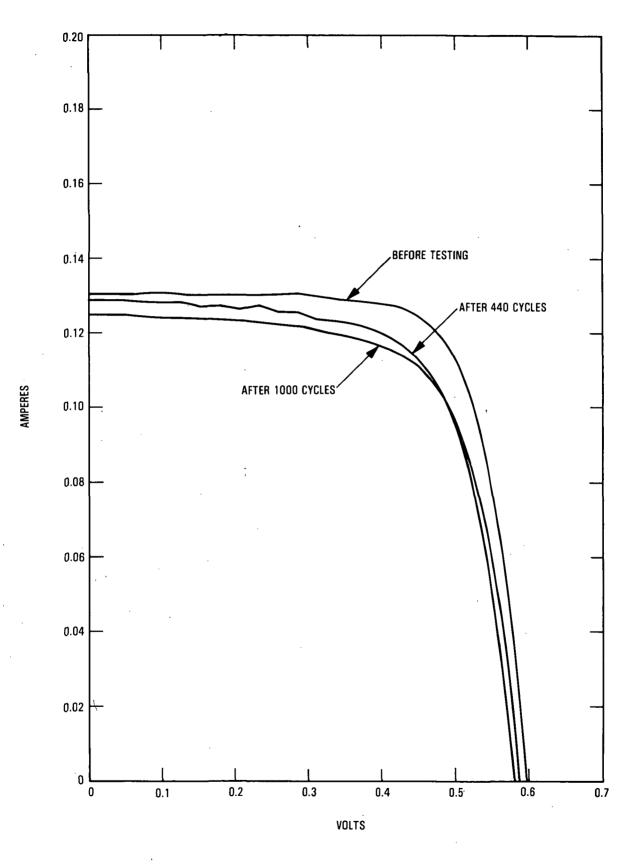


Figure 6-29. I-V Curves of Temperature Cycling Test, Selected Sample, Ti/Pd/Ag

Ti/Pd/Cu	Before	After	After
Cell	Testing	13 Days	123 Days
ID	B3-21	B3-21	B3-21
I <sub>sc</sub>	125.3 mA	123.5 mA	109.5 mA
J <sub>oc</sub>	584.3 mV	577.4 mV	576.6 mV
mp	52.4 mW	48.9 mW	26.2 mW
I <sub>mp</sub>	116.2 mA	110.5 mA	73.4 mA
V <sub>mp</sub>	451.0 mV	442.7 mV	356.4 mV
Efficiency	13.1%	12.2%	6.5%
Cell Area	4 sq cm	4 sq cm	4 sq cm
Fill Factor	0.715	0.685	0.414
s	0.471 ohms	0.573 ohms	1.742 ohms
Rsh	229.0 ohms	183.4 ohms	20.3 ohms
I <sub>sc</sub> = Short Cir		V <sub>mp</sub> = Voltage a	at Maximum Power
l <sub>oc</sub> = Open Circ	cuit Voltage	R <sub>s</sub> = Series Re	
2mp = Maximum 1	Power	$R_{sh} = Shunt Res$	sistance

. مەربى مەرب

# Table 6-4. Data for I-V Curves of Humidity Exposure Test, Selected Sample, Ti/Pd/Cu

Table 6-4 corresponds with Figure 6-30 on the following page.

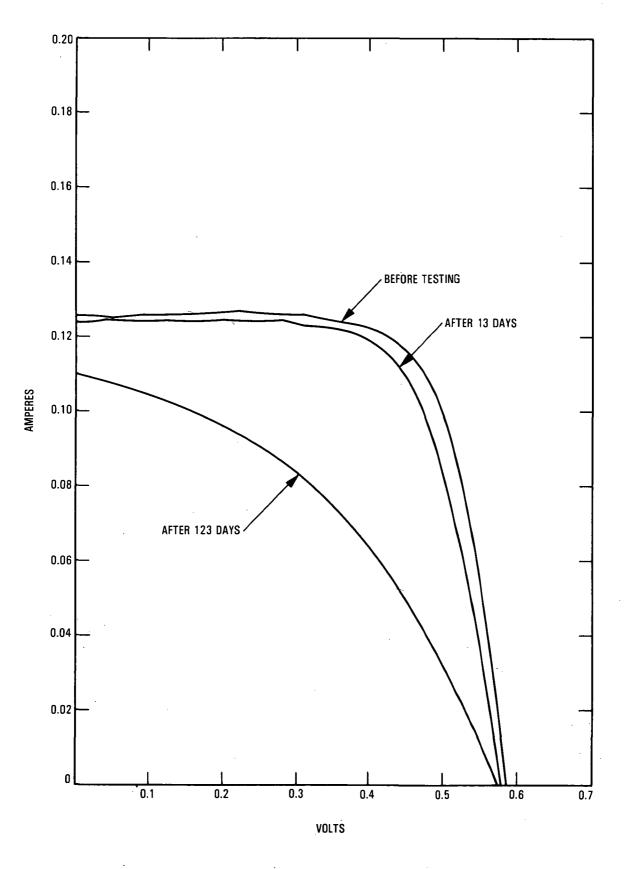


Figure 6-30. I-V Curves of Humidity Exposure Test, Selected Sample, Ti/Pd/Cu

13 Days B2-5 126.0 mA 565.6 mV 51.8 mW	123 Days B2-5 122.5 mA 584.4 mV
126.0 mA 565.6 mV 51.8 mW	122.5 mA 584.4 mV
565.6 mV 51.8 mW	584.4 mV
51.8 mW	
	49.2 mW
110.3 mA	103.8 mA
469.7 mV	474.0 mV
13.9%	12.3%
4 sq cm	4 sq cm
0.691	0.686
0.396 ohms	0.412 ohms
106.9 ohms	242.5 ohms
V <sub>mp</sub> = Voltage	at Maximum Power
5	
0	sistance
	13.9% 4 sq cm 0.691 0.396 ohms 106.9 ohms

Table 6-5. Data for I-V Curves of Humidity Exposure Test, Selected Sample, Ti/Pd/Ag

Table 6-5 corresponds with Figure 6-31 on the following page.

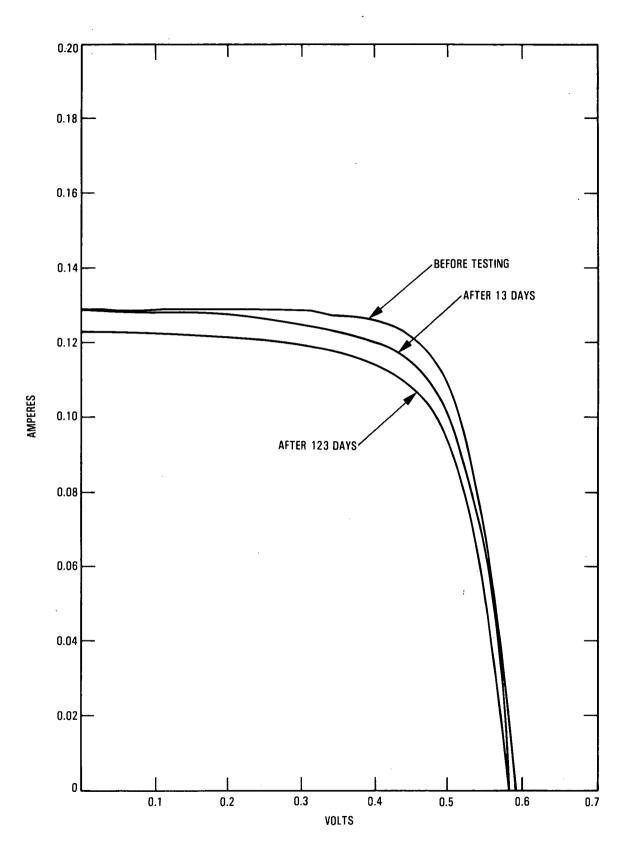


Figure 6-31. I-V Curves of Humidity Exposure Test, Selected Sample, Ti/Pd/Ag

#### SECTION VII

#### DISCUSSION OF RESULTS

#### A. OVERVIEW

There were no big surprises in the test results of the seven metallization systems after temperature cycling and humidity tests. A small surprise was that the Cr/Pd/Ag cell performed the best, i.e., showed the least degradation in cell efficiency after humidity tests, outperforming the highly touted Ti/Pd/Ag metallization system. The two systems, Cr/Pd/Ag and Ti/Pd/Ag, both performed considerably better than the other five systems. The Pd/Ni/Solder system performed respectably also. Not totally unexpected, the copper based systems performed the worst, in that they showed the most degradation in cell efficiency in both the temperature cycling and the humidity tests.

It should be pointed out that these test results do not necessarily rank metallization systems as to their ultimate use. Terrestrial cells are encapsulated and largely protected from the environment by an encapsulation system. There are studies in the FSA Project which investigated the environmental impact on encapsulated cells. The works of S. Shalaby (Reference 2) and J. Lathrop, et al. (Reference 3) address these areas. What this test program did was to present unencapsulated cell test data that show the relative vulnerabilities of different metallization systems to temperature cycling and humidity tests. The test program also isolated or separated unencapsulated cell data from encapsulated cell data, thereby enabling the researcher to identify specific variables which effect cell performance.

Regarding the poor performance of the copper based metal systems after humidity exposure, the question could be raised as to whether or not copper based metallization systems are suitable for terrestrial solar cells. The answer would be a qualified "yes." The test results suggest that copper based contact systems may need additional surface protection during shelf periods between cell completion and module fabrication. In large volume production, this shelf period could be several weeks or even months. A nickel or tin dip after copper plateup would suffice in giving surface protection to copper based systems.

### B. TEMPERATURE CYCLING TESTS

On the temperature cycling tests, another one of the small, but pleasant, surprises was how reasonably well the temperature cycling tests matched with published data (References 3, 4, and 5). Six of the seven metallization systems showed a slight increase in cell efficiency, generally around 10 cycles, and then tapered off to a lower efficiency at the end of 1,000 cycles. The Ti/Ag system showed the largest increase in efficiency (6.22%) and this occurred after 440 cycles. The one metallization system that showed no increase in cell efficiency, but a slow steady slight decline in efficiency at the end of 1,000 cycles, was Ti/Pd/Ag (3.69% decrease).

Firor and Hogan (Reference 6) show data on their thick film silver paste, solder dipped, that agree reasonably well with the Pd/Ni/Solder temperature cycling data of this program. Both curves of Reference 6 and this work show a slight increase in cell efficiency at 10 cycles followed by a slow decline in efficiency to a lower level than the starting efficiency after 30 cycles.

Discussions with space cell investigators indicate that they temperature cycle space modules for 20,000 cycles and more with little or no degradation in module efficiency. Because these space cells use Ti/Pd/Ag, a comparison with the Ti/Pd/Ag data might be made. The 3.69% decrease in cell efficiency of the Ti/Pd/Ag system in 1,000 cycles is statistically significant and seems to be at variance with space cell data which were reported verbally. The temperature excursions on space module testing can typically range from  $100^{\circ}$ C to  $-180^{\circ}$ C for a delta T of  $280^{\circ}$ C. This compares with our  $150^{\circ}$ C to  $-65^{\circ}$ C for a delta T of  $215^{\circ}$ C. There may be an alleviating effect on metallization stresses when cells are encapsulated.

A review of terrestrial module performance data (Reference 7) shows that terrestrial modules exhibit performance changes after temperature cycling. Twelve different mini-module types from different vendors were temperature cycled between 25 to 200 cycles at temperature ranges of  $+90^{\circ}$ C to  $-40^{\circ}$ C at 6 h/cycle. All of the mini-modules, after disallowing some mini-modules for obvious degradation reasons such as cracked cells, etc., still exhibited either a slight increase in power output (1 to 3%) or, in most cases, a slight decrease in power output (1 to 3%) after being subjected to 25 to 200 cycles (Reference 7 did not identify which mini-modules were subjected to the exact number of cycles). However, the mini-module data collectively showed similar behavior to the temperature cycling data of this test program, even though the temperature extremes and delta Ts were different, this program being the more severe with a delta T of 215°C versus their 130°C. A review of the temperature cycling curves in our tests show that within the first 200 cycles there is an overall slight decrease (1 to 3%) in cell efficiency with a slight increase occurring somewhere during the first 20 to 30 cycles, very much in agreement with the mini-module temperature cycling data (see Reference 7).

A review of the temperature cycling data in the Appendix shows that the  $V_{OC}$  remains (essentially) constant for all of the metallization systems during all of the 1,000 cycles. The significant changes occurred in the  $I_{SC}$  values and  $R_s$  (series resistance) values. This would infer that changes in the metallization system are occurring. Firor and Hogan (see Reference 4) indicate that the mechanical stress in metallization systems may be relieved by temperature excursions, some more than others. It is assumed that Firor

and Hogan meant mechanical stress at the metal-silicon interface. This seems to be the general assumption of most of the solar cell researchers and would explain the slight increases in cell efficiency after initial cycling tests. However, the steady fall-off in cell efficiency after continued temperature cycling may indicate a rebuilding of mechanical stress in the metal contact interfaces. Solar Cell Array Handbook (Reference 8) has a good section on fatigue of solar module components including cell interconnects, metal contacts, cell adhesion, etc.

J. Lathrop and others (see Reference 3) describe the results of their temperature cycling/temperature shock tests. Their bias-temperature data show remarkable similarity to the JPL temperature cycling data. Their bias temperature tests consisted of passing current through cells equal to approximately three times their use condition while subjecting the cells to temperatures at 75°, 135°C and 150°C. Their curves of solar cell power output versus exposure time showed a slight increase in power output initially (within the first 300 to 400 hours of testing), followed by a continuing decline in power output through 8000 hours of testing. This was true for three of their four metallization systems tested. Their Ti/Pd/Ag and a solder coated system both showed initial power output increase of 2 to 3% followed by a slight decrease of 2 to 3%, very similar in trend to the metallization systems in the temperature cycling tests of the JPL program. Lathrop and others (see Reference 3) also conducted temperature cycling/temperature shock Their temperature extremes were the same as JPL's, from  $-65^{\circ}$ C to tests. +150°C. However, their cells were transferred (immediately) between two separate chambers each at one of the two temperature extremes, producing temperature failure modes, one involving lead-loss/cell fracture and the other mode involving gradual power loss. The JPL temperature cycling test, being much more gradual in reaching the temperature extremes (14 min ramp time between temperatures), also experienced several cell fractures during temperature cycling and exhibited overall decrease in power output after 1000 cycles.

### C. DISCUSSION OF HUMIDITY TESTS

The results of the humidity tests were fairly predictable. As expected, because of the faster oxidation rate of copper, the copper based systems, Pd/Ni/Cu and Ni/Cu, performed the worst in that they exhibited the largest degradation in cell efficiencies of the seven metallization systems after 123 days of humidity exposure. All of the cells on all of the seven metallization systems showed evidence of blistering during humidity testing. Pictures of cells at 40x magnification after the total 123 days humidity exposure are shown herein. Bishop (Reference 9) presents a description of the mechanisms by which Ti/Ag contacts degrade. The model that he postulates to explain the degradation mechanism involves capillary condensation of water in the silver layer followed by electrochemical corrosion of the titanium. The reaction is assumed to be:  $Ti + H_2O \longrightarrow TiO_2 + 2H_2$ . It is believed by most researchers (including the author) that the tearing and blistering of the metal contacts is due to the release of hydrogen (or gaseous products) upon oxidation of the metal under the metal surface. Bishop further develops the argument of oxidation under the metal surface by demonstrating that water can reach a silicon-silver interface through the silver under humidity conditions. After subjection to humidity conditions, water presence at the interface of silver coated silicon samples was determined by using internal reflection spectroscopy techniques involving reflection of infrared radiation through single crystal silicon. The presence of water was indicated at the interface by a decrease in transmission in the wave number region of  $3400 \text{ cm}^{-1}$ . The presence of water at the silicon-silver interface would provide the necessary catalyst for the degradation mechanism suggested by Bishop and others.

Becker and others (see Reference 10) looked at the silicon-titanium contact structure by the use of transmission electron microscopy techniques. They determined the presence of significant amounts of titanium hydride (TiH<sub>2</sub>) at the contact interface and suggested the oxidation of the TiH<sub>2</sub> in the presence of water as a contributing factor in the formation of H<sub>2</sub> which leads to contact blisters and ultimate contact degradation. This is entirely plausible because many contact metals are normally sintered at 500 to 600°C in a forming gas of N<sub>2</sub>/H<sub>2</sub> mixture. The Ti contacts used in this program were sintered in 100% N<sub>2</sub> and it is doubtful if any hydride was formed. Becker and others (see Reference 10) also indicated that the TiH<sub>2</sub> distribution in the Ti layers were highly uneven with some samples showing high TiH<sub>2</sub> concentrations while other samples showed little or no concentrations.

Becker and others (see Reference 10) indicated that they could not get a clear understanding of the oxygen behaviour of the Ti/Ag and Ti/Pd/Ag systems. This was due to the complex nature of oxide formations. Although the main thrust of this program was not to investigate degradation mechanisms, one of the interesting observations made was to determine the oxygen content of some of the metallization systems before and after environmental exposure. The thinking was that if the moisture (water) from the humidity tests was absorbed into the metallization system and reacted to form metal oxides, then an increase should be seen in oxygen content of the metallization system after exposure to humidity tests. A SIMS was used to determine oxygen content. The control sample, a 1000 temperature cycled sample, and a 123 day humidity exposed sample, were each tested for oxygen content from the Ti/Pd/Ag metallization system, the Ti/Ag system and the Pd/Ni/Cu metallization system (a total of nine samples tested). No significant differences could be found in oxygen content (count) in any of the samples. Because the SIMS cannot discern between bound oxygen (as in the case of metal oxides) and unbound oxygen (as in the case of trapped oxygen or oxygen agglomerates), it was surmised that the unbound oxygen count, being so much larger and variable, swamped (or masked) the subtle changes in oxygen count due to metal oxide formation. It was concluded that the SIMS was not the proper instrument to determine metal oxide formation in solar cells and that achieving a clear understanding about the oxygen behaviour of the metallization system was, indeed, as difficult a task as Becker (see Reference 10) alluded to. There were no further measurements of the oxygen content of the metallization systems, because this type of effort was not a major thrust of this program.

The summary remarks about this environmental test program are that: (1) it showed decided differences in the performances of different metallization systems after being subjected to environmental exposures; (2) these performance differences, however, did not rank the metallization system, as stated earlier, but did (and does) allow researchers to compare the relative sensitivities of different metallization systems to environmental exposures; (3) the test results showed remarkable agreement with other published results on environmental testing; and (4) the tabulated data in the Appendix should provide detailed information on cell performances after environmental exposures.

#### SECTION VIII

#### REFERENCES

- Hoffman, A.R., Griffith, J.S., and Ross, R.G., "Qualification Testing of Flat-Plate Photovoltaic Modules," <u>IEEE Transactions on Reliability</u>, Vol. R-31, pp. 252-257, August 1982.
- Shalaby, H., "The Degradation Mechanism of Ti-Pd-Ag Solar Cell Contacts by an Accelerated Electrochemical Testing Technique," <u>Solar Cells</u>, Vol. 11, pp. 189-193, 1984.
- Lathrop, J.W., Hawkins, D.C., Prince, J.L., and Walker, H.A., "Accelerated Stress Testing of Terrestrial Solar Cells," <u>IEEE</u> <u>Transactions on Reliability</u>, Vol. R-31, pp. 258-265, August 1982.
- 4. Firor, K., and Hogan, S., "Environmental Testing of Single-Crystal Silicon Solar Cells with Screen-Printed Silver Contacts," <u>IEEE</u> Transactions on Reliability, Vol. R-31, pp. 271-275, August 1982.
- 5. Prince, J.L., Lathrop, J.L., and Whitter, G.W., "Contact Integrity Testing of Stress-Tested Silicon Terrestrial Solar Cells," Paper presented at 14th IEEE Photovoltaic Specialists Conference, San Diego, California, January 7-10, 1980. <u>Conference Record</u> (A81-27076 11-44), pp. 952-957, 1980.
- Firor, K., and Hogan, B., "Effects of Processing Parameters on Thick Film Inks Used for Solar Cell Front Metallization," <u>Solar Cells</u>, Vol. 5, pp. 87-100, December 1981.
- Maxwell, H.G., Grimmett, C.A., Repar, J., Frickland, P.O., and Amy, J.A. <u>FSA Field Test Report 1980-1982</u>, JPL Publication 83-29, Jet Propulsion Laboratory, Pasadena, California, April 15, 1983.
- 8. Rauschenbach, H.S., <u>Solar Cell Array Design Handbook</u>, Vols. 1 and 2, JPL Publication ST 43-38, Jet Propulsion Laboratory, Pasadena, California, October 1978.
- 9. Bishop, C.J., <u>The Fundamental Mechanisms of Humidity Degradation in Silver Titanium Contacts</u>, Paper presented at 8th IEEE Photovoltaic Specialists Conference, Seattle, Washington, August 4-6, 1970, pp. 51-61, AIAA 71A16061, August, 1970.
- Becker, W.H., and Pollack, S.R., <u>The Formation and Degradation of Ti-Ag</u> and <u>Ti-Pd-Ag Solar Cell Contacts</u>, Paper presented at 8th IEEE Photovoltaic Specialists Conference, Seattle, Washington, August 4-6, 1970, pp. 40-50, AIAA 71A16060, August, 1970.

8-1

#### SECTION IX

#### SELECTED BIBLIOGRAPHY

- Aroian, L.A., Luft, W., and McCraven, C.C., "Temperature and Humidity Effects on Silicon Solar Cells," Paper presented at 7th Photovoltaic Specialists Conference, Pasadena, California, November 19-21, 1968. <u>Conference Record</u> (A69-35678 19-03), pp. 214-225, 1968.
- Berman, P., Mueller, R., and Solana, M., "Results of Accelerated Thermal Cycle Tests of Solar Cell Modules," Paper presented at 12th Photovoltaic Specialists Conference, Baton Rouge, Louisiana, November 15-18, 1976. Conference Record (A78-1090201-44), pp. 379-387, 1976.
- Boller, H.W., and Koch, J., "Accelerated Fatigue Tests of Solar Cell Interconnectors for Simulation of Thermal Cycles," Paper presented at 11th Photovoltaic Specialists Conference, Scottsdale, Arizona, May 6-8, 1975. Conference Record (A76-14727 04-44), pp. 153-161, 1975.
- Hoffman, A.R., and Ross, R.G., "Environmental Qualification Testing of Terrestrial Solar Cell Modules," Paper presented at 13th Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978. <u>Conference</u> <u>Record</u> (A79-40881 17-44), pp. 835-842, 1978.
- Luft, W., "Silicon Solar Cells at Low Temperature," <u>IEEE Transactions on</u> <u>Aerospace and Electronic Systems</u>, Vol. AES-7, pp. 332-339, August, 1971.
- Luft, W., and Maiden, E., "Temperature Cycling Effects on Solar Panels," Paper presented at 4th Intersociety Energy Conversion Engineering Conference, Washington, D.C., September 22-26, 1969. <u>Conference Record</u> (A69-42236 23-03), pp. 582-589, September, 1969.
- Peterson, R.C., and Muled, A., "Silicon Solar Cells with Nickel/Solder Metallization," <u>Proceedings of the Third International Photovoltaic Solar</u> <u>Energy Conference</u>, Cannes, France, October 27-31, 1980. <u>Conference Record</u> (A82-24101 10-44), pp. 684-690, 1981.
- Smokler, M.I., and Runkle, L.O., "Experience in Design and Test of Terrestrial Solar-Cell Modules," Paper presented at AS/ISES 1982 Annual Meeting, Houston, Texas, June 1-5, 1982.

9-1

# APPENDIX

Tables A-1 through A-14 present the JPL test data after temperature cycling and humidity exposure.

• •.

1

Table A-1. I-V Test Data After Temperature Cycling (Ti/Ag)<sup>a,b</sup>

Cumulative No. of Temperature Cycles	Six Cells Total	I <sub>sc</sub> (mA)	V <sub>oc</sub> (mV)	Р <sub>тр</sub> (ти)	I <sub>тр</sub> (тА)	۲ <sub>۳</sub> р (۳۷)	E f f (%)	F111 Factor (FF)	Rs (Series Resis- tance, ohms)	Rsh (Shunt Res1s- tance, ohms)	% Change in Efficiency
0	Average	130.583	591.733	55.817	118.300	471.367	13.917	0,722	786.0	811.767	0
	Std. Dev.	1.579	2.736	2.938	3.092	14.240	0.734	0.031	0.034	964.789	
10	Average	130.117	591.083	55.583	118.683	468.217	13.900	0.722	0.409	650.333	-0.12
	Std. Dev.	1.945	2.486	2.874	4.345	10.761	0.737	0.028	0.028	676.285	
40	Average	130.233	591.950	55.550	118.417	469.050	13.900	0.720	0.405	339.583	-0.12
	Std. Dev.	2.641	2.689	3.678	6.472	10.742	0.916	0.034	0.036	93.119	
140	Average	130.800	591.950	55.300	119.150	463.450	13.833	0.713	0.436	362.950	-0*60
	Std. Dev.	2.574	2.545	4.145	5.633	14.305	1.031	0.040	0.068	349.047	
440	Average	130.400	589.200	55.183	120.117	463.100	14.783	0.718	0.466	236.567	+6.22
	Std. Dev.	1.457	2.265	2.628	4.544	13.444	2.019	0.030	0.125	62.189	-
1000	Average	126.100	590.517	53.267	115.067	462.783	13.333	0.715	0.443	304.217	-4,20
	Std. Dev.	1.376	2.752	2.812	2.869	14.160	0.672	0.030	0.051	137.209	,
<sup>a</sup> Temperature excursions were: From -65°C for approximately 6 min dwell at -65°C to approximately 14 min ramp time between temperatures. <sup>b</sup> IV test conditions were: AM1, 28°C	Temperature excursions were: From -65°C for approximately 6 min dwell at -65°C to approximately 14 min ramp time between temperatures. IV test conditions were: AM1, 28°C	were: were: ately 6 ml: mp time be: : AM1, 28'	n dwell at tween tempe °C		H150°C for Total cycl	approximat le time was	+150°C for approximately 6 min dwell at +150°C, and Total cycle time was approximately 40 min/cycle.	dwell at + tely 40 mi	150°C, and n/cycle.		

:/

(Ti/Pd/Ag) <sup>a,b</sup>
Cycling
Temperature
After
Data
Test
<b>U−</b> Ι
Table A-2.

Cumulative No. of Temperature Cycles	Six Cells Total	I <sub>sc</sub> (mA)	V <sub>oc</sub> (mV)	(мт) (мт)	Imp (Am)	۲ سم س	Eff (%)	F111 Factor (FF)	Rs (Series Resis- tance, ohms)	Rsh (Shunt Resis- tance, ohms)	% Change in Efficiency
0	Average	131.283	591.350	56.883	119.600	475.583	14.200	0.732	0.385	297.517	0
	Std. Dev.	1.158	1.590	1.191	0.913	10.640	0.289	0.020	0.022	80.181	
10	Average	130.233	590.750	56.033	119.517	487.717	14.017	0.727	0.406	380.867	-1.29
	Std. Dev.	1.064	2.376	1.872	1.943	45.621	0.460	0.024	0.026	188.084	
40	Average	130.340	590.540	56.580	119.400	473.940	14.080	0.735	0.414	380.280	-0.84
	Std. Dev.	1.650	3.433	1.418	2.772	0.952	0.397	0.009	0.039	319.765	
140	Average	131.160	590.500	55.920	119.600	467.300	14.000	0.721	0.402	204.720	-1.41
	Std. Dev.	1.375	3.199	2.871	3.566	11.720	0.713	0.032	0.024	60.521	
440	Average	130.650	588.325	56.750	120.075	472.625	13.850	0.739	0.459	477.175	-2.46
	Std. Dev.	0.743	2.124	0.634	1.291	0.414	0.166	0.006	0.158	307.766	
1000	Average	125.750	590.025	54.650	114.800	476.150	13.675	0.736	0.410	196.800	-3.70
	Std. Dev.	1.006	1.677	0.589	1.138	0.287	0.148	0.002	0.017	34.046	
<sup>a</sup> Temperature excursions were: From -65°C for approximately 6 min dwell at -65°C to +150°C for approximately 6 min dwell at +150°C, and approximately 14 min ramp time between temperatures. Total cycle time was approximately 40 min/cycle. <sup>b</sup> IV test conditions were: AMI, 28°C	excursions v excursions v or approximé y 14 min ram itions were:	were: ately 6 min np time bet : AMI, 28°	dwell at . ween tempe <sup>1</sup> C	-65°C to + ratures.	150°C for Total cycl	approximat e time was	ely 6 min ( approxima)	-150°C for approximately 6 min dwell at +150°C, a Total cycle time was approximately 40 min/cycle.	50°C, and /cycle.	].	

Table A-3. I-V Test Data After Temperature Cycling (Ti/Pd/Cu)<sup>a,b</sup>

Efficiency Z Change -20.74 0 +0.63 -5.62 +0.63 -1.24 510.950 426.333 342.250 tance, ohms) 134.246 342.917 107.660 380.920 512.817 327.767 201.607 137.856 509.570 R<sub>sh</sub> (Shunt Resis-From -65°C for approximately 6 min dwell at -65°C to +150°C for approximately 6 min dwell at +150°C, and approximately 14 min ramp time between temperatures. Total cycle time was approximately 40 min/cycle. 0.035 Resistance, ohms) 0.439 0.058 0.451 0.653 0.143 0.442 0.039 0.454 0.057 1.074 0.412 (Serles Rs 1 0.035 0.699 0.033 0.042 0.695 0.034 0.692 0.036 0.062 Fill Factor (FF) 0.654 0.577 0.698 13.333 0.736 0.736 0.832 13.417 0.727 12.583 13.417 0.767 13.167 10.567 1.104 Eff સિ 463.000 432.567 14.047 462.550 13.536 461.767 455.600 20.079 13.599 13.483 409.667 30.136 (nu) ۷mp 116.100 3.645 3.968 3.538 4.050 3.885 117.050 115.833 116.000 114.067 103.150 6.301 ( ww) Imp 42.283 53.367 3.252 53.683 50.267 2.945 53.700 3.049 2.992 2.987 4.386 52.700 ( MШ) Pap. 2.049 1.730 589,183 2.929 1.685 2.879 586.467 4.611 588.800 586.000 589.767 590.267 ( <u>n</u> voc 28°C 1.218 1.314 1.038 1.393 1.064 124.900 1.121 129.567 130.017 30.350 130.733 129.917 AM1, Isc (WW) <sup>a</sup>Temperature excursions were: conditions were: Std. Dev. Dev. Std. Dev. Dev. Std. Dev. Std. Dev. Average Average Average Average Average Average Six Cells Total Std. Std. Cumulative Ng. of Temperature test Cycles 140 440 <del>9</del> 1000 0 2 ٩IV

<b>بد</b> م	(Ni/Cu)
	Cycling
	Temperature
	ata After
	I-V Test Da
	Table A-4.

Cumulative No. of	Six Cells	Isc	Voc	Pmp	Imp	V ap	E F	F111 Factor	Rs (Series	Rsh (Shunt	% Change	
<i>lemperature</i> Cycles	lotal	( @\ )	{ (mV)	( m/m )	( ## )	(/m)	(2)	(FF)	kesis- tance, ohms)	tance, ohms)	ы Efficiency	
0	Average	130.400	587.350	53.950	119.400	451.900	13.450	0.704	0.440	439.100	0	
	Std. Dev.	0.400	0.950	0.550	1.100	0.400	0.150	0.006	0.036	42.000		
10	Average	130.800	588.700	55.000	116.450	472.200	13.750	0.714	0.453	207.250	+2.23	
	Std. Dev.	0.400	006.0	0.300	0.550	0.200	0.050	0.004	0.002	60.550		
40	Average	131.200	588.600	53.000	118,750	446.650	13.250	0.686	0.572	200.500	-1.49	
	Std. Dev.	0.200	1.600	0.600	1.350	0.050	0.150	0.007	0.023	23.500		
140	Average	131.350	587.700	52.400	117.800	445.000	13.100	0.678	0.575	278.400	-2.60	
	Std. Dev.	0.450	1.700	1.000	2.000	0.600	0.200	0.012	0.029	87.400		
440	Average	130.400	587.750	51.950	116.900	444.550	12.950	0.678	0.591	228,750	-3.72	
	Std. Dev.	0.300	0.250	2.650	1.100	26.750	0.650	0.036	0.135	37.350		
1000	Average	125.450	587.200	44.600	108.950	406.900	11.150	0.606	0.985	465.750	-17.10	
	Std. Dev.	0.150	1.700	7.500	6.950	42.800	1.850	0.103	0.521	145.150		
<sup>a</sup> Temperature excursions were: From -65°C for approximately approximately 14 min ramp ti	Temperature excursions were: From -65°C for approximately 6 min dwell at -65°C to approximately 14 min ramp time between temperatures.	s were: Lmately 6 m ramp time b	in dwell at etween temp	t -65°C to peratures.	+150°C fo Total cy	r approximé cle time wa	ately 6 min as approxin	dwell at -65°C to +150°C for approximately 6 min dwell at +150°C, and ween temperatures. Total cycle time was approximately 40 min/cycle.	+150°C, an in/cycle.	- Pu		
D <sub>IV</sub> test con	<sup>D</sup> IV test conditions were:	re: AMl, 28 °C	2 <b>.</b> 8									

(Pd/Ni/Solder) <sup>a,b</sup>
Cycling
: Temperature
Data After
ىد
I-V Test
Table A-5.

Cumulative No. of Temperature Cycles	Six Cells Total	Isc (mA)	Voc (mV)	Р <sub>шр</sub> (ти)	Imp (mA)	V <sup>mp</sup> (mV)	Eff (%)	F111 Factor (FF)	R <sub>S</sub> (Series Resis- tance, ohms)	Rsh (Shunt Resis- tance, ohms)	% Change in Efficiency
0	Average	123.150	578.000	42.867	104.667	409.300	10.717	0.602	0.581	1227.183	0
	Std. Dev.	0.930	6.372	2.698	4.754	13.717	0.664	0.035	0.036	1117.428	
10	Average	125.350	581.617	43.350	106.750	406.183	10.867	0.594	0.583	425.350	.+1.40
	Std. Dev.	0.714	4.817	2.345	3.972	12.946	0.579	0.032	0.043	105.834	
40	Average	125.800	580.933	43.000	106.683	402.867	10.750	0.589	0.601	567.283	+0.30
	Std. Dev.	1.667	4.018	2.179	2.827	13.890	0.538	0.034	0.058	279.860	
140	Average	126.400	580.833	40.733	104.650	387.033	10.183	0.554	0.769	389.100	-4.98
	Std. Dev.	1.271	5.078	6.308	6.612	40.127	1.591	0.084	0.426	257.060	
440	Average	125.500	578.283	41.817	104.417	400.267	10.500	0.576	0.595	573.117	-2.02
	Std. Dev.	1.153	5.936	3.155	5.005	14.451	0.688	0*0*0	0.056	519.443	
1000	Average	121.483	577.383	39.867	99.683	399.650	9.967	0.568	0.616	2862.317	-7.00
	Std. Dev.	0.869	3.544	2.535	4.090	13.233	0.621	0.036	0.053	5577.968	
<sup>a</sup> Temperatur From -65°C 14 min ram	<sup>a</sup> Temperature excursions were: From -65°C for approximately 6 min dwe 14 min ramp time between temperatures.	s were: imately 6 π een tempera		tal cycle	<pre>/ / / / / / / / / / / / / / / / / / /</pre>	dwell at -65°C to +150°C for approximately 6 min dwell es. Total cycle time was approximately 40 min/cycle.	l ately 6 mi ly 40 min/	6 min dwell at min/cycle.	+150°C, a	at +150°C, and approximately	lately

Table A-6. I-V Test Data After Temperature Cycling (Thick Film Ag Paste)<sup>a,b</sup>

Cumulative No. of Temperature Cycles	Six Cells Total	I <sub>sc</sub> (mA)	V <sub>oc</sub> (mV)	Pmp (mW)	Imp (mA)	V <sub>m</sub> р (ли)	Eff (%)	Fill Factor (FF)	Rs (Series Resis- tance, ohms)	Rsh (Shunt Resis- tance, ohms)	% Change 1n Efficiency
0	Average	114.167	578.617	28.600	77.917	363.050	7.167	0.432	1.316	23.067	C
	Std. Dev.	4.140	2.669	6.562	7.628	53.263	1.630	0.092	0.554	9.740	
10	Average	114.380	578.400	28.820	78.920	364.000	7.240	0.436	1.295	24.220	+1.02
	Std. Dev.	6.823	4.370	5.688	8.688	47.754	1.424	0.081	0.469	9.808	-
40	Average	114.600	577.560	27.720	79.060	348.500	6.900	0.417	1.444	22.040	-3.72
	Std. Dev.	5.912	2.525	6.490	10.955	50.830	1.616	0.087	0.505	9.156	
140	Average	114.120	578.440	27.440	77.360	352.020	6.860	0.413	1.499	20.680	-4.28
	Std. Dev.	8.284	1.679	6.829	10.914	52.599	1.707	0.087	0.508	7.791	
440	Average	113.620	579.620	27.380	77.340	351.660	6.840	0.413	1.514	21.360	-4.56
	Std. Dev.	9.073	1.975	6.822	13.377	46.263	1.693	0.087	0.502	9.095	
1000	Average	107.160	578.100	24.620	72.220	339.260	6.140	0.397	1.929	18.560	-14.33
	Std. Dev.	7.927	2.923	5.058	7.874	41.304	1.245	0.071	0.655	3.237	-
<sup>a</sup> Temperature excursions were: From -65°C for approximately 6 min 14 min ramp time between temperatur <sup>b</sup> IV test conditions were: AM1, 28°C	Temperature excursions were: From -65°C for approximately 6 min dwe 14 min ramp time between temperatures. IV test conditions were: AMI, 28°C	were: imately 6 m een temperai re: AM1, 2	in dwell at tures. Tot 8°C	: -65°C to al cycle t	+150°C fo time was a	dwell at -65°C to +150°C for approximately 6 min dwell at +150°C, and approximately tes. Total cycle time was approximately 40 min/cycle.	stely 6 mir y 40 min/c	ı dwell at ycle.	+150°C, a	nd approxit	nately

A-- 7

٠

(Cr/Pd/Ag) <sup>a,b</sup>
Cycling
Temperature
After
Data
I-V Test
Table A-7.

Cumulative No. of Temperature	S1x Cells Total	Isc (тА)	V <sub>oc</sub> (mV)	Pmp (mW)	Imp (mA)	۲۳ (مس ( ۳۷	Eff (%)	F111 Factor (FF)	Rs (Series Resis-	Rsh (Shunt Resis-	% Change in
Cycles									tance, ohms)	tance, ohms)	Efficiency
0	Average	130.833	588.400	55.083	117.083	470.183	13.767	0.715	0.418	283.267	0
	Std. Dev.	1.216	3.426	2.540	2.839	13.907	0.605	0.027	0.032	98.764	
10	Average	129.983	586.683	54.317	117.083	463.600	13.583	0.712	0.432	374.417	-1.33
	Std. Dev.	2.193	4.160	2.796	3.149	13.560	0.722	0.029	0.035	371.628	
40	Average	131.700	588.467	54.933	119.250	460.717	13.750	0.709	0.421	923.300	-0.123
	Std. Dev.	1.547	3.723	2.749	3.495	13.915	0.665	0.031	0.034	1202.774	
140	Average	132.000	588.217	55.367	119.383	463.617	13.833	0.713	0.414	238.217	+0.48
	Std. Dev.	1.179	3.392	2.769	2.807	13.455	0.692	0.030	0.018	100.856	
740	Average	131.350	587.433	54.917	118.533	463.050	13.733	0.711	0.418	348.217	-0.25
	Std. Dev.	1.355	3.065	2.687	2.857	13.379	0.680	0.029	0.035	170.960	
1000	Average	125.833	585.683	52.533	114.617	458.250	13.133	0.712	0.427	278.417	-4.6
	Std. Dev.	1.217	3.124	2.502	4.125	12.854	0.639	0.029	0.037	59.742	
<sup>a</sup> Temperaturé From -65°C	<sup>a</sup> remperature excursions were: From -65°C for approximately 6 min	were: mately 6 m1	n dwell at	-65°C to	+150°C foi	r approxima	itely 6 mir	ı dwell at	+150°C, an	dwell at -65°C to +150°C for approximately 6 min dwell at +150°C, and approximately	ltely
bIV test cor	l4 min ramp time between temperatures. <sup>b</sup> IV test conditions were: AMI, 28°C	een temperatur :e: AMI, 28°C		al cycle i	cline vas a	Total cycle time was approximately 40 min/cycle.	г/ чо шти,	c) cre.			

(Ti/Ag) <sup>a,b</sup>
Tests
Humidity
After
Data
Test
I-Λ
Table A-8.

						·						· · · · · · · · · · · · · · · · · · ·
% Change in Cell Efficiency	0	-2.80		-3.45		-14.79		-17.67		-30.16		or
Rsh (Shunt Resis- tance, ohms)	1080.344	2500.552 240.011	88.434	269.211	155.320	282.244	270.799	387.622	316.881	530.844	822.928	The reason for mens on other
Rs (Series Resis- tance, ohms)	0.414	0.038	0.029	0.436	0.031	0.514	0.058	0.529	0.062	0.861	0.375	
F111 Factor (FF)	0.701	0.034 0.692	0.030	0.686	0.032	0.638	0.045	0.621	0.053	0.535	0.076	98% Relative Humidity for 14 through 123 days. The reason f specimens were tested piggyback with other specimens on other
Eff (%)	13.522	0.744	0.675	13.056	0.818	11.522	0.959	11.133	1.115	9.444	1.604	ty for 14 ( d piggybach
V <sub>тр</sub> (тv)	467.222	14.418 462.778	13.126	469.933	1.856	442.678	9.878	438,833	12.361	411.367	35.806	ive Humidi were testec
I <sub>mp</sub> (mA)	115.733	5.198 113.711	4.001	111.244	6.403	103.822	6.898	101.322	8.325	91.233	7.920	98% Relat
Р <sub>тр</sub> (ты)	54.067	2.997 52.633	2.685	52.300	3.201	46.011	3.837	44.511	4.427	37.789	6.415	) days and 70°C at because the cell est conditions.
V <sub>oc</sub> (mV)	588.133	4.866 585.167	3.138	585.578	3.456	581.333	4.273	581.989	3.401	582.567	2.963	13 days and 70°C as because the ce e test conditions °C
I <sub>sc</sub> (mA)	130.994	1.972 129.922	1.496	130.078	2.254	123.811	2.595	123.033	3.358	120.689	3.771	e: 1 for first nditions w rity on th : AMI, 28
Six Cells Total	Average	Std. Dev. Average	Std. Dev.	Average	Std. Dev.	ditions wer saturation in test cc ch had prio itions were						
Cumulative No. of Days Exposure to Humidity	0	ñ		13		33		63		123		<sup>a</sup> Humidity conditions were: 60°C at 100% saturation for first 13 days and 70°C at 98% Relative Humidity for 14 through 123 days. the variance in test conditions was because the cell specimens were tested piggyback with other speci programs which had priority on the test conditions. <sup>b</sup> IV test conditions were: AMI, 28°C

Þ

													T
Z Change 1n Cell Efficiency	0		-4.52		-3.26		-10.87		-10.00		-11.35		L L
Rsh (Shunt Resis- tance, ohms)	257.356	71.486	364.556	187.134	600.244	835.344	327.156	206.946	1444.756	3016.517	288.487	101.762	The reason for iens on other
Rs (Series Resis- tance, ohms)	0.411	0.020	0.441	0.039	0.425	0.032	0.490	0.107	0.450	0.053	0.487	0.144	3 days. 3 er specim
Fill Factor (FF)	0.727	0.014	-0° 109	0.023	0.712	0.024	0.694	0.035	0.700	0.035	0.691	0.055	3 days and 70°C at 98% Relative Humidity for 14 through 123 days. because the cell specimens were tested piggyback with other spectest conditions.
Eff (%)	14.000	0.279	13.367	0.540	13.544	0.534	12.478	0.533	12.600	0.600	12.411	1.018	ity for 14 ed piggybac
۲ مس <sup>۷</sup> ( ۱۳ )	470.811	12.911	460.422	13.083	468.244	8.029	454.156	. 16.662	462.367	13.264	454.422	25.574	tive Humidi were teste
( ար)	118.933	3.029	116.167	4.411	115.344	4.588	110.011	3.527	109.033	4.341	108.967	4.571	t 98% Relat specimens
գա <sup>գ</sup>	55.988	1.109	53.456	2.162	54.178	2.171	49.922	2.075	50.400	2.376	49.567	4.094	3 days and 70°C at because the cell test conditions.
V <sub>oc</sub> (mV)	590.556	2.276	586.856	2.726	587.389	1.849	583.644	1.864	584.056	1.424	583.489	1.458	t 13 days a vas because ne test cor 8°C
Lsc (mA)	130.267	1.194	128.344	1.480	129.289	1.440	123.267	1.551	123.278	1.319	122.900	0.814	re: n for first l onditions was ority on the e: AMI, 28°C
Six Cells Total	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	nditions we % saturatio 2 in test c 1ch had pri 1tions wer						
Cumulative No. of Days Exposure to Humidity	о		n		13		33		63		123		<sup>a</sup> Humidity conditions were: 60°C at 100% saturation for first 13 days and 70°C at 98% Relative Humidity for 14 through 123 days. The reason f the variance in test conditions was because the cell specimens were tested piggyback with other specimens on other programs which had priority on the test conditions. <sup>b</sup> IV test conditions were: AMI, 28°C

Table A-9. I-V Test Data After Humidity Tests (Ti/Pi/Ag)<sup>a,b</sup>

Table A-10. I-V Test Data After Humidity Tests (Ti/Pd/Cu)<sup>a,b</sup>

.

c, e					_								
% Change in Cell Efficiency	0		-9.83		-5.94		-39.10		-51.44	_	-54.43		0.
Rsh (Shunt Resis- tance, ohms)	848.111	1384.937	274.889	180.793	284.000	162.539	99.867	119.413	31.986	19.586	21.533	8.632	3 days and 70°C at 98% Relative Humidity for 14 through 123 days. The reason for because the cell specimens were tested piggyback with other specimens on other conditions.
Rs (Series Resis- tance, ohms)	0.486	0.130	0.688	0.288	0.514	0.074	1.117	0.575	2.004	0.817	1.672	0.734	1 5
F111 Factor (FF)	0.665	0.096	0.617	0.105	0.638	0.096	0.463	0,093	0.408	0.064	0.402	0.056	through 123 k with othe
E <sub>f</sub> f (%)	12.533	2.004	11.300	2.005	11.789	1.923	7.633	2.337	6.086	2.115	5.711	1.806	ty for 14 t d piggybac
V <sub>mp</sub> ( wv )	449.011	35.945	427.067	42.907	444.289	35.138	373.244	43.550	339.214	33.782	350.578	38.628	ive Humidi were teste
I mp (mA)	111.044	11.038	105.000	10.755	105.389	11.240	80.611	18.298	69.957	19.057	63.689	14.900	98% Relat specimens
Pmp (mW)	50.222	7.993	45.211	8.063	47.156	7.751	30.578	9.348	24.371	8.560	22.833	7.248	nnd 70°C at e the cell ions.
V <sub>oc</sub> (mV)	584.256	6.698	581.178	5.952	580.878	5.649	573.222	12.066	568.671	16.167	566.200	18.514	13 days and 7 as because the st conditions.
I <sub>sc</sub> (mA)	128.689	2.966	125.667	3.132	126.744	2.683	112.789	17.072	101.628	22.140	97.633	19.186	re: n for first onditions w ority on te e: AMl, 28
Six Cells Total	Average	Std. Dev.	ditions wei saturatio i in test co ch had prio itions wer										
Cumulative No. of Days Exposure to Humidity	0		e		13		33		63		123		<sup>a</sup> Humidity conditions were: 60°C at 100% saturation for first 13 days and 70°C at 98% Relative Humidity for 14 through 123 days. the variance in test conditions was because the cell specimens were tested piggyback with other spec programs which had priority on test conditions. <sup>b</sup> IV test conditions were: AMI, 28°C

Table A-11. I-V Test Data After Humidity Tests  $(Ni/Cu)^{a,b}$ 

Efficiency Z Change -57.46 in Cell -3.73 -11.19 -36.07 -71.14 0 60°C at 100% saturation for first 13 days and 70°C at 98% Relative Humidity for 14 through 123 days. The reason for the variance in test conditions was because the cell specimens were tested piggyback with other specimens on other 22.933 20.100 29.087 88.583 91.633 84.532 5.074 6.505 Resistance, 146.900 424.100 275.770 272.200 R<sub>sh</sub> (Shunt ohms) Rs (Series 0.559 0.858 0.038 0.909 0.089 2.718 0.733 tance, 0.093 0.053 1.666 Resis-0.541 0.293 ohms) Fill Factor (FF) 0.022 0.625 0.007 0.680 0.014 0.520 0.039 0.425 0.019 0.374 0.034 0.689 0.216 12.900 8.567 1.763 5.700 1.470 0.801 13.400 0.608 0.374 3.867 11.900 Eff (%) 0.873 4.712 4.287 1.228 0.450 32.291 451.533 412.933 378.800 417.433 444.267 330.667 ( mV ) ۷mp 59.767 118.900 4.182 114.200 1.705 3.205 82.533 15.907 14.699 47.300 10.881 115.967 (W) I m 34.167 6.925 22.700 5.838 3.253 53.667 2.034 0.759 1.506 15.500 51.533 47.667 ( MIL ) Pmp programs which had priority on test conditions. 0.942 1.478 2.412 5.102 6.246 5.961 591.700 586.800 580.400 576.733 567.433 588.600 ( m ) ۷ ٥ ۵ AM1, 28°C 1.846 0.694 0.368 128.900 112.100 21.532 73.667 17.020 131.467 129.367 14.799 92.067 (**W**) I sc <sup>a</sup>Humidity conditions were: <sup>b</sup>IV test conditions were: Std. Dev. Std. Dev. Std. Dev. Std. Dev. Std. Dev. Std. Dev. Average Average Six Cells Total Average Average Average Average Exposure to Humidity No. of Days Cumulative 0 63 123 m 13 33

Table A-12. I-V Test Data After Humidity Tests (Pd/Ni/Solder)<sup>a,b</sup>

Cumulative No. of Days Exposure to Humidity	Six Cells Total	Isc (mA)	V <sub>oc</sub> (mV)	Р <sub>шр</sub> (ты)	I тр	ү <sub>шр</sub> (лп)	Eff (%)	F111 Factor (FF)	R <sub>s</sub> (Series Resis- tance,	Rsh (Shunt Resis- tance,	% Change 1n Cell Efficiency	r
0	Average	124.133	577.889	44.233	107.778	410.267	11_056	0.616	ohms) 0.569	ohms) 660.778	c	
	Std. Dev.	0.738	2.396	2.150	2.659	13.783	0.529	0.032	0.058	794.566		
e	Average	123.078	575.289	42.489	105.456	403.056	10.633	0.600	0.597	2050.033	-3.83	
	Std. Dev.	1.863	2.688	2.640	. 5.449	13.504	0.673	0.034	0.052	4687.784		
13	Average	120.967	575.489	41.233	101.833	404.167	10.500	0•590	0.625	466.400	-5.03	
	Std. Dev.	4.591	3.652	4.387	8.933	13,885	0.720	0.047	0.096	514.583		
33	Average	116.756	577.233	38.733	96.922	399.144	9.878	0.576	0.684	790.322	-10.65	
	Std. Dev.	4.379	7.534	4.206	8.238	18,658	0.725	0.050	0.136	1065.202		
63	Average	116.565	574.800	38.844	96.689	401.644	006*6	0.579	0.672	421.067	-10.46	
	Std. Dev.	4.461	3.026	3.995	8.658	13.859	0.618	0.045	0.090	226.738		
123	Average	112.156	571.889	36.444	92.200	395.044	9.622	0.567	0.704	429.900	-12.97	
	Std. Dev.	10.148	3.072	5.127	12.278	10.931	0.611	0.047	0.125	505.046		
<sup>a</sup> Humidity conditions were: 60°C at 100% saturation for first 13	ditions wer saturatior	te: 1 for first	13 days ar	nd 70°C at	98% Relati	ve Humidit	ty for 14 t	days and 70°C at 98% Relative Humidity for 14 through 123 days.		The reason for	or	I
the variance in test conditions was programs which had priority on the t	e in test co ch had pric	onditions wa	~ <del>~</del>	the cell i Htions.	spectmens v	vere teste	d piggybacl	because the cell specimens were tested piggyback with other specimens on other set conditions.	r specimei	ns on other		
bIV test conditions were:	ittions were	e: AM1, 28°C	ç									

Table A-13. I-V Test Data After Humidity Tests (Cr/Pd/Ag)<sup>a,b</sup>

	<u> </u>	<u> </u>						· _ · ·	<u> </u>				T
% Change 1n Cell Efficiency	0		-3,32		-3.88		-7.83	•	-8.54		-9.33		
Rsh (Shunt Resis- tance, ohms)	10903.889	29778.329	1384.389	1584.351	447.067	490.354	385.411	304.854	3630.944	9352.993	753.889	930.781	: 98% Relative Humidity for 14 through 123 days. The reason for specimens were tested piggyback with other specimens on other
Rs (Series Resis- tance, ohms)	0.399	0.030	0.395	0.021	0.409	0.019	0.398	0.022	0.433	0.104	0.404	0.021	4
Fill Factor (FF)	0-730	0.020	0.720	0.020	0.715	0.018	0.719	0.017	0.712	0.026	0.718	0,016	days and 70°C at 98% Relative Humidity for 14 through 123 days. ecause the cell specimens were tested piggyback with other spec st conditions.
Eff (%)	14.056	0.430	13.589	0.666	13.511	0.612	12.956	0.574	12.856	0.583	12.744	0.501	ty for 14 t d piggybach
۲ <sub>m</sub> p (۳۷)	476.900	9.075	469.100	8.466	468.422	8.323	472.11	8.279	465.811	17.579	469.122	11.248	ive Humidi were teste
I mp (mA)	118.000	2.329	115.789	5.090	115.389	4.741	109.722	4.616	110.456	4.509	108.522	3.279	98% Relat specimens
P <sub>mp</sub> (mW)	56.267	1.652	54.311	2:644	54.056	2.371	51.800	2.291	51.400	2.335	50.922	1.997	] <b>ដ</b> ក ·
V <sub>o</sub> c (mV)	590.600	2.780	586.656	2.980	586.667	2.586	583.811	2.070	584.444	1.640	582.378	1.721	
I <sub>sc</sub> (mA)	130.389	2.574	128.578	3.766	128.667	3. 633	123.322	3.440	123.422	3.283	121.700	2.816	re: n for first onditions w ority on th e: AM1, 28
Six Cells Total	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	ditions wei saturation in test co ch had pric itions were
Cumulative No. of Days Exposure to Humidity	. 0		M	· .	13		33		63		123		<sup>a</sup> Humidity conditions were: 60°C at 100% saturation for first 13 days and 70°C the variance in test conditions was because the cel programs which had priority on the test conditions. <sup>b</sup> IV test conditions were: AMI, 28°C

Table A-14. I-V Test Data After Humidity Tests (Thick Film Ag Paste)<sup>a,b</sup>

Cumulative No. of Days Exposure to Humidity	Six Cells Total	Isc (mA)	Voc (mV)	Pmp (mw)	I тр (та)	۲ مس <sup>۷</sup> ۲	Eff (%)	F111 Factor (FF)	Rs (Series Resis- tance, ohms)	Rsh (Shunt Resis- tance, ohms)	Z Change in Cell Efficiency	r
0	Average	118.822	586.922	34.200	90.344	372.978	8.544	0.487	1.348	95.600	0	··
-	Std. Dev.	4.208	2.531	8.400	11.480	48.286	2.096	0.105	0.529	67.638		
e	Average	114.844	572.733	29.533	82.244	354.044	7.378	0.443	1.535	73.556	-13.65	
	Std. Dev.	7.268	22.720	7.065	13.336	37.072	1.762	0.080	0.597	71.679		
13	Average	114.233	578.778	29.778	83.678	350.800	7.444	0.444	1.578	93.822	-12.87	<u> </u>
	Std. Dev.	8.293	11.244	7.261	13.712	37.979	1.793	0.083	0.572	118.880		
33	Average	111.450	578.963	29.512	82.675	351.712	7.362	0.452	1.671	126.362	-13.83	· · · ·
	Std. Dev.	7.263	5.036	7.212	12.462	43.084	1.810	0.088	0.716	139.800		
ŕ 63	Average	110.300	578.375	27.738	79.175	343.925	6.938	0.427	1.879	213.200	-18.80	
	Std. Dev.	8.522	3.360	7.7.7	15.593	36.989	1.940	0,092	0.797	302.839		
123	Average	99.125	577.062	19.075	62.600	302.500	4.750	0.326	3.042	25.938	-44.40	
	Std. Dev.	18.693	4.807	5.531	16.877	11.411	1.399	0.044	1.347	14.611		
<sup>a</sup> Humidity conditions were: 60°C at 100% saturation for first 13 days and 70°C at 98% Relative Humidit <sup>y</sup> for 14 through 123 days. The reason for the variance in test conditions was because the cell specimens were tested piggyback with other specimens on other programs which had priority on the test conditions.	Humidity conditions were: 60°C at 100% saturation for first 1 the variance in test conditions was programs which had priority on the	re: n for first onditions w ority on th	t 13 days and 70°C was because the center test conditions	3 days and 70°C at because the cell test conditions.	: 98% Relat specimens	:1ve Humid: were teste	lṫy for 14 ≥d piggybac	98% Relative Humidity for 14 through 123 days. The reason f specimens were tested piggyback with other specimens on other	3 days. T er specime	he reason ens on othe	for r	r
b <sub>IV</sub> test conditions were:	ditions wer	e: AM1, 28°C	8°C									

<ul> <li>4. Title ord Subtitle</li> <li>A. Title ord Subtitle</li> <li>Environmental Tests of Metallization Systems for Terrestrial Photovoltaic Cells</li> <li>2. Author(a)</li> <li>2. Author(b)</li> <li>3. Performing Organization Name and Address</li> <li>JET PROPULSION LABORATORY Galifornia Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109</li> <li>2. Sponsoring Agency Name and Address</li> <li>NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546</li> <li>3. Supplementory Notes Sponsored by the U.S. Department of Energy through Interagency Agreement DE-AI01-76ET20356 with NASA; also identified as DDE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).</li> <li>4. Abstract</li> <li>3. Author(b)</li> <li>3. Author(c)</li> <li>4. Abstract</li> <li>3. Author(c)</li> <li>3. Author(c)</li> <li>4. Abstract</li> <li>3. Author(c)</li> <li>4. Abstract</li> <li>5. Supplementory commend Address (Code Transmitted as DDE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).</li> <li>4. Abstract</li> <li>4. Abstract</li> <li>5. Author(c)</li> <li>5. Author(c)</li> <li>6. Abstract</li> <li>6. Abstract</li> <li>6. Author(c)</li> <li>7. Key Word Galesch by Author(c)</li> <li>3. Super Science at Fer Science at Institution systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also cell efficiencies after temperature cycling. All 64 the seven metallization systems showed slight to moderate decrease in cell efficiencies after temperature cycling. All 65 the seven metallization systems showed slight to consert cost for after decreases in cell efficiencies after temperature cycling. All 65 the seven metallization systems showed slight to consert cost for advert cycling. All 65 the seven metallization systems showed moderate to large decreases i</li></ul>	r	r		·							
Environmental Tests of Metallization Systems for Terrestrial Photovoltaic Cells       December 31, 1985         7. Author(s)       8. Performing Organization Code         7. Author(s)       8. Performing Organization Report No.         9. Performing Organization Name and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109 JUANAN       10. Work Uhit No.         12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS ND SPACE ADMINISTRATION Vashington, D.C. 20546       11. Contract or Grant No. MAST-918         13. Supplementary Notes Sponsoring Agency Notes Agreement DE-AIOI-76ET20356 with NASA; also identified as DDE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).       14. Sponsoring Agency Code         16. Abstract       Seven different solar cell metallization systems were subjected to temperature cycling testa and hmidity rests. Temperature cycling excursions were -50%C to 150%C per cycle. Humidity conditions were 70%C at 987 relative humidity. The seven metallization systems subce tight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycling. All <i>st</i> -the-seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycling. All <i>st</i> -the-seven metallization systems showed moderate to large decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate mubers of cycles, generally less than .100 cycles. The copperShased systems showed the largest decrease in cell efficiencies after tundity exposure. Craphs of the envirommental exposures versus cell efficiencies a	1. Report No. 85-86	2. Government Accession No.	3. Recipient's Catalog No.								
in Hommany Tests of metallization systems       6. Performing Organization Code         for Terrestrial Photovoltaic Cells       6. Performing Organization Code         7. Author(6)       P. Alexander, Jr.         9. Performing Organization Nome and Address       10. Work Uhit No.         JET PROPULSION LABORATORY       10. Work Uhit No.         California Institute of Technology       4800 Oak Crove Drive         4800 Oak Crove Drive       7.         Pasadena, California 91109       J.J.J.J.J.         12. Sponsoring Agency Nome and Address       11. Contract or Grant No.         NATIONAL AEDONAUTICS AND SPACE ADMINISTRATION       13. Type of Report and Period Covered         Agreement DE-AIOL-76E720356 with NASA; also identified as DOEJPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).       14. Sponsoring Agency Code         16. Abtract       Seven different solar cell metallization systems were subjected to temperature cycling tests and hundity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Rundity conditions were 70°C at 987 relative hundity. The seven metallization systems subsect slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven, metallization systems also evidenced slight increases in cell efficiencies after moderate decrease in cell efficiencies after moderate decrease in cell efficiencies after temperature cycling.         All of the oweven metallization systems alwoed moderate to large decrease in cell efficiencies after properucture cycling. </td <td>4. Title and Subtitle</td> <td></td> <td>5. Report Date</td> <th></th>	4. Title and Subtitle		5. Report Date								
for Terrestrial Photovoltaic Cells       6. Performing Organization Code         7. Author(6)       P. Alexander, Jr.       6. Performing Organization Report No.         9. Performing Organization Nome and Address       JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109 JCAUAO       10. Work Unit No.         12. Sponsoring Agency Nome and Address NATIONAL AEDONUTICS AND SPACE ADMINISTRATION Vashington, D.C. 20546       11. Contract or Grant No. NAS7-918         13. Type of Report and Period Covered Agreement DE-A101-76ET20356 with NASA; also identified as DDE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).       14. Sponsoring Agency Code         16. Abstract       Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50%C to 150%C per cycle. Humidity conditions were 70%C at 967 relative humidity. The seven metallization systems were: IR: 11/Ag, 49. T1/20/Ag, 80. T1/20/Au, 49. N1/Au (59. RMN/Solder, 69. Cr/R/Ag, and G9. Thick film Ag. All of the oewer.metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copperSpases in cell efficiencies after la3 days of humidity exposure. The copperSpases in cell efficiencies after the cycling: All of the sever metallization systems showed moderate to large decreases in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus fill factors or series resistance.       18. Distribution Statement Maclassifi	Environmental Tests of Met	allization Suctome	December 31, 1985								
P. Alexander, Jr.         9. Performing Organization Name and Address         JET PROFULSION LABORATORY         California Institute of Technology         4800 Oak Grove Drive         Pasadena, California 91109         JES Sponsoring Agency Name and Address         NATIONAL AERONAUTICS AND SPACE ADMINISTRATION         Vashington, D.C. 20546         15. Supplementory Notes         Sponsoring Agency Nome and Address         JPL Froject 5101-260 (RTOP or Customer Code 776-52-61).         16. Abstract         Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 130°C per cycle. Humidity conditions were 70°C at 98°C relative humidity. The seven metallization systems such as the moder of the cycles. Six of the seven metallization systems such as the indice of the seven metallization systems also evidenced slight increases in cell efficiencies after mubers of cycles, generally less than 100 cycles. The copper/based systems showed the largest decrease in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decr			6. Performing Organization	Code							
P. Alexander, Jr.         9. Performing Organization Name and Address         JET PROFULSION LABORATORY         California Institute of Technology         4800 Oak Grove Drive         Pasadena, California 91109         JES Sponsoring Agency Name and Address         NATIONAL AERONAUTICS AND SPACE ADMINISTRATION         Vashington, D.C. 20546         15. Supplementory Notes         Sponsoring Agency Nome and Address         JPL Froject 5101-260 (RTOP or Customer Code 776-52-61).         16. Abstract         Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 130°C per cycle. Humidity conditions were 70°C at 98°C relative humidity. The seven metallization systems such as the moder of the cycles. Six of the seven metallization systems such as the indice of the seven metallization systems also evidenced slight increases in cell efficiencies after mubers of cycles, generally less than 100 cycles. The copper/based systems showed the largest decrease in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling.         All State evene metallization systems showed moderate to large decr	7 4 11 - ()		8 Performine Oranzization	Parant Ma							
9. Performing Organization Nome and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109 JUSAUAN 12. Sponsoring Agency Nome and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Vashington, D.C. 20546       11. Contract or Grant No. NAS7-918         12. Sponsoring Agency Nome and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Vashington, D.C. 20546       JPL Publication         15. Supplementary Notes Seven different solar cell metallization systems were subjected to temperature cycling tests and hunidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Hunidity conditions were 70°C at 982 relative hunidity. The seven metallization systems were: Sh, Ti/Ag, Sh, Ti/Pd/Cu, Gh, Ni/Cu, Sh, Pd/Ni/Solder, Gh, Cr/Pd/Ag, and Gh, Thick film Ag. All sf-the-seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 100 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copper&based systems showed the largest decrease in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copper&based systems showed the largest decrease in cell efficiencies after temperature cycling. All st-the-seven metallization systems showed moderate to large decreases in cell efficiencies after 100 temperature cycles. Six of the seven, metallization systems also evidenced slight increases fill efficiencies after temperature cycling. All st-the-seven metallization systems showed moderate to large decreases in cell efficiencies after 10 systems, as well as environmental exposures. Graphs of the environmental exposures versus cell efficiencies after hunidity exposure. Sterency Storage Netavartice cells Netavartice cells Netavartice cells Netavartice cells			o, remorning Organization	Report INO.							
JET PROPULSION LABORATORY California Institute of Technology A800 0ak Grove Drive Pasadena, California 91109 JUSAKO Pasadena, California 91109 JUSAKO Pasadena DE-AGID-765720350 with NASA: also identified as DOE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).         16. Abstract Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity conditions were 70°C at 98% relative humidity. The seven metallization systems were: 19, Tri/Ag, (2), Tri/Cd/Cu, 49, Ni/Cu, SQ PA/Ni/Solder, 19, Cr/PA/Ra, and (F3), Tri/Cd/Cu, 49, Ni/Cu, SQ PA/Ni/Solder, 19, Cr/PA/Ra, and (F3), Tri/Cd/Cu, 49, Ni/Cu, SQ PA/Ni/Solder, 19, Cr/PA/Ra, and (F3), Tri/Cd/Cu, 59, Tri/Cd/Cu, 49, Ni/Cu, SQ PA/Ni/Solder, 19, Cr/PA/Ra, and (F3), Tri/Cd/Cu, 50, The seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copperphased systems showed the largest decrease in cell efficiencies after temperature cycling. All st-the-seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copperphased systems again showed the largest decrease in cell efficiencies are presented for each SG the environmental exposures versus cell efficiencies are presented for each SG the metallization systems, as well as environmental exposures versus fill factors or series resistance.			10 Work I with No								
California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109 IKHUKU 12. Sponsoring Agency Nome and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Vashington, D.C. 20546 15. Supplementary Note: Sponsored by the U.S. Department of Energy through Interagency Agreement DE-AIOL-76ET20356 with NASA; also identified as DDE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61). 16. Abstract Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Humidity conditions were 70°C at 98% relative humidity. The seven metallization systems were: B> TI/Ag, B> TI/Ad/Ag, B> TI/Ad/Cu, A> NI/Cu, B) Pd/Ni/Solder, GO Cr/Pd/Ag, and G> Thick Yilm Ag. All sf-the-seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copper&based systems showed the largest decrease in cell efficiencies after temperature cycling. All sf-the-seven metallization systems showed slight to moderate to large decreases in cell efficiencies after subjection to 1000 temperature to large decreases in cell efficiencies after largest decrease in cell efficiencies after tumidity exposure. Craphs of the environmental exposures versus cell efficiencies are presented for each sf the-metallization systems, as well as environmental exposures versus fill factors or series resistance. 17. Key Words (Selected by Author(b)) Sheergy Storage humidity moderate fetty subjection of setty proformance fetty backasefied-unlimited coch reduction backasefied-unlimited coch reduction the cycly shorage 19. Security Clasif. (of this report) Unclassified Unclassified Unclassified Unclassified Case reduction Case reduction Case reduction Case reduction	- <del>-</del> -										
4800 Oak Grove Drive Pasadena, California 91109 JULANKA       NAS7-918         12. Sponsoring Agency Nome and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546       13. Type of Report and Period Covered JPL Publication         15. Supplementory Notes Agreement DE-ADI-76EF20356 with NASA; also identified as DOE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).       14. Sponsoring Agency Code         16. Abstract       Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Humidity conditions were 70°C to 927 relative humidity. The seven metallization systems were: IAN Tri/Ag, IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Ni/Cu, ISN PA/Ni/Solder, IAN Cor/Pd/Ag, and IAN Tri/PA/Ag, IAN Tri/PA/Cu, IAN Tri	· · · · · · · · · · · · · · · · · · ·		11. Contract or Grant No.								
Pasadena, California 91109 15 1444       13. Type of Report and Period Covered         12. Sponsoring Agency Name and Address       JPL Publication         NATIONAL AERONAUTICS AND SPACE ADMINISTRATION       14. Sponsoring Agency Code         15. Supplementary Notes       Sponsorie by the U.S. Department of Energy through Interagency Agreement DE-AIOL-76ET20356 with NASA; also identified as DOE/JPL 1012-113 and as JPL Project SIOL-280 (RTOP or Customer Code 776-52-61).         16. Abstract       Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Humidity conditions were 70°C 49 87 relative humidity. The seven metallization systems were 50°C to 1000 temperature cycles. Six of the seven, metallization systems also evidenced slight increases in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven, metallization systems also evidenced slight increases in cell efficiencies after subjection to 1000 temperature cycles. The copper&based systems again showed the largest decrease in cell efficiencies after temperature cycling.         All settle seven metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling.         All settle seven metallization systems, as well as environmental exposure. The copper&based systems fill factors or series resistance.         17. Key Word (Selected by Author(h))       Its. Distribution Statement makers decrease in cell efficiencies after temperature cycling.         18. Distribution Statement metallization systems, as well as environmental exposures versus fill factors or series resistance.											
12. Sponsoring Agency Nome and Address       JPL Publication         NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546       JPL Publication         13. Supplementory Notes Agreement DE-AIOI-76ET20356 with NASA; also identified as DDE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).       14. Sponsoring Agency Code         14. Astract       Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Humidity conditions were 70°C at 987 relative humidity. The seven metallization systems were: BN Ti/Ag, EN Ti/Pd/Ag, SD Ti/Pd/Cu, CN Ni/Cu, EN Pd/Ni/Solder, GD Cr/Pd/Ag, and CD Thick film Ag.         All of the seven metallization to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after systems showed the largest decrease in cell efficiencies after temperature cycling. All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copperAbased systems showed the largest decrease in cell efficiencies after temperature cycling. All of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.         17. Key Word (Selected by Author(s)) Senergy Storage       18. Distribution Stotement mass spectroscopy performance tests       graphs(charls) tables(cdata)         17. Key Word (Selected by Author(s)) Senergy S			13. Type of Report and Perio	od Covered							
Vashington, D.C. 20546       14. Sponsoring Agency Code         15. Supplementary Notes       Sponsored by the U.S. Department of Energy through Interagency Agreement DE-AI01-76ET20356 with NASA; also identified as DOE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).         16. Abstract       Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Rumidity conditions were 70°C at 98% relative humidity. The seven metallization systems were: 18-71/Ag, E3-T1/Pd/Ag, E3-T1/Pd/Cu, C4-Ni/Cu, C50 Pd/Ni/Solder, G9 Cr/Pd/Ag, and G9 Thick film Ag.         All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copper&Based systems showed the largest decrease in cell efficiencies after temperature cycling. All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper&Based systems and the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each Si the metallization systems, as well as environmental exposures versus fill factors or series resistance.         17. Key Word (Selected by Author(b)) Sharery Storage       18. Distribution Storement ' graphs(charts) mass spectroscopy performance fests         18. Distribution Storement ' Baser Sources       9 raphs(charts) mass spectroscopy performance fests         18. Distribution Storement ' Bas	12. Sponsoring Agency Name and Ad	dress	JPL Publication	Ó							
<ul> <li>15. Supplementory Note: Sponsored by the U.S. Department of Energy through Interagency Agreement DE-AI01-76E720356 with NASA; also identified as DOE/JPL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).</li> <li>16. Abstract Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50%C to 150%C per cycle. Humidity conditions were 70%C at 98% relative humidity. The seven metallization systems were is 20, Pd/Ni/Solder, GD, Cr/Pd/Ag, and GD, Thick film Ag. All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copperabased systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each GC the metallizing metallizing metallizing metallizing metallizing temperature effect informance tests inclassified without cells </li> <li>17. Key Word (Selected by Author(b)) Shaery Storage metallizing metallizing temperature effect informance tests inclassified without cells </li> <li>18. Distribution Statement decrease in cells </li> <li>19. Security Clasif, (of this report) 20. Security Clasif, (of this poge) 21. No. of Pages 22. Price Unclassified without cells </li> </ul>	NATIONAL AERONAUTICS AND	SPACE ADMINISTRATION	14. Sponsoring Accessive Code								
Agreement DE-A101-76ET2035 with NASA; also identified as DC/JFL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).         16. Abstract         Seven different solar cell metallization systems were subjected to temperature cycling tests and hunidity tests. Temperature cycling excursions were -50% to 150% (Per cycle. Hunidity conditions were 70% at 98% relative hunidity. The seven metallization systems were: D. Ti/Ag, D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Ni/Cu, D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Ni/Cu, D. Ti/Pd/Ga, D. T	Washington, D.C. 20546		14. Shorson was weench rode								
Agreement DE-A101-76ET2035 with NASA; also identified as DC/JFL 1012-113 and as JPL Project 5101-280 (RTOP or Customer Code 776-52-61).         16. Abstract         Seven different solar cell metallization systems were subjected to temperature cycling tests and hunidity tests. Temperature cycling excursions were -50% to 150% (Per cycle. Hunidity conditions were 70% at 98% relative hunidity. The seven metallization systems were: D. Ti/Ag, D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Pd/Ni/Solder, GD cr/Pd/Ag, and D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Ni/Cu, D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ti/Pd/Ga, D. Ni/Cu, D. Ni/Cu, D. Ni/Cu, D. Ti/Pd/Ga, D. T	15. Supplementary Notes	11									
JPL Project 5101-280 (RTOP or Customer Code 776-52-61).         16. Abstract         Seven different solar cell metallization systems were subjected to temperature cycling tests and hunidity tests. Temperature cycling excursions were -50% to 150% per cycle. Humidity conditions were 70% at 98% relative humidity. The seven metallization systems were: B3, Ti/Rds, B3, Ti/Rd/Cu, G3, Ni/Cu, G3, Pd/Ni/Solder, G3, Cr/Pd/Ag, and G3, Thick Film Ag.         All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems showed slight increases in cell efficiencies after temperature cycling.         All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the mutallization systems, as well as environmental exposures versus fill factors or series resistance.         17. Key Words (Selected by Author(s))       18. Distribution Statement ' graphs (charts) factors or series resistance.         17. Key Words (Selected by Author(s))       18. Distribution Statement ' graphs (charts) factors or series resistance.         18. Distribution Statement ' graphs (charts) factors or series resistance.       9/20/20/20/20/20/20/20/20/20/20/20/20/20/	sponsore	d by the U.S. Department of	Energy through Interag	ency							
<ul> <li>16. Abstract Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Humidity conditions were 70°C at 98% relative humidity. The seven metallization systems were: (A), Ti/Ag, (B), Ti/Ad/Cu, (A), Ni/Cu, (B), Pd/Ni/Solder, (B), Cr/Pd/Ag, ad (B), Thick Jilm Ag. All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after temperature cycling. All of the seven metallization systems showed moderate to large decreases in cell efficiencies after temperature cycling. All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell afficiencies are presented for each <u>of the metallization systems</u>, as well as environmental exposures versus fill factors or series resistance. </li> <li>17. Key Word (Selected by Author(s)) Benergy Storage humidity Enverses temperature effect Benergy Storage metallizing Declassified minidity Casif, (of this report) Unclassified Unclassified Benergy Storage Benergy Storage</li></ul>	JPL Project 5101-280 (PTOP	or Customer Code 776_52_61	as DUE/JPL 1012-113 and A	nd as							
Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50% to 150% per cycle. Humidity conditions were 70% at 9% relative humidity. The seven metallization systems were: (A) Ti/Pd/Ag, (B) Ti/Pd/Cu, (A) Ni/Cu, (B) Pd/Ni/Solder, (G) Cr/Pd/Ag, and (G) Thick Film Ag.         All site the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven, metallization systems also evidenced slight increases in cell effectiencies after moderate numbers of cycles, generally less than 100 cycles. The copper based systems showed the largest decrease in cell efficiencies after temperature cycling.         All of the seven metallization systems showed moderate to large decreases in cell efficiencies after to coper based systems again showed the largest decrease in cell efficiencies after humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure.         To each §c the metallization systems, as well as environmental exposures versus fill factors or series resistance.         17. Key Words [Selected by Author(s)]         Shergy Storage       humidity         Bowar Sources       temperature effect         Mass spectroscopy       performance tests         Suclassified unlimited       gat reduction         Bowar Sources       metallizing         Bowar Sources       metallizing         Broclassified withing       20. Security Classif. (of this poge)       21. No. of Poges       22. Price	512 110jeet 5101-200 (KIOF		-/ •								
<ul> <li>cycling tests and humidity tests. Temperature cycling excursions were -50%C to 150%C per cycle. Humidity conditions were 70%C at 98% relative humidity. The seven metallization systems were: B). Ti/Ag, B). Ti/Ag, B). Ti/Pd/Cu, A). Ni/Cu, B). Pd/Ni/Solder, G). Cr/Pd/Ag, and G). Thick film Ag.</li> <li>All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven, metallization systems also evidenced slight increases in cell effectioncies after temperature cycling. All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after temperature cycling. All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the mutallization systems, as well as environmental exposures versus fill factors or series resistance.</li> <li>18. Distribution Statement ' graphs(charts) mass spectroscopy ' fables (data) ' graphs(charts) ' fables (data) ' performance tests' ' aloles (data) ' performance tests' ' aloles (data) ' performance tests' ' aloles (data) ' proposition cells' storage ' temperature effect ' storage ' temperature effect ' storage' storage ' temperature cells' ' storage' ' sto</li></ul>	16. Abstract										
<ul> <li>cycling tests and humidity tests. Temperature cycling excursions were -50%C to 150%C per cycle. Humidity conditions were 70%C at 98% relative humidity. The seven metallization systems were: B). Ti/Ag, B). Ti/Ag, B). Ti/Pd/Cu, A). Ni/Cu, B). Pd/Ni/Solder, G). Cr/Pd/Ag, and G). Thick film Ag.</li> <li>All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven, metallization systems also evidenced slight increases in cell effectioncies after temperature cycling. All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after temperature cycling. All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the mutallization systems, as well as environmental exposures versus fill factors or series resistance.</li> <li>18. Distribution Statement ' graphs(charts) mass spectroscopy ' fables (data) ' graphs(charts) ' fables (data) ' performance tests' ' aloles (data) ' performance tests' ' aloles (data) ' performance tests' ' aloles (data) ' proposition cells' storage ' temperature effect ' storage ' temperature effect ' storage' storage ' temperature cells' ' storage' ' sto</li></ul>	Seven different solar	cell metallization excteme	were subjected to temp	oratura							
<ul> <li>150°C per cycle. Humidity conditions were 70°C at 98% relative humidity. The seven metallization systems were: (2) Ti/Ag, (2) Ti/Pd/Ag, (3) Ti/Pd/Cu, (2) Ni/Cu, (3) Pd/Ni/Solder, (3) Cr/Pd/Ag, and (3) Thick film Ag.</li> <li>All of the seven metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copper based systems showed the largest decrease in cell efficiencies after temperature cycling.</li> <li>All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell efficiencies are presented for each of the environmental exposures versus cell as environmental exposures versus fill factors or series resistance.</li> <li>17. Key Word (Selected by Author(s)) Senergy Storage humidity metallization systems, as well as environmental exposures versus fill factors or series resistance. 18. Distribution Statement ' graphs (charts mass spectroscopy performance tests ' graphs (charts is aclassified unlimited cast reduction energy storage. 19. Security Clasif. (of this report) 20. Security Clasif. (of this page) 21. No. of Pages 22. Price the security clasified uffluences</li></ul>	cycling tests and humidity	tests. Temperature cyclin	were subjected to temps $excursions$ were $-50\%$	to							
<ul> <li>metallization systems were: [A]. Ti/Ag, (B). Ti/Pd/Ag, [B]. Ti/Pd/Cu, (A). Ni/Cu, (B). Pd/Ni/Solder, [G]. Cr/Pd/Ag, and [G]. Thick Film Ag.</li> <li>All of the overn metallization systems showed slight to moderate decrease in cell efficiencies after subjection to 1000 temperature cycles. Six of the seven, metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The copper based systems showed the largest decrease in cell efficiencies after temperature cycling.</li> <li>All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.</li> <li>17. Key Words (Selected by Author(s)) <ul> <li>Benergy Storage humidity</li> <li>Benergy Storage humidity</li> <li>Benergy Storage metallizing</li> <li>Calassified uffluencies</li> </ul> </li> <li>18. Distribution Statement ' graphs (charts) fables (aata) ' fables (charts) ' fables (aata) ' fables (aata</li></ul>	150°C per cycle. Humidity	conditions were 70°C at 98	7 relative humidity. T	he seven							
<ul> <li>cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The coppersbased systems showed the largest decrease in cell efficiencies after temperature cycling.         <ul> <li>All set the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The coppersbased systems again showed the largest decrease in cell efficiencies after humidity exposure.</li> <li>Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.</li> </ul> </li> <li>17. Key Words (Selected by Author(s))         <ul> <li>Senergy Storage humidity effect moderate to each of the metallizing metallizing metallizing</li> <li>I8. Distribution Statement graphs(charts) fables (data)</li> <li>Security Clasif. (of this report)</li> <li>20. Security Clasif. (of this poge)</li> <li>21. No. of Pages</li> <li>22. Price Unclassified for some set of the security Clasified of the security classified</li> </ul> </li> </ul>	metallization systems were	: 12) Ti/Ag, (2) Ti/Pd/Ag,	(B) Ti/Pd/Cu, (A) Ni/Cu	<b>&gt;</b>							
<ul> <li>cell efficiencies after subjection to 1000 temperature cycles. Six of the seven metallization systems also evidenced slight increases in cell efficiencies after moderate numbers of cycles, generally less than 100 cycles. The coppersbased systems showed the largest decrease in cell efficiencies after temperature cycling.         <ul> <li>All set the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The coppersbased systems again showed the largest decrease in cell efficiencies after humidity exposure.</li> <li>Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.</li> </ul> </li> <li>17. Key Words (Selected by Author(s))         <ul> <li>Senergy Storage humidity effect moderate to each of the metallizing metallizing metallizing</li> <li>I8. Distribution Statement graphs(charts) fables (data)</li> <li>Security Clasif. (of this report)</li> <li>20. Security Clasif. (of this poge)</li> <li>21. No. of Pages</li> <li>22. Price Unclassified for some set of the security Clasified of the security classified</li> </ul> </li> </ul>	All <del>of the seven</del> meta										
metallization systems also evidenced slight increases in cell efficiencies aftermoderate numbers of cycles, generally less than 100 cycles. The coppershasedsystems showed the largest decrease in cell efficiencies after temperature cycling.All of the seven metallization systems showed moderate to large decreases incell efficiencies after 123 days of humidity exposure. The coppershased systemsagain showed the largest decrease in cell efficiencies after humidity exposure.Graphs of the environmental exposures versus cell efficiencies are presentedfor each of the metallization systems, as well as environmental exposures versusfill factors or series resistance.17. Key Words (Selected by Author(s))SterrageHornidityBuser Sourcestemperature effectSolar Armaysmetallizingbrodovoltaic cells19. Security Clasif. (of this report)20. Security Clasif. (of this poge)21. No. of Pages22. PriceUnclassified88	cell efficiencies after subjection to 1000 temperature cycles. Six of the seven										
<ul> <li>systems showed the largest decrease in cell efficiencies after temperature cycling. All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.</li> <li>17. Key Words (Selected by Author(s)) Senergy Storage humidity emperature effect mass spectroscopy performance tests temperature effect metallizing metallizing metallizing technology storage</li> <li>18. Distribution Statement ' graphs (charts) tables (data)</li> <li>Basers Sources metallizing metallizing technology storage</li> <li>19. Security Classif. (of this report) Unclassified wffurences Unclassified wffurences</li> </ul>	metallization systems also evidenced slight increases in cell effectioncies after										
All of the seven metallization systems showed moderate to large decreases in cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance. 17. Key Work (Selected by Author(s)) Benergy Storage humidity Power Sources temperature effect Pawer Sources temperature effect Materials solar armays metallizing bolovoltaic cells 19. Security Classif. (of this report) Unclassified Afficiencies are presented on the solar afficiencies are presented unclassified Afficiencies are presented on the solar afficiencies are presented on the solar afficiencies are presented unclassified Afficiencies are presented on the solar afficiencies are presented unclassified afficiencies are presented on the solar afficiencies are presented on the solar afficiencies are presented and the solar afficiencies are presented afficiencies are presented afficiencies are presented afficiencies afficiencies are presented afficiencies are presented afficiencies are presented afficiencies are p	moderate numbers of cycles	moderate numbers of cycles, generally less than 100 cycles. The copper $\pounds$ based									
<ul> <li>cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each <u>off the metallization systems</u>, as well as environmental exposures versus fill factors or series resistance.</li> <li>17. Key Words (Selected by Author(s))         <ul> <li>Inclassified uffuences</li> <li>Inclassified uffuences</li> <li>Inclassified uffuences</li> </ul> </li> </ul>	systems showed the largest	decrease in cell efficience	ies after temperature c	ycling.							
<ul> <li>cell efficiencies after 123 days of humidity exposure. The copper based systems again showed the largest decrease in cell efficiencies after humidity exposure. Graphs of the environmental exposures versus cell efficiencies are presented for each <u>off the metallization systems</u>, as well as environmental exposures versus fill factors or series resistance.</li> <li>17. Key Words (Selected by Author(s))         <ul> <li>Inclassified uffuences</li> <li>Inclassified uffuences</li> <li>Inclassified uffuences</li> </ul> </li> </ul>	All <del>of the seven</del> meta	llization systems showed mo	derate to large decrease	es in							
Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.17. Key Words (Selected by Author(s))18. Distribution Statement ' graphs (charts) mass spectroscopy' tables (data)17. Key Words (Selected by Author(s))18. Distribution Statement ' graphs (charts) mass spectroscopy' tables (data)18. Distribution Statement ' graphs (charts) mass spectroscopy' tables (data)19. Security Classif. (of this report) Unclassified withwardes20. Security Classif. (of this page) Unclassified19. Security Classif. (of this report) Unclassified withwardes20. Security Classif. (of this page) Unclassified21. No. of Pages 88	cell efficiencies after 12	3 days of humidity exposure	. The copper based syst	tems							
for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance. 17. Key Words (Selected by Author(s)) Binergy Storage humidity Bower Sources temperature effect Materials solar arrays metallizing energy storage 18. Distribution Statement ' graphs(charts) mass spectroscopy tables (data) Binergy Storage humidity Performance tests Solar arrays metallizing Photovoltaic cells 19. Security Classif. (of this report) Unclassified Afficience Unclassified 10. Security Classif. (of this poge) Unclassified Afficience 10. Security Classif. (of this poge) 11. No. of Pages 22. Price 12. No. of Pages 22. Price	again showed the largest de	ecrease in cell efficiencie	s after humidity exposu	re.							
for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance. 17. Key Words (Selected by Author(s)) Binergy Storage humidity Bower Sources temperature effect Materials solar arrays metallizing energy storage 18. Distribution Statement ' graphs(charts) mass spectroscopy tables (data) Binergy Storage humidity Performance tests Solar arrays metallizing Photovoltaic cells 19. Security Classif. (of this report) Unclassified Afficience Unclassified 10. Security Classif. (of this poge) Unclassified Afficience 10. Security Classif. (of this poge) 11. No. of Pages 22. Price 12. No. of Pages 22. Price											
17. Key Words (Selected by Author(s))18. Distribution Statement ' graphs (charts)Senergy Storagehumiditymass spectroscopytables (data)Bower Sourcestemperature effectperformance teststables (data)Solar arraysmetallizingsolar reductionenergy storage19. Security Classif. (of this report)20. Security Classif. (of this poge)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified8888	for each <u>of the metallizat</u> :	ion systems, as well as env	ironmental exposures ver	sus							
Hower-Sourcestemperatule effectperior mance resisMaterialsmetallizingUnclassified-unlimitedsolar arraysmetallizingcost reductionobtovoltaic cellsenergy storage19. Security Classif. (of this report)20. Security Classif. (of this page)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified88	IIII factors or series res	istance.									
Hower-Sourcestemperatule effectperior mance resisMaterialsmetallizingUnclassified-unlimitedsolar arraysmetallizingcost reductionobtovoltaic cellsenergy storage19. Security Classif. (of this report)20. Security Classif. (of this page)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified88											
Hower-Sourcestemperatule effectperior mance resisMaterialsmetallizingUnclassified-unlimitedsolar arraysmetallizingcost reductionobtovoltaic cellsenergy storage19. Security Classif. (of this report)20. Security Classif. (of this page)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified88	· · · · ·										
Hower-Sourcestemperatule effectperior mance resisMaterialsmetallizingUnclassified-unlimitedsolar arraysmetallizingcost reductionobtovoltaic cellsenergy storage19. Security Classif. (of this report)20. Security Classif. (of this page)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified88	-	•									
Hower-Sourcestemperatule effectperior mance resisMaterialsmetallizingUnclassified-unlimitedsolar arraysmetallizingcost reductionobtovoltaic cellsenergy storage19. Security Classif. (of this report)20. Security Classif. (of this page)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified88	17 Kay Work Kalanted L. Anteria		Statement ' a manha	(charte)							
Hower-Sourcestemperatule effectperior mance resisMaterialsmetallizingUnclassified-unlimitedsolar arraysmetallizingcost reductionobtovoltaic cellsenergy storage19. Security Classif. (of this report)20. Security Classif. (of this page)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified88			tmemory yraphist								
MaterialsmetallizingUnclassified-unlimited cost reduction energy storagesolar arraysmetallizingcost reduction energy storage19. Security Classif. (of this report)20. Security Classif. (of this page)21. No. of Pages22. PriceUnclassified ufficienciesUnclassified88			pretests tables	(aata)							
solar arrays metallizing cost reduction photovoltaic cells cost reduction energy storage Inclassified ufficiencies Unclassified 88	Most control o			· ·							
Construction </th <th></th> <th></th> <th>-</th> <th></th>			-								
Unclassified référencies Unclassified 88	photovoltaic cells			= -							
	19. Security Classif. (of this report)	20. Security Classif. (of this p	age) 21. No. of Pages	22. Price							
	Unclassified ufficiencies	Unclassified	88								
		L		L 0184 R 9/83							

1

•. • •

•

.

.

•••••

a taka manantin a tisutisi.