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DE94000236

PHOTOVOLTAIC PERFORMANCE AND RELIABILITY WORKSHOP

September 8-10, 1993

Golden, Colorado

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September 8-10, 1993

Golden, Colorado

Denver Marriott West/Golden, Colorado

Edited by: Laxmi Mrig (NREL)

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PREFACE

The papers and presentations compiled in this volume form the Proceedings of the "PV Performance and Reliability" workshop held in Golden, Colorado on September 8-10, 1993. This workshop was the sixth in a series of Workshops sponsored by NREL/DOE under the general subject areas of photovoltaic testing and reliability during the period 1986-1993.

PV performance and PV reliability are at least as important as PV cost, if not more. Performance and reliability are two strategic parameters that are used to assess the development of any technology. The average consumer researches regarding the performance and reliability of any product prior to purchase whether it is an automobile or some other major product and the same will hold true when a consumer purchases PV. Those PV companies that emphasize performance and reliability as part of their product information and marketing attributes are the ones that are likely to be successful in today's competitive marketplace.

Many researchers are involved in the research, development, performance monitoring and reliability testing of photovoltaics around the world. In the U.S., PV manufacturers, DOE laboratories, electric utilities and others are engaged in the photovoltaic reliability research and testing. This group of researchers and others interested in this field were brought together under NREL/DOE sponsorship to exchange the technical knowledge and field experience as related to current information in this evolving field of PV reliability. The papers presented here reflect this effort since the last workshop held in September 1992.

My sincere thanks go to excellent speakers, session chairs, and NREL conference coordinators in making this workshop a success.

Laxmi Mrig
Workshop Chairman
NREL

Photovoltaic Performance and Reliability Workshop
September 8-10, 1993
Table of Contents

Preface	i
Laxmi Mrig, National Renewable Energy Laboratory	
Opening Session	1
James Rannels, U.S. Department of Energy	3
Anthony Catalano, National Renewable Energy Laboratory	13
Cell and Module Characterization	19
PV Efficiency Measurements Overview	21
Keith Emery, National Renewable Energy Laboratory	
Characteristics of Spectrolab Solar Simulator	48
James Lovelady, Spectrolab	
Pulsed Solar Simulator Design and Applications	58
Stephen Hogan, Spire	
Indoor and Outdoor Efficiency Measurements of a-Si Multijunction Modules	76
Troy Glatfelter, USSC	
Radiometric Measurements for PV Characterization	99
Daryl Myers, National Renewable Energy Laboratory	
Module and System Testing	111
Overview of Photovoltaic Module Reliability Testing at NREL	113
Joseph Burdick, National Renewable Energy Laboratory	
Results of Module Hot Spot Testing	138
Robert Hammond, Arizona State University	
Relative Humidity, Temperature and Irradiance Testing at Mobil Solar Energy Corporation	153
Moneer Azzam, Mobil Solar Energy Corporation	

Performance and Stress Testing of CdTe Modules	167
Daniel Sandwisch, Solar Cells, Inc.	
Investigation of Lamination Induced Metastability in CIS-Based Modules	184
Dennis Willett, Siemens Solar	
Testing for Module Warranties	200
John Wohlgemuth, Solarex	
Field Wet Resistance Test Procedure and Results at PVUSA	206
Charles Whitaker, Endecon	
Performance of a 1.8 kWac Dual-Junction Amorphous Silicon System	215
Troy Strand, National Renewable Energy Laboratory	
The Virginia Solar Photovoltaic Manufacturing Incentive Grant Program (SPMIGP) . .	239
Robert Somers, II, 2rw Consulting Engineers	
Durability and Reliability	249
Contact Corrosion on CdS/CdTe Solar Cells: A Photoemission Study of the Formation of the CdS/SnO ₂ Interface	251
David Niles, National Renewable Energy Laboratory	
Thermal Bond Aging of Thick Film Silver Metallized Solar Cells	264
Ronald Gonsiorawski, Mobil Solar Energy Corporation	
Outdoor and Indoor UV Exposure Testing	279
William Putman, DSET Laboratories, Inc.	
EVA Degradation Mechanisms: A Review of What is and is Not Known	311
Al Czanderna, National Renewable Energy Laboratory	
Modification of EVA Formulation for Improved Stability	358
John Pern, National Renewable Energy Laboratory	
Durability of PV Modules at The Southwest Region Experiment Station Las Cruces, New Mexico	375
Andrew Rosenthal, Southwest Technology Development Institute	
Teamed Research and Development on PVMaT, Phase 3A-Shared Process Issues	387
William Holley, Springborn Laboratories, Inc.	
Stability of EVA in PV Modules	394
John Wohlgemuth, Solarex	

System Field Experiences	399
PSCO Energy Involvement to Date	401
Chris Thompson, Public Service Company of Colorado	
Photovoltaic System Experience at Arizona Public Service Company	406
Peter Eckert, Arizona Public Service Company	
Performance of Maspeth a-Si PV System	418
Byron Stafford, National Renewable Energy Laboratory	
PV System Field Experiences at SMUD	425
David Collier, Sacramento Municipal Utility District	
Building Integrated PV Systems NEES's Gardner & EPA's PV-DSM Projects	436
Edward Kern, Ascension Technology	
Seven Years of Experience with Austin's 300 Kilowatt Single-Crystal Photovoltaic Array	439
John Hoffner, City of Austin Electric Utility Department	
The Performance of PV Systems	453
Margie Whipple, Sandia National Laboratories	
Standards and Codes	461
Report on 1993 PV Standards and Codes Forum	463
Carl Osterwald, National Renewable Energy Laboratory	
International PV Performance Standards	473
Robert Klein, Solar Energy Industries Association	
Photovoltaic and the National Electric Code	485
David Meakin, Solar Energy Industries Association	
Final Attendee List	491

OPENING SESSION

Photovoltaic Performance and Reliability Workshop

Golden, Colorado

James E. Rannels

Director, Photovoltaics Division
U.S. Department of Energy

September 8, 1993

IMPROVED EFFICIENCY

The efficiencies of laboratory cells have increased steadily in all PV technologies.

PV COST REDUCTION

 

SOLAR 2000 Strategy Framework

Partnership of Key Players

Priorities

- **Market Conditioning**
- **Balance of Systems**
- **Thin Films**

PV Program Budget History

DOE FY94 PV Budget Request (\$000)

\$78,045

Fundamental Research
\$11,000

Capital Equipment
\$6,700

**Advanced Materials
& Devices**
\$21,000

**Collector Research &
Systems Development**
\$39,345

Research Funding, U.S. and Competitors

\$ in Millions

Energy Priorities for the 1990's

- **Environment**
- **Exports**
- **Economy**
- **Employment**

Photovoltaic Performance and Reliability Workshop

Anthony Catalano

September 8, 1993

NREL Capabilities

- Facilities Complete for Qualification Testing
- New DC Simulator On Order
- Field Area Available for New Products
 - ▶ 3-4 1kw System Deployments Planned
- Outdoor Test Facility
 - ▶ 3/94 start 12/94 Completion

High Priority Areas

- Accelerated Testing Methods
- Standard Measurement Methods for Emerging Technologies
- Resolve Difficulties with Present Encapsulants

The Opportunity

- Utilities and Other Large Markets Will Vastly Increase Need for PV
 - ▶ **BUT....**
- They Will Demand...
 - ▶ Proven Reliability & Safety
 - ▶ System Approach to Design
 - ▶ Low Cost

The PV "Climate"

- Healthy Market Growth at 15%+
- Serious, Growing Interest by Utilities
- Emerging Technologies Nearing Marketplace
- Major Business Expansion Possible

17

CELL AND MODULE CHARACTERIZATION

PV Efficiency Measurements - Overview

Keith Emery (303-231-1032)

Modules

Steve Rummel (231-1917)

Yehoshua Caiyem

Cells

Halden Field (231-1485)

Don Dunlavy

Standard Reporting Conditions

Advantages

Fixed set of reference conditions

Site independent

Easy to perform in the lab or on the factory floor

25°C reference temperature easy to achieve

Internationally accepted

Disadvantages

25°C cell temperature predicts greater performance
than observed in the field

Alternative rating methods are not widely accepted

Standards do not exist for alternative rating methods

$$\eta \equiv \text{Efficiency} = 100 \times \frac{P_{\max}}{E_{\text{tot}}}$$

$P_{\max.}$ { Maximum PV power density
Power at a fixed load

E_{tot} { Prevailing - pyranometer
Reference irradiance - reference cell

Temperature { air / ambient
Junction

Area { TOTAL
active
aperture

U₉₅ Uncertainty Limits

Reference cell calibration	$\pm 1-5 \%$
Pyranometer calibration	$\pm 3-8 \%$
Absolute cavity radiometer	$\pm 0.3 \%$
Single-junction cell η	$\pm 2-10\%$
Single-junction module η	$\pm 3-10 \%$
Multi-junction cell η	$\pm 3-15 \%$
Multi-junction module η	$\pm 5-15 \%$

*Axiom for efficiency measurements
and reports:*

Trust but verify.

ARTIFACTS / ANOMALIES

nature.

primary cause

Excess current density

Definition

Photo-current outside of the
device area

Hysteresis in I-V

Large capacitance

Pre-measurement Conditions Recombination centers

Optics

Stray reflections

Leveling

Field-of-view

CdS/CuInSe2

Sample: 430

Temperature = 25.0°C

May. 27, 1986 4:13 pm

Area = 0.0784 cm²

$V_{oc} = 0.4093$ volts

$V_{oc} = 0.4291$ volts

$J_{sc} = 28.07$ mA/cm²

$J_{sc} = 28.13$ mA cm²

Fill factor = 61.85 %

Fill factor = 64.35 %

Efficiency = 7.1 %

Efficiency = 7.8 %

Spectrolab X-25 Solar Simulator

$\pm 3\%$ Spatial and
spectral uniformity
over test plane

Summary of PV Calibration Uncertainties

Calibration Method	E_{tot}	Bias (%)	Random (%)	Total (U_{95}) (%)
Global fixed-tilt	pyranometer	3.06	1.48	4.26
Global fixed-tilt	direct + diffuse	2.29	1.16	3.24
Global-normal	pyranometer	2.49	1.48	3.69
Global-normal	direct + diffuse	0.82	1.16	2.46
Direct-normal	cavity radiometer	0.47	0.27	0.72
X25 simulator	direct-normal reference cell	1.03	0.21	1.09
SPi-SUN Simulator	direct-normal reference cell	1.44	1.23	2.97
AM0 (JPL balloon calibration) †		0.50	0.24	0.69
AM0 (NASA airplane calibration) †		1.00	—	1.00

† A standard uncertainty analysis has not been performed for AM0 calibration methods; these are estimates based upon published information

U_{95} Global Fixed-Tilt PV Calibration Uncertainty

Source	Bias (%)	Random (%)	Total (U_{95}) (%)
$I^{R,S}$	0.10	0.05	0.14
E_{tot} Kipp and Zonen CM11 pyranometer	2.12	0.95	2.85
E_{tot} Cavity radiometer + shaded pyranometer	0.59	0.24	0.71
3° pointing or leveling error for 20° incidence $\angle$	2.08	—	2.08
Spectral correction	0.20	0.50	1.02
Deviation from ideal cosine response	0.20	—	0.20
PV temperature correction	0.15	0.10	0.25
PV $I^{R,S}$ linearity	0.05	0.05	0.11
Thermal voltages	0.05	0.05	0.11
Time constants	0.50	0.10	0.54
Field-of-view and ground reflections	0.50	1.00	2.06
Total (E_{tot} from pyranometer)	3.01	1.48	4.26
Total (E_{tot} from cavity radiometer + pyranometer)	2.29	1.16	3.24

U_{95} Global-Normal with a Moveable False-Horizon PV Calibration Uncertainty

Source	Bias (%)	Random (%)	Total (U_{95}) (%)
$I^{R,S}$	0.10	0.05	0.14
E_{tot} Kipp and Zonen CM11 pyranometer, or	2.12	0.95	2.85
E_{tot} Cavity radiometer + shaded pyranometer	0.59	0.24	0.71
5° off normal-incidence alignment error	0.20	—	0.20
⌘ Spectral correction	0.20	0.50	1.02
Deviation from ideal cosine response	0.02	—	0.02
PV temperature correction	0.15	0.10	0.25
PV $I^{R,S}$ linearity	0.05	0.05	0.11
Thermal voltages	0.05	0.05	0.11
Time constants	0.20	0.10	0.28
Field of view and ground reflections (false horizon)	0.50	1.00	2.06
Total (E_{tot} from pyranometer)	2.49	1.48	3.69
Total (E_{tot} from cavity radiometer + pyranometer)	0.82	1.16	2.46

USSC a-Si/a-Si UPM 880 module

Sample: 70

Temperature = 25.0°C

Sep. 28, 1992 12:46 pm

Area used = 3685.4 cm²

Solar Cells Inc 34W,CdS/CdTe module

Sample: 69-08

Temperature = 25.0°C

Jun. 18, 1993 10:17 am

Area used = 6815.000 cm²

Light bias = 2.00 mA

Zero voltage bias

ISCT CIS submodule

Sample: 289

Temperature = 25.0°C

May. 18, 1993 1:00 pm

Area used = 900.0 cm²

Light bias = 1.37 mA

Zero voltage bias

SPIRE 240A Spectral Error

Reference	Test	Error (%)
Si Cell in Module	single & poly-Si	< 2 %
	CdS/CIS	-3 - 4 %
	CdS/CdTe	-3 - 4 %
	thin film Si	-3 - 4 %
	Sphere Si	-3 %
a-Si module	a-Si module	< 1 %
	a-Si tandem top	< 1 %
	a-Si tandem bottom	8 - 9 %
	a-Si triple top	< 2 %
	a-Si triple middle	< 2 %
	a-Si triple bottom	9 - 12 %

Amorphous Silicon Intercomparison

Group	V _{oc} (V)	I _{sc} (mA)	FF (%)	P _{max} (W)	Comments
Solarex SA5-23751 a-Si module					
NREL	24.0	324	67	5.2	Outdoors PSP ref., normalized
	24.9	346	68	5.8	SPI-240A, filtered Si reference cell
	24.7	331	68	5.6	SPI-240A, a-Si module reference
⁴⁴ USSC	24.8	315	69	5.4	SPI-240A, NREL calibrated ref
Solarex	24.9	343	67	5.7	SPI-240A, custom load
Spire	25.3	340	68	5.9	SPI-240A
Solarex a-Si/a-Si/a-Si:Ge module, M2037-3					
NREL	53.8	176	63	6.0	Outdoors PSP ref., normalized
	57.0	188	59	6.3	SPI-240A, filtered Si reference cell
	-	182	-	6.1	SPI-240A, a-Si module ref.
USSC	57.3	176	60	6.0	SPI-240A, NREL calibrated ref
Solarex	57.5	189	59	6.4	SPI-240A, custom load
Spire	57.8	180	59	6.1	SPI-240A

Amorphous Silicon Intercomparison

Group	V _{oc} (V)	I _{sc} (mA)	FF (%)	P _{max} (W)	Comments
USSC a-Si/a-Si:Ge light soaked module, S935					
NREL	9.15	1.19	61	6.7	Outdoors PSP ref., normalized
	9.61	1.27	60	7.3	SPI-240A, filtered Si reference
	-	1.23	-	7.1	SPI-240A, a-Si module ref.
USSC	9.65	1.19	61	7.0	SPI-240A, NREL calibrated ref
‡ Solarex	9.52	1.30	58	7.3	SPI-240A, custom load
Spire	9.72	1.23	59	7.0	SPI-240A
USSC a-Si/a-Si:Ge module, 2B1932					
NREL	1.62	8.83	61	8.8	Outdoors PSP ref., normalized
	1.67	9.50	60	9.5	SPI-240A, filtered Si reference cell
	1.67	9.33	60	9.3	SPI-240A, a-Si module reference
USSC	1.67	8.68	63	9.1	SPI-240A, NREL calibrated ref
Spire	1.67	8.97	60	9.1	SPI-240A

Amorphous Silicon Intercomparison

Differences in $P_{\max}$ from 3 to 12% were observed depending on the module with 5% being typical when the participants set their Spire 240A solar simulator following their routine procedures.

When the participants set their simulator to give the same I_{sc} the differences in $P_{\max}$ were reduced to 2-8% with 2% being typical

45

For these modules the variation in $P_{\max}$ measured at NREL under the SPIRE simulator and outdoors under prevailing clear sky conditions was between 1 and 8% without corrections for temperature or spectral mismatch error.

SUMMARY

Differences in Efficiency occur because of measurement error, definition, and artifacts.

Reversible improvements of ~3% in the performance with forward bias has been observed in CdS/CuInSe₂ , Si, and CdS/CdTe cells and Modules. V_{oc} changes with time after shorting then open-circuiting the sample.

Existing single-source simulators can be easily modified to be a multi-source simulator

Multi-source simulators are essential for optimization of a two-terminal multi-junction PV device

CHARACTERISTICS OF SPECTROLAB SOLAR SIMULATORS

J. Lovelady, System Engineer
Spectrolab, Inc.

1.0 INTRODUCTION

Spectrolab has been manufacturing Solar Simulators since the early 1960's. This paper gives a little of the history of the company and describes the general characteristics of the current Solar Simulator products, both steady state and pulsed.

2.0 COMPANY HISTORY

Spectrolab was formed as a manufacturer of state of the art optical thin films, quickly branching out into other areas. In addition to other types of electro-optical instruments, the business of the company soon settled down into three main branches: photovoltaic solar panels, solar cells, and solar simulators. Searchlights (originally an outgrowth of solar simulator technology) have recently formed a fourth line of business. Some dates of interest are:

Solar panels since 1958 (Pioneer 1).

Solar Radiation Simulators since 1961.

Solar cells since 1961.

Electronic loads (for cell and panels) since 1965

Pioneers in large area simulation since 1965.

Large Area Pulse Solar Simulators since 1972

Searchlights since 1970

3.0 TYPES OF SOLAR SIMULATORS

Spectrolab manufactures two distinct types of solar simulators: steady state and pulsed. The steady state simulator is the older of the two and is applicable both to the testing of photovoltaic power panels and to the thermal balance and longevity testing of space materials from samples to complete satellites. The pulse simulators are really complete photovoltaic panel test systems, including not only the pulsed light source (solar simulator), but a fast sweeping electronic load, data acquisition system, and data processing system. Each has its own characteristics and areas of application.

The steady state simulators offer good stability, both long and short term, excellent uniformity of illumination over the test plane, and close spectral match to sunlight. The pulse systems offer large test plane area, simple control of sample temperature, speed, and convenience at a cost considerably lower than an equivalent steady state unit.

3.1 Steady State Simulators

Spectrolab has built simulators ranging in size from 3"x6" test plane to 16 foot diameter test plane. The largest is an array of 38 modular simulators which together can illuminate an area of over 300 square feet. The most widely used simulator is the model X-25, a self contained laboratory instrument designed for a 2500 watt Xenon lamp, and capable of using a variety of lamps from 2500 to 4200 watts in size. The XT-10 is a smaller, less expensive unit with less stringent specifications.

Typical specifications for the X-25 and XT-10 are shown in Figures 1, 2 and 3.

3.2 Pulsed Simulators (LAPSS)

The LAPSS system uses a specially designed Pulse Forming Network (PFN) to obtain a pulse of light with steep rise time and a flat top. (See Figure 4). The pulse is about 2 milliseconds long including rise and fall times and some overshoot at each end. There is a "flat spot" for 1 millisecond within which the light level is constant within $\pm 3\%$. All measurements are taken during this time.

During this 1 millisecond measurement period, 40 to 50 sets of data are taken, at 20 microsecond intervals. Each data set includes the test panel voltage, test panel current, and light level. The test panel voltage is varied during the pulse to sweep out the I-V curve. For testing panels with rapid response to load changes, it is possible to sweep the entire I-V curve in one light pulse, starting at a slight back bias and sweeping to a point beyond Voc. For slower panels, the curve is measured in several overlapping segments, each starting at preset voltage and sweeping at the maximum rate allowable for accurate measurements.

Accuracy is assured by using only that portion of the pulse where the light level is constant and by controlling the voltage sweep rate to assure that deviations from steady state measurements will be negligible. Each data point is then corrected mathematically for the small residual error due to light level variations.

The spectral match of the LAPSS is quite good, though not as good as with the steady state simulator. An optional spectral filter is available to reduce the excess in the ultraviolet (see Figure 5). The target plane uniformity is very good, particularly for sizes up to 10 ft square. Specifications are given in Figure 6.

4.0

FUTURE DEVELOPMENTS

The Automatic Cell Evaluator (ACE) is nearly ready for production. This system used the same type of data acquisition system as the LAPSS for testing of cells and small modules under steady state light. It offers the same correction for minor light level fluctuations and the same convenience in data handling and storage. The first unit will be in use at Spectrolab early in 1994 and will be offered for sale soon thereafter.

The need is well established for more accurate spectral simulation for testing multi-junction cells and panels. Spectrolab is looking into developing a small area accurate spectrum simulator using multiple light sources. There is no firm schedule on this project.

An attachment for the X-25 will soon be available for adjustment of the spectrum for multi-junction cells using the techniques developed at NREL.

Finally, to extend the LAPSS performance for economical testing of large panels with slow response times, Spectrolab is working on the development of a system with a very long pulse time (>50ms) and good stability during the pulse.

X-25 SPECIFICATIONS

Target Area

(Typical) 13 inch diameter

(Wide variety of optical systems available)

Uniformity of Irradiance

+/- 2% (Most optical systems)

Stability

+/- 1%

Spectral Match

Close match in 14 discrete bands.

Meets ASTM E 927-91 Class A in all requirements.

FIGURE 1

SPECTRAL MATCH TOLERANCES FOR SPECTROSUN X-25
WHEN EQUIPPED WITH
CLOSE SPECTRAL FILTERING ACCESSORY

WAVELENGTH INTERVAL (microns)	TOLERANCE OF INTEGRATED ENERGY OVER WAVELENGTH INTERVAL (per cent)	TOLERANCE OF PERCENT SPECTRAL MATCH OF TOTAL INTENSITY*
.25 - .35	± 40	± 1.85
.35 - .40	± 20	± 0.92
.40 - .45	± 10	± 0.71
.45 - .50	± 10	± 0.78
.50 - .60	± 10	± 1.41
.60 - .70	± 10	± 1.20
.70 - .80	± 10	± 0.95
.80 - .90	± 15	± 1.11
.90 - 1.0	± 15	± 0.89
1.0 - 1.2	± 20	± 1.80
1.2 - 1.5	± 20	± 1.65
1.5 - 1.8	± 20	± 0.90
1.8 - 2.2	± 30	± 0.98
2.2 - 2.7	± 30	± 0.62

FIGURE 2

XT-10 SPECIFICATIONS

Target Area

8 x 8 inch square

Uniformity of Irradiance

+/- 3% (Most optical systems)

Stability

+/- 1% (Vertical output beam)

+/- 3% (Horizontal output beam)

Projection angle

9 deg.

Spectral Match

Less stringent match in 5 discrete bands.

FIGURE 3

SPECTROLAB

a subsidiary of Hughes Aircraft Co.

TYPICAL LIGHT PULSE FROM SPECTROSUN LAPSS

TYPICAL LAPSS SPECTRAL DISTRIBUTION

LAPSS II SPECIFICATIONS

Complete test system, including Electronic Load, Data Acquisition, Data Processing, and Temperature Correction

Target Area

16 foot diameter

Uniformity of Irradiance

+/- 3% over 16 foot diam.

+/- 1.5% over 2.5 x 2.5 M. (10 x 10 ft) area

Better over smaller areas.

Spectral Match

Controlled by selection of lamp current density.

Voltage range Single cells to 100 volt panels

Current ranges Single cells to 20 amp panels

FIGURE 6

PULSED SOLAR SIMULATOR DESIGN AND APPLICATIONS

spire

Steve Hogan

Spire Corporation
One Patriots Park/Bedford, MA 01730-2396
617-275-6000/FAX 617-275-7470

*Presented at the Photovoltaic Performance and Reliability Conference
September 8, 1993*

PRESENTATION OVERVIEW

► Simulator Characteristics

- Pulsed Light Characteristics
- Spectrum
- Uniformity
- Electronic Load

► Applications

- Crystalline Silicon
- Thin Films

SUN SIMULATOR FLASH TIMING

PULSE VS. STEADY STATE

- ▶ ***Limits Panel Heating***
- ▶ ***Reduces Power Requirement***
- ▶ ***Smaller Footprint***
- ▶ ***dv/dt or di/dt (?)***
- ▶ ***Spectrum (?)***

SPI-SUN SIMULATOR™ 240A

Spectral Composition

Courtesy of NREL

SPI-SUN SIMULATOR™ 240A SPECTRAL COMPOSITION COMPARED TO ASTM STANDARD

Courtesy of NREL

SIMULATOR OPTICS

SPI-SUN SIMULATOR™ 240A

Pulsed Solar Simulator

spire

IRRADIANCE UNIFORMITY DISTRIBUTION

(Parts per Thousand)

	1	8	15	22	29	36	43	50	57	64	71	78	85	92	99	106	113	120
1	-20	+07	+08	+02	+11	+07	+07	+04	+04	+03	+02	+02	+01	+08	+16	+15	+08	-10
2	-06	+00	+08	+08	-04	+05	-07	-06	-05	-06	-08	-07	-03	+08	+00	+08	+10	-12
3	+07	+10	+13	+03	-01	-13	-14	-12	-14	-12	-15	-08	-13	-10	+10	+13	+07	+16
4	+05	+11	+08	-01	-15	-15	-16	-17	-15	-13	-19	-15	-04	-05	+05	+10	+10	+05
5	+13	+22	-05	+07	-06	-08	-09	-15	-14	-14	-15	-11	-09	-01	+00	+07	+07	+05
6	+09	+03	+16	+03	-05	-05	-08	-03	-11	-05	-07	-04	-05	+01	-00	-03	-07	-15
7	+01	+23	+30	+19	+17	+04	+07	+09	+08	+02	+00	+08	+10	+16	+06	+13	-09	-13

932317

SIMPLIFIED ELECTRONIC LOAD SCHEMATIC

COMPUTER SOFTWARE

- ▶ **Operator Inputs**
(Irradiance, Corrections, Serial #, etc.)
- ▶ **Adjust Lamp Intensity**
- ▶ **Determine V_{oc} and I_{sc}**
- ▶ **Adjust Ranges**
- ▶ **Sweep Current $I_{sc} \rightarrow I=0$**
- ▶ **Input Voltage**
- ▶ **Display I-V Curve and Computations**
- ▶ **Print/Save Option**

SAMPLE I-V OUPUT CURVE

ID #: SOLARPAC
12-05-1992, 13:16:57

Sun	(mW/cm ²)	= 60
Temp	(deg C)	= 24,24
Voc	(Volts)	= 20.62
Isc	(Amps)	= 1.47
Pmax	(Watts)	= 21.51
Vmp	(Volts)	= 16.29
Imp	(Amps)	= 1.32
Fill Factor:		= .709
Rs	(Ohms)	= 1.51
Cell Eff (%)		= 12.6

932277

spire

MEASUREMENTS TO DATE

Silicon

- Cz, Multicrystal, Ribbon

Thin Films

- α -Si, Multijunction, CdTe

High Efficiency

- GaAs, Si

spire

CORRELATION EFFORTS

Customers

NREL

ISPRA

JMI

SIMULATOR DEVELOPMENT DIRECTION

▶ ***Large Area***

▶ ***Automation***

▶ ***Options***

- Multiple Samples
- Ranges
- Low Irradiance Levels

LARGE AREA SIMULATOR IRRADIANCE UNIFORMITY

SIMULATOR REPEATABILITY

SunBurn: 50 passes

9/2/93 10:12:08

Sun = 100 mW/cm²

	Minimum	Maximum	Average	Std. Dev. (%)
V _{oc} (volts)	20.89	21.17	20.99	± .262
I _{sc} (amps)	2.30	2.41	2.33	± .639
P _{max} (Watts)	33.48	34.25	33.71	± .394
V @ P _{max} (volts)	15.97	16.81	16.37	± 1.36
I @ P _{max} (amps)	2.00	2.12	2.06	± 1.44
Fill Factor	.669	.703	.689	± .691
Temperature (°C)	23.19	24.90	24.17	± 1.53
R _{series} (ohms)	1.02	3.00	1.35	± 26.24
R _{shunt} (ohms)	74.76	224.5	150.5	± 20.76

932325

LARGE AREA (660) SIMULATOR

spire

Indoor and Outdoor Efficiency Measurements of a-Si Multijunction Modules

by

**Troy Glatfelter
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1100 W. Maple
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**Partially supported by NREL under
Subcontract #ZM-1-19033-2**

TOPICS

- State of Module Research
at USSC
- Comparison of DC and Pulsed
Simulator η Measurements
- Comparison of Indoor and
Outdoor η Measurements

Research on Stable, High-Efficiency Amorphous Silicon Multijunction Modules

S. Guha, Principal Investigator

A. Banerjee

E. Chen

R. Clough

T. Glatfelter

G. Hammond

K. Hoffman

M. Hopson

N. Jackett

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T. Palmer

K. Parker

I. Rosenstein

D. Wolf

X. Xu

J. Yang

K. Younan

Manufacturer: USSC ~~a-Si~~:Ge

Sample Type : a-Si/~~a-Si~~ tandem module

Sample # : 2B2185

Test Date : July 25, 1993

Test Time : 10:13 PM

Spectrum : ASTM E892 Global

File Name : C:\IV\data\IV4383.xy

NREL Spire 240A solar simulator (peak)

Estimated total uncertainty in efficiency is $\pm 5\%$

Total irradiance = 1000 W/m^2

Temperature = 25°C

Aperature Area = 902.9 cm^2

Voc = 1.683 V

Isc = 9.186 A

Pmax = 10.31 W

V at Pmax = 1.321 V

I at Pmax = 7.800 A

Fill Factor = 66.6 %

Efficiency = 11.41 %

USSC Module Efficiencies

Module #	NREL Spire	NREL Outdoor	USSC Spire
2B 2178	11.4	10.9	11.3
2B 2180	11.3	10.9	11.2
2B 2185	11.4¹	11.0	11.2

1. This represents the highest thin-film module η measured by NREL.

Multijunction Module Stability

USSC Stabilized Module Efficiencies

Module #	Initial η	Stabilized η
2B 2181	11.1	9.5
2B 2220	10.8	9.5
2B 2178	11.4	?
2B 2185	11.4	?

USSC Simulator Calibrations and Correlations

● Small-area Dot Matrix

- 144 one-cm² devices over one-ft²
- Establishes thin-film deposition uniformity
- Establishes module derating factors (Module η / small cell active-area η)
- Predicts module efficiency using DC simulator

● Coupon Modules

- Varying size "mini" modules ranging 2"x 2" to 6"x 6"
- Correlates DC simulator to pulsed simulator

● 1 ft² Modules

- Establishes module efficiency under pulsed simulator

● Spectral Analysis

- Establishes simulator spectral match to AM 1.5 Global in narrow bands

Module / Dot pattern Correlation

Module #	Module η	Ave. Cell η	Module ¹ Derating
2175	11.2%	11.5%	2.7%
2166	10.7%	11.3%	5.6%
1968	10.5%	11.1%	5.7%
1963	10.4%	10.9%	4.6%
1942	10.4%	11.0%	5.4%
1937	10.6%	11.2%	5.5%

1. Module derating factor defined as the module η / average small cell active-area η . Theoretical derating factor for these modules is 4.5% (2.5% shadow loss, 2% electrical loss).

Coupon Module Measurements

Single-cell Fill Factor

Sample #	Coupon Type	Spire ¹	Oriel ²
G6a	a-Si:Ge 6"x 6"	.594	.584
G4a	a-Si:Ge 4"x 4"	.620	.608
G4b	a-Si:Ge 4"x 4"	.579	.579
S6a	a-Si 6"x 6"	.557	.566
S4a	a-Si 4"x 4"	.568	.579
S4b	a-Si 4"x 4"	.566	.576

1. Spire model 240A Pulsed Simulator with peak detector circuit
2. Oriel 8"x 8" DC simulator

Coupon Module Measurements

a-Si/a-Si:Ge Multijunction

Sample #	Size	Spire (Pmax)	Oriel (Pmax)	%Diff
A	6"x 6"	1.88	1.90	-0.8
B	6"x 6"	1.78	1.79	-0.3
7	4"x 4"	.822	.812	+1.2
8	4"x 4"	.806	.816	-1.2
9	2"x 2"	.433	.433	0.0

Simulator Spectral Analysis

$$\left(\frac{I_{std}}{I_{ss}} \right)_{cell} = \left(\frac{1}{M} \right) \left(\frac{I_{std}}{I_{ss}} \right)_{ref}$$

$$M = \frac{\int N(\lambda)_{std} Q(\lambda)_{ref} d\lambda}{\int N(\lambda)_{std} Q(\lambda)_{cell} d\lambda} \frac{\int N(\lambda)_{ss} Q(\lambda)_{cell} d\lambda}{\int N(\lambda)_{ss} Q(\lambda)_{ref} d\lambda}$$

Simulator Spectral Analysis

<i>Component Cell</i>	$(\frac{I_{std}}{I_{Spire}})$	$(\frac{I_{std}}{I_{Oriel}})$
Top 2-jnctn	0.997	0.998
Bottom 2-jnctn	1.030	1.040
Top 3-jnctn	0.996	0.981
Middle 3-jnctn	1.002	1.003
Bottom 3-jnctn	1.016	1.012

USSC Simulator Correlations

- Spectral analysis showed small spectral mismatch for all spectral bands (<1% for most bands) pertaining to a-Si multijunction devices for both the USSC Oriel DC and Spire pulsed simulators.
- Measurement of "mini" modules under both USSC Oriel DC and Spire pulsed simulators showed agreement of 1% for all samples tested.
- Based on the previous conclusions, it is evident that the Spire 240A simulator (with peak detector) is sufficiently accurate to determine the η of a-Si based multijunction modules.

Effect of Season on Multijunction Outdoor Efficiency Measurements

06

A scatter plot showing the relationship between the Month of Year (X-axis) and Normalized Current (Y-axis). The X-axis is labeled 'Month of Year' and has major ticks for APR, AUG, and DEC for both '92 and '93. The Y-axis is labeled 'Normalized Current' and ranges from 0.80 to 1.10 with major ticks every 0.05. The plot displays data points for each month from April 1992 to August 1993. A horizontal dotted line is drawn at Normalized Current = 1.00. The data points are generally clustered around this line, with some variability, particularly in the first half of 1992 where values range from approximately 0.99 to 1.02.

Month of Year	Normalized Current
APR '92	0.998
MAY '92	0.998
JUN '92	1.008
JUL '92	1.005
AUG '92	1.005
SEP '92	1.005
OCT '92	1.005
NOV '92	1.005
DEC '92	1.005
JAN '93	1.005
FEB '93	1.005
MAR '93	1.005
APR '93	1.005
MAY '93	1.005
JUN '93	1.005
JUL '93	1.005
AUG '93	1.005

April 1993

93

Outdoor to Indoor Correlation Factors

Spectral Corrections

Reference Cell Type	Mean	Deviation
Pyronometer	.945	5.0%
a-Si single	.970	3.0%
a-Si:Ge single	.970	2.1%
a-Si top tandem cell	.961	4.3%

Comparison of Outdoor to AM1.5G1

Comparison of Outdoor to AM1.5G1

Comparison of Outdoor to AM1.5G1

Conclusions

- Applying spectral mismatch corrections to outdoor η measurements reduced the standard deviation in those measurements from $\pm 5\%$ to $\pm 2\%$ for a-Si based multi-junction devices.
- The maximum range of spectral corrections applied to the outdoor module efficiencies was -2.6% to $+12.5\%$.

Radiometric Measurements for PV Characterization

Daryl R. Myers
Theodore W. Cannon
David Trudell
National Renewable Energy Laboratory

PV Performance and Reliability Workshop
September 8-10, 1993
Golden, CO

Introduction

We describe radiometric measurements performed by the PV Solar Radiation Research (PV SRR) Task supporting the NREL PV Module and System Performance and Engineering Project. As stated in the Annual Operating Plan for the Photovoltaic Advanced Research and Development Project for fiscal year 1993 [1], PV SRR task activities are performed

"...in direct support of characterization, measuring, testing, designing, and understanding the performance of PV cells, submodules, modules, and systems by providing a scientific and engineering understanding of incident solar irradiance, and through the development of instruments and/or measurement methods."

In the past, we have described radiometer calibration and characterization for broadband [2-4] and spectral instrumentation [5-8]. Here, we investigate the quality of our radiometric measurements applied to PV performance and characterization.

Solar Radiation Instrumentation: A Historical Perspective

We remind the reader some of the instrumentation in use today for PV performance testing was originally developed with completely different objectives in mind. As shown in Figure 1, radiometric instrumentation has evolved over the past 40 to 50 years to measure various solar radiation parameters for the meteorological, agricultural, and climate analysis communities. Only later (some 15 to 20 years ago) was that same instrumentation applied to solar energy conversion device and system performance data collection.

In concert with the climate, meteorological, and agricultural applications, various atmospheric physics and transmission models were developed, including transformation algorithms to compute solar irradiance on variously oriented surfaces [9-12]. As the needs of the solar energy conversion design and performance community expanded, the algorithms for providing application-specific data (tracking, tilted surface, etc.) [12] were developed, derived from and adding to the complement of conversion techniques available. Today these tools provide data for design, prediction, and evaluation of conversion system performance [13].

The point of this historical perspective is to emphasize that, to a great extent, design and performance solar irradiance data are still based on instrumentation (especially) and models (less so) developed with other scientific objectives in mind. This is the reason for continuing PV SRR emphasis on application-specific calibration and characterization of instrumentation.

Recent efforts to develop improved radiometers and measurement techniques [14] and radiation transformation algorithms with performance evaluation needs as a primary objective indicate a promising future; meanwhile, PV SRR is providing current best-practice broadband and spectral measurement services.

Broadband Radiometric Measurements

Typical solar radiation measurements, such as direct normal or beam radiation, or so-called global radiation on a plan-of-array (POA) surfaces are typical broadband radiometric measurements. These measurements generally are made with relatively simple detectors, (pyrheliometers and pyranometers, respectively) and represent the total radiation in the spectral region from 280 nm to 2800 nm.

Currently, the performance testing at NREL relies upon well calibrated individual radiometers assigned to each specific test activity. To examine the performance of these radiometers and the NREL metrology laboratory calibration procedures, a pyranometer comparison experiment was performed in November of 1992. Five pyranometers assigned to the field test site, were mounted on a tilt of latitude + declination (55 degrees) so as to receive near-normal incidence radiation around noon. This configuration is that used for much of the PV module performance outdoor testing on clear days.

Figure 2 presents the mean irradiance and the standard deviation of the irradiances (as percents of reading) for clear and overcast days. The figure shows that the precision of these five radiometers was better than 1% around noon on clear days; increased to more than 2% between 10 am and 2 pm, and increased to more than 10% at early morning and late afternoon hours. Note the difference in the standard deviations on the overcast day compared to the clear days. The distribution is very flat, and at about 1.5% all day long, reflecting the minimal impact of geometrical response under isotropic irradiance conditions.

These data show that the repeatability among the population of radiometers deployed at the NREL outdoor test site, calibrated at near normal incidence, is of the order of 2.8% after application of the Student's-t correction factor of 2.8 for 4 degrees of freedom to the 1% clear sky sigma achieved in this experiment.

We have also experimented with using the direct, global and diffuse radiation data to compute, with the Perez Anisotropic Model [12], POA irradiances at 10 degree tilt intervals. Comparing the modeled and measured POA data for systems with 50 and 40 degree tilt measured data, respectively, we have been able to identify instrument tilt errors. In Figure 3, modeled values are generally within 10% of measured values over a wide regime of radiation levels.

In the near future, PV SRR will deploy an array of precision, characterized radiation and meteorological sensors and data acquisition and distribution system (see Figure 4) to provide reference data to use in quality assessment of POA radiation and ancillary data collected for specific systems and module tests. We plan to compute and provide PV test engineers with incremental 10 degree tilted surface data derived from the reference measured irradiances on a near real-time basis as part of this quality assurance system.

We studied the effects of small (1.25 degree) errors in direct-beam incidence angles resulting from sensors being tilted in the east-west direction, say as a result of installation or mounting problems. Figures 5 and 6 illustrate the apparent (relative) shifts in data seen when errors of this magnitude exist, assuming normal incidence at solar noon, and setting the contribution to the global of the diffuse component to 0. Note from Figure 6 that for even a 1 degree east-west tilt to the west, errors of 1%-3% occur in indicated irradiance within 30 degrees of the normal incidence case. We have experimentally confirmed such measurement/error sensitivities at the NREL PV Outdoor Test Site by intercomparing radiometers mounted in the field, and comparing modeled and measured POA irradiance data.

Spectroradiometric Measurements

One of the most important measurement problems addressed by the PV SRR team has been the measurement of the spectral distribution for pulsed solar simulators used in testing modules indoors. We [6] and others [7,8] have addressed the problems of accuracy and uncertainty in spectral irradiance measurements in general elsewhere. The challenge of obtaining spectral data for systems with pulses only milliseconds long was faced in particular by T. Cannon and D. Trudell, who have developed a powerful Pulse Analysis Spectroradiometer System (PASS) for accomplishing accurate quantitative measurements of these systems.

This system collects information on spectral distribution within a pulse, as well as from pulse to pulse and over extended periods of time. Figure 7 shows the calibration precision of the PASS system as determined experimentally, and Figure 8 is a *representative* spectral irradiance curve taken during operational testing of the system. Further refinement of our data collection technique and post-processing of the data will assist others in the task of quantifying the impact of spectral error (mismatch and calibration number) computations.

Conclusion

Because of the importance of PV module and system performance characterization at NREL, our attention to the accuracy and importance of radiometric measurements is a fundamental requirement. Presently, we are confident in our ability to achieve 1% to 2% precision in clear sky broadband POA irradiance data during outdoor testing. The development of a powerful, flexible, accurate spectroradiometer system opens the door for quantifying spectral errors more definitively, and maintaining control over indoor simulator testing and calibration for a wide variety of simulators, including the pulsed sources used in large area (module and submodule) testing. We plan to stay on the cutting edge of solar radiometry for PV performance measurements and applications by continuous improvement of our instrumentation and measurement techniques.

Acknowledgements

Without the cooperation and assistance of David Waddington, Troy Strand, Kieth Emery, Steven Rummel, Robert Hansen, and Joshua Caiyem at the NREL PV Outdoor Test Site, the measurements and results presented here could not have been possible. The support of the engineering and scientific value of this work by Richard DeBlasio as project leader has been essential in making this work possible.

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Solar Radiation Data Paths

P122-G1087202

Figure 2: Statistics for 5 Pyranometers Measuring
Global Plane of Array Irradiance, DEC 1992 at NREL

Figure 3. Performance of Perez Anisotropic Diffuse Model for
Computing Hourly 50 Degree POA Irradiance versus Measured POA Data

Brazilian Lighting System RSR Irradiance and POA Data @ 50 Deg

Figure 4. Reference Irradiance and Meteorological Station

Reference Meteorological And Irradiance Station
Block Diagram

Figure 5. Apparent Shifts in Global Data for East-West Tilt Error of 1,2,5 Degrees

Assumption is that sensor is tilted to East.

Figure 6. Relative Error in Global Data Vs Incidence Angle for Tilt Errors in East-West Direction of 1,2,5 Degrees.

Figure 7. Calibration Performance: PASS

Random variation about Mean Value of PASS measurement of (chopped) NIST lamp - % of reading

Figure 8. PASS Pulse Xenon-Arc Solar Simulator Spectrum

MODULE AND SYSTEM TESTING

Overview of Photovoltaic Module Reliability Testing at NREL

by Joseph Burdick and Jim Pruett

Photovoltaic Performance & Reliability Workshop
September 8, 1993

NREL Photovoltaics Program

PV MODULE & SYSTEM PERFORMANCE and ENGINEERING PROJECT

Team/Task:

***Module Qualification Testing, Test Method Development,
and Failure Analysis***

Photovoltaics:

- Materials
- Cells
- *Modules*
- Systems

Photovoltaic Modules:

- Fabrication
- **Testing:**
 - Performance
 - Reliability: Qualification, Stability, etc.

PV Module Testing:

Are We Asking the Right Questions ?

117

"We need to obtain at least approximate answers to the right questions rather than what we believe are right answers to only approximate questions"

PV Module Reliability & Stability:

What are the right questions ?

We believe they are:

- 1) Can we correlate ***indoor/accelerated*** testing and results to ***outdoor/real-time/natural*** exposure ?
- 2) From this, can we predict the ***service lifetime*** of photovoltaic modules (is it 5, 10, 20, 30 years) ?

To accomplish these goals (and answer these questions) we begin with an outline of our PV module reliability testing program here at NREL

NREL PV Module Reliability Testing Program

Goals:

1. Help PV Manufacturers Make Better Modules
2. Predict PV Module Service Lifetime

Strategy:

1. Understand and obtain correlation between indoor (accelerated) test results and outdoor (natural, real-time) exposure as related to reliability/stability/weathering issues
2. Identify module failure mechanisms
3. Work to obtain solutions to reliability problems

Method: Indoor Testing and Outdoor Testing Programs

Indoor Module Testing Program

- Qualification Testing
- Photostability Studies
- Accelerated Weathering

Outdoor Module Testing Program

- Natural, Real-Time Exposure Testing

Outdoor Phenomena Affecting Module Reliability, Stability & Weathering

Phenomenon

Related Effect

<u>Natural:</u>	Sun: UV Photons	Light-induced degradation of plastics, polymers, paints, textiles, metals, etc.
	Sun: Visible & IR Photons	Light-induced degradation of PV materials and loss of performance
	Heat & Cold	Thermal stresses on materials, mechanical & electrical interconnects
	Mechanical: Wind, snow, hail, etc.	Mechanical stresses on materials, mechanical & electrical interconnects
	Moisture: Humidity, Precipitation, etc.	Corrosion of materials, degradation of performance

Outdoor Phenomena Affecting Module Reliability, Stability & Weathering

Phenomenon

Related Effect

Artificial: Electrical Loads

Losses due to mismatch, wiring,
power conditioning equipment,
improper grounding, etc.

Pollutants, etc.

Corrosion, performance degradation

Any one or more of these effects, or their synergistic combination, can lead to shorts, open-circuits, and other failures in the PV modules which may, in turn, lead to module and/or system losses, performance degradation, a decrease in PV efficiency and output, and even to catastrophic failures in the components and/or the overall PV system.

Indoor Module Testing Program

- *Qualification Testing*
- Photostability Studies
- Accelerated Weathering

Outdoor Module Testing Program

- Natural, Real-Time Exposure Testing

Indoors: Module Qualification Testing (MQT) Program

<u>Test</u>	<u>Outdoor Phenomenon Simulated</u>	<u>Accomplishments & Present Status</u>	<u>Future Plans</u>
Thermal Cycling	Heat & Cold; Thermal Stresses	<i>BMA chamber used</i>	<i>New BMA being delivered</i>
Humidity-Freeze Cycling	Moisture, Precipitation, etc.	" " " " <i>Modification completed to measure open-circuits and shorts-to-ground in-situ during the cycling tests</i>	" " "
Damp Heat		<i>BMA environmental chamber used</i>	
=====			
Dry Hi-pot	Electrical Loads	<i>Hi-pot tester completed</i>	<i>Cage being built at JSF</i>
Wet Hi-pot Wet Insulation-Resistance	Electrical Loads + Moisture	<i>Trough tester completed New tray purchased</i>	<i>Immersion test being set up and tested</i>
Ground Continuity	Electrical Loads	<i>Test set-up completed</i>	

Indoors: Module Qualification Testing (MQT) Program

<u>Test</u>	<u>Outdoor Phenomenon Simulated</u>	<u>Accomplishments & Present Status</u>	<u>Future Plans</u>
Hot-Spot Endurance	Shadowing, etc.	<i>Two thermal/IR video systems purchased</i>	<i><u>Non-intrusive</u> hot-spot test under development</i>
Bypass Diode Thermal			
Mechanical Loading: Static	Snow loads, etc.		
Mechanical Loading: Dynamic	Wind loads, etc.	<i>Mechanical Flex Tester (MFT) operational; Received, Installed & Tested (April 1993)</i>	
Hail Impact	Hail storms, etc.	<i>Hail Impact Test System (H.I.T.S.) operational; Performed tests: Golden Photon , UPG samples</i>	
Saltwater Immersion & Corrosion	Marine Effects	<i>Performed tests: Iowa Thin-Film samples</i>	

Indoors: Module Qualification Testing (MQT) Program

<u>Test</u>	<u>Outdoor Phenomenon Simulated</u>	<u>Accomplishments & Present Status</u>	<u>Future Plans</u>
Surface-Cut Susceptibility	Scratches, cuts, etc.	<i>Surface-cut instrument completed</i>	
Termination Robustness		<i>Under development</i>	
Twist		<i>Under development</i>	
=====			
Accelerated Weathering	UV/Vis/IR Radiation with Heat/Moisture	<i>Accelerated-weathering chamber proposals received & are being evaluated</i>	
=====			
Laser Scanning		<i>Working with micro-characterization group to identify problem/failure areas in the modules</i>	

MQT Project: Test Plan & Status

- 10 PV manufacturers, ~ 9 modules each: latest commercial products
- Entire NREL (IQT) / IEEE (Proposed) Test Sequence will be run: started Sept. '93

<u>Manufacturer</u>	<u>Model</u>	<u>Structure/Composition</u>
APS	EN-25	a-Si
Solarex	SA-5	a-Si
UPG	PowerGlass	a-Si/a-Si
USSC	UPM-880	a-Si/a-Si
ECD	1' x 4'	a-Si/a-Si/a-Si:Ge
Solar Cells, Inc.	2' x 5'	CdTe
Golden Photon	2' x 2'	CdTe
Siemens Solar	Black Frame	CIS (CuInSe ₂)
Solarex	MSX-60	m-Si
Siemens	M55 & PC-4	x-Si

Indoor Module Testing Program

- Qualification Testing
- *Photostability Studies*
- Accelerated Weathering

Outdoor Module Testing Program

- Natural, Real-Time Exposure Testing

Indoor/Outdoor: Photostability Testing Program

- Light-Soak Test #1 completed; modules now deployed outdoors
- Light-Soak Test #2 completed (April 1993)
- Light-Soak Test #3 underway (to be completed Nov. 1993)
- Following Light-Soak Test #3, a new photostability study will begin:

Obtain 7 commercial a-Si PV modules from each of the following manufacturers (and perhaps some others): APS, ECD, Solarex, UPG and USSC. Keeping one module from each company as a control, perform the following tests on the other 6 modules:

Indoor/Outdoor: Photostability Testing Program (cont.)

- **Indoor Continuous-Illumination Test:** Our "standard" 1-sun continuous illumination test, at a module temperature of 50°C, electrically loading each module at its maximum power point (P_{max}), for a total of at least 1000 hours, with periodic I-V curves taken at 25, 50, 100, 250, 500, and 1000 hours. Two modules from each manufacturer (a total of 10 modules) will be exposed in this test. Modifications have been made to the Tenney chamber with the Vortek argon-arc lamp to take I-V curves in-situ during exposure with a new multi-tracer apparatus, as well as the ability to monitor irradiance and temperature.
- **Indoor Cycled-Illumination Test:** A second group of two modules from each manufacturer (a total of 10 modules) will be exposed in this test. The illumination will be 1-sun and 50°C for 5 hours, and then the modules will be kept in the dark at 25°C for 19 hours. This light-dark cycling will be continued until the modules have been exposed to a total of at least 1000 cumulative hours of 1-sun illumination. The modules will also be loaded at P_{max}. Periodic I-V curves will be taken after 25, 50, 100, 250, 500, and 1000 hours of illumination. The purpose of this experiment is to approximate the actual light-dark exposure which modules see in the field.

Indoor/Outdoor: Photostability Testing Program (cont.)

- **Outdoor Natural Exposure Test:** A third group of two modules from each manufacturer (a total of 10 modules) will be exposed in this test. This will involve mounting the modules at the outdoor PV test site, loading them at P_{max} , and then periodically obtaining I-V curves on each module. This test will continue for at least one year of outdoor exposure; the test was begun in August, 1993. The modules are electrically loaded, and I-V curves are taken in-situ, using a new multi-plexing module I-V curve tracer apparatus (Multi-Tracer).

A comparison of the results from these three tests may provide insight into the photo-induced degradation in a-Si PV modules, from various perspectives: (1) the PV material structure and composition, (2) the effect of their exposure history on the shape and total amount of degradation, as well as the time to "stabilization", (3) the general effects of continuous versus cycled illumination and temperature, both natural and artificial, and (4) other effects not yet anticipated but possibly revealed by this study.

Indoor Module Testing Program

- Qualification Testing
- Photostability Studies
- *Accelerated Weathering*

Outdoor Module Testing Program

- Natural, Real-Time Exposure Testing

Indoors: Accelerated Weathering Program

- Proposals for an **Accelerated Weathering/Environmental Test Chamber** have been received and are being evaluated
- Expect delivery and program start-up in early 1994
- **Concerns:** Cost is high to obtain everything we *really* need in one large-area apparatus/chamber, i.e., UV, visible, and IR illumination, thermal cycling, and humidity, with monitoring and control features
- This is *important* because the effects of the light-source spectrum and intensity, as well as test chamber temperature and moisture, can dramatically alter the results of the accelerated test, thereby giving little or no correlation to outdoor natural exposure

**Pitfalls in accelerated testing with a light source
differing in emission properties (total and spectral irradiance)
from the natural source (*):**

1. Possible reversal in stability ranking of materials under test
 2. May cause an unnatural mechanism and type of degradation
 3. Misleading information on the effectiveness of certain absorbers and stabilizers
 4. Alters bleaching vs yellowing and other antagonistic reactions
 5. Alters surface vs bulk degradation
- => These may lead to inaccurate prediction of material and/or module lifetimes**

(*) Norma Searle, "Effect of Light on Materials", Atlas School for Natural and Accelerated Weathering, May, 1993.

Indoor Module Testing Program

- Qualification Testing
- Photostability Studies
- Accelerated Weathering

Outdoor Module Testing Program

- *Natural, Real-Time Exposure Testing*

Outdoor Testing Program

- **SOMS:** Standardized Outdoor Measurement System:
 - 1) Reference Cells / Module Package
 - 2) Outdoor Temperature-Controlled PV Test Enclosure

- **Multi-Tracer:** PV Module Multi-plexing I-V Curve Tracer:
 - => In-situ monitoring and data acquisition of I-V curves, irradiance, temperature, etc.

 - => Loading of modules via max. power tracking or constant voltage

NREL
PHOTOVOLTAIC
PERFORMANCE & RELIABILITY
WORKSHOP

SEPTEMBER 8-10, 1993

RESULTS OF MODULE HOT SPOT TESTING

BOB HAMMOND
CENTER FOR ENERGY SYSTEMS RESEARCH
ARIZONA STATE UNIVERSITY

SHADING CAN OCCUR DUE TO

- . BIRD DROPPINGS**
- . LEAVES OR OTHER DEBRIS**
- . SHADOWS (TREES, POLES, ETC.)**

**CRACKED CELLS CAN PRODUCE THE
SAME EFFECT AS SHADING**

HOT-SPOT HEATING

- . WORST CASE CONDITION IS WITH MODULE (OR CELL STRING) SHORTED**
- . EIGHTY PERCENT OF STAND-ALONE SYSTEMS USE SHUNT TYPE CHARGE CONTROLLERS WHICH SHORT THE MODULE**

UL 1703

FLAT-PLATE PHOTOVOLTAIC MODULES & PANELS

36.0 HOT-SPOT ENDURANCE

"...MODULE SUBJECTED TO SIMULATED REVERSE VOLTAGE HOT-SPOT HEATING CONDITIONS FOR 100 HOURS, INTERMITTENTLY

THE TESTS SHALL NOT RESULT IN:

- . THE ACCESSIBILITY OF PARTS INVOLVING A RISK OF ELECTRICAL SHOCK (*HIGH POT TEST*)**
- . MELTING OF SOLDER OR**
- . ANY OTHER INDICATION OF A RISK OF FIRE OR ELECTRICAL SHOCK**

CONCLUSIONS

- **CELLS CAN GET VERY HOT DUE TO SHADING (OR CRACKED CELLS)**
- **HOT-SPOT HEATING IS NOT LIMITED TO UTILITY SIZE SYSTEMS**
- ***THE NUMBER OF CELLS BYPASS IS A MAJOR FACTOR IN SHADED CELL TEMPERATURE***
- **OUTDOOR TESTS ARE RELIABLE, SIMPLE, INEXPENSIVE AND REALISTIC COMPARED TO SIMULATED INDOOR TESTS (BUT TEST CONDITIONS ARE NOT AS WELL CONTROLLED).**

MODULE SUMMARY DATA

MFG.	1	2	3	4	5	6
SUBSTRATE	Tedlar [1]	Glass [4]	Tedlar [2]	Tedlar [5]	Tedlar [6]	Tedlar [3]
POWER W						
[7] DATA SHEET	-	-	53	64	48	62.7
[8] MEASURED	20.28 [9]	88.7	53.0	58.9	47.3	58.8
Voc Vdc						
[7] DATA SHEET	-	-	21.7	21.3	21.3	26.0
[8] MEASURED	10.42 [9]	46.1	21.8	21.2	21.7	25.9
Isc Adc						
[7] DATA SHEET	-	-	3.35	4.0	3.2	3.25
[8] MEASURED	2.74 [9]	2.65	3.33	3.66	3.1	3.14
FILL FACTOR						
[7] DATA SHEET	-	-	0.729	0.751	0.704	0.742
[8] MEASURED	0.700	0.726	0.728	0.757	0.703	0.724
SERIES CELLS	18	80	36	36	36	44
CELL LAYOUT	1x18	8x10	3x12	4x9	4x9	4x11
CELL SIZE, mm	96x96	100x100	103x103	115x115	100x100	102x102
BYPASS DIODES	None	4; 20 cells	2; 24 cells	None	None	None
"BYPASSED CELLS	18	20	24	36	36	44
Vr, RANGE	3.45-8.75	4.99-10.13	5.05-11.76	8.40-12.12	0.22-18.18	0.65-5.50

Note 1: Tedlar-mylar-polyethylene

Note 2: Tedlar-mylar-Tedlar

Note 3: Tedlar-foil-mylar-Tedlar

Note 4: Glass-acrylic

Note 5: Tedlar-mylar

Note 6: Tedlar-foil-mylar-Tedlar

Note 7: From manufacturer's data sheet

Note 8: Measured by MSEC

Note 9: Single string (i.e., 1 of 12 strings)

Manufacturer	Bypassed Series Cell
1	18
2	20
3	24
4	36
5	36
6	44

Vr by Manufacturer

CELL #6, THERMAL RESPONSE

CELL #0302 (25% Shading @ Columns 1 & 2, and Rows 3 & 4). Module short-circuited.

MFG #1; CELL #6; G = 1000

NORMALIZED MAXIMUM CELL TEMPERATURE (Average of five points)													
		1		2		3		4		5		6	
G	R-shunt	T-norm	%	T-norm	%	T-norm	%	T-norm	%	T-norm	%	T-norm	%
1000	HI	75.4	25	90.9	20	101.7	30	102.7	30	112.0	30	105.8	30
1000	AVE	77.1	25	89.9	25	102.7	30	104.1	30	78.2	30	81.8	30
1000	LO	67.1	30	73.9	30	84.9	30	96.9	30	55.4	20	63.2	30
800	HI	68.9	20	85.2	30	88.2	30	100.1	30	91.4	30	87.2	30
800	AVE	74.3	30	82.0	25	90.2	30	98.7	30	68.1	30	72.6	30
800	LO	67.5	30	67.2	30	77.2	30	91.3	30	41.5	20	52.3	30
600	HI	62.6	30	53.7	25	70.3	25	73.8	25	78.5	25	67.0	30
600	AVE	58.9	30	52.1	30	61.7	25	81.1	30	59.4	30	57.9	30
600	LO	53.9	30	51.4	30	53.3	30	76.4	30	39.9	0	47.3	20
NORMALIZED MAXIMUM HOT SPOT OF SHADED CELL (One of five points)													
		1		2		3		4		5		6	
G	R-shunt	T-norm	%	T-norm	%	T-norm	%	T-norm	%	T-norm	%	T-norm	%
1000	HI	78.2	20, 25	92.9	0-	113.1	30	109.2	30	121.9	30	111.6	30
1000	AVE	79.1	25	93.7	30	115.2	30	111.3	30	90.6	30	85.8	30
1000	LO	68.0	30	79.5	30	90.2	30	104.5	30	56.6	20	64.7	30
800	HI	72.1	20	88.8	30	97.0	30	107.3	30	97.3	30	90.3	30
800	AVE	75.9	30	84.9	25	91.7	30	104.3	30	71.1	30	75.2	30
800	LO	68.8	30	70.8	30	78.8	30	97.9	30	42.4	20	52.9	30
600	HI	63.9	30	72.8	25	73.8	25	77.9	25	84.7	25	69.7	30
600	AVE	58.5	30	69.7	30	64.6	25	84.4	30	62.4	30	60.7	30
600	LO	55.0	30	54.6	30	55.7	30	79.3	30	40.4	0	47.6	20

T-RANK2.XLS

RANK	MFG	G & TYPE	%	T-NORM
1	5	1000-H	30	112.0
2	6	1000-H	30	105.8
3	4	1000-A	30	104.1
4	4	1000-H	30	102.7
5	3	1000-A	30	102.7
6	3	1000-H	30	101.7
7	4	800-H	30	100.1
8	4	800-A	30	98.7
9	4	1000-L	30	96.9
10	5	800-H	30	91.4
11	4	800-L	30	91.3
12	2	1000-H	20	90.9

151

DARK IV CURVES

Relative Humidity, Temperature and Irradiance Testing at Mobil Solar Energy Corporation:

M. Azzam

Summary:

The objective of this paper is to present methods of temperature, relative humidity and irradiance testing and discuss our findings to date and plans for future tests.

Temperature, moisture and irradiance are the environmental conditions that have the most significant impact on PV module lifetime. Driven by customer satisfaction, time-to-market and a strong desire to deliver a highly reliable product to the market, these conditions are accelerated in product tests. In an effort to maintain relevance to operating conditions, while seeking to rapidly improve our product lifetime, Mobil Solar has devoted significant resources towards understanding the relationships between these conditions and the failure mechanisms that inevitably result in module performance degradation.

To date, our irradiance test results support NREL's hypotheses regarding EVA degradation. Our temperature and humidity test results do not agree with JPL's temperature/RH model. We have also learned that PV module electrical performance can vary from one manufacturer to another in these tests. Our plans are to further combine test environments and more accurately monitor product parameters.

Definition of Acronyms:

EVA- Ethyl Vinyl Acetate
EMMA - Equitorial Mount with Mirrors for Acceleration
EMMAQUA - EMMA with water spray
DSET - Desert Sunshine Environmental Test Labs
JPL Jet Propulsion Labs
NREL - National Renewable Energy Labs
PV - Photovoltaic
RH - Relative Humidity
UV - Ultraviolet

Background:

The combination of the high cost of PV, the increased competitiveness in the utility industry and the increasing costs of electric outages places a special importance on the reliability of PV modules. This importance provides PV manufacturers with significant opportunities for competitive advantage. On the other hand, the consequence of NOT providing reliable modules can be devastating to the manufacturer, if not the industry. Fortunately, in many respects, PV is up to the task. PV modules in grid connected

systems are inherently fault tolerant. Improvements in manufacturing as well as understanding of early PV module failures have made infant mortality problems minimal. The random or "freak" failure rate of PV modules has been demonstrated to be quite low (2 per 10,000 per year) or a Mean Time Between Failure (MTBF) of 43.8 million hours versus typical electronic sub-assemblies of 100,000 hours. However, there is one aspect of module reliability Mobil Solar is not yet comfortable with: useful life. Although manufacturers appear to have resolved the long term effects of thermal cycling and mechanical loading, Mobil Solar is still quite concerned with the effects that irradiance, high temperature, and moisture have on module lifetime. That is why Mobil Solar has focused its efforts on improving our test capabilities, our analysis and most importantly, our understanding of the failure mechanisms resulting from these conditions.

The Bath Tub Curve:

Product and component (hardware, not software) reliability is best described by the bathtub curve. This curve is typically broken up into three phases: "infant mortality", "random or freak failures" and "wearout". Infant mortality failures usually occur within 90 days to a year, during which the product population exhibits a higher than normal failure rate. This higher failure rate occurs because the weakest of the population are unable to endure the typical stresses associated with normal start-up and operation. The light switch or automobile transmission that fails upon first use are examples of infant mortality failures. Workmanship warranties are designed to protect the customer from such problems. The second phase, freak failure rate phase, include the failures that occur over the useful life of the product. Most often the failure is caused by a stress that exceeds the median strength of the product, hence the term "freak" failure rate. An example might be a power surge blowing a transistor or a pot hole damaging the struts in an automobile. The "freak" failure rate is mathematically modeled by a straight line, because it is considered "random". The third phase, or the wearout phase, defines the end of the useful life of the product. In this phase, failure mechanisms such as corrosion, fatigue and polymer degradation cause the product to operate below specifications. These failure mechanisms are caused by the long term exposure to the normal stresses that the product was designed to withstand during its useful life. Most products that we use as consumers-cars, dishwashers, computers - only have useful lives on the order of 5 to 10 years. PV modules are expected to have lifetimes on the order of 20 years, anywhere in the U.S.. This poses some very special challenges to those who develop and test PV products.

Why Temperature, Relative Humidity, and Irradiance?

The Jet Propulsion Labs (JPL) did a lot of work on the environmental conditions and failure mechanisms that are most likely to end a crystalline Si PV module's useful life. They determined that PV modules could be "worn out" by:

fatigue failures in the cell-to-cell interconnect system due to diurnal thermal cycling and/or wind/snow loading.

corrosion related failures due to moisture ingress and accelerated by higher temperatures.

electromigration failures due to the combination of moisture, voltage and temperature, further aggravated by encapsulant breakdown due to UV.

encapsulant degradation due to long term exposure to UV and high temperatures.

For the most part, failures attributed to cell-to-cell interconnect fatigue failures were addressed by the dual strap interconnection method and other JPL recommended design guidelines employed by most manufacturers. It is clear that the encapsulant degradation has not been solved. Cell and module material, processes and construction have changed rapidly enough to make it difficult for the industry to assess how much of a problem moisture/temperature induced failure mechanisms really are. Although Mobil Solar still does extensive thermal cycling and mechanical loading testing, we placed special emphasis on UV/Irradiance testing and temperature/humidity testing.

Past Testing:

Temperature and Humidity: Damp Heat (85°C/85RH)

This accelerated test environment originated in the painting industry to determine the resistance of paint coatings to moist/hot environments. It was later adopted by the microelectronics industry and later by the PV industry as a form of accelerated life testing. Mobil Solar has found this testing the most aggressive of accelerated "life" tests on PV product, in terms of inducing module failures, (more effective than Thermal Cycling, Mechanical Loading, UV exposure).

85/85 tests are conducted in environmental chambers. Mobil Solar has two walk-in chambers that can accommodate our full-sized 4 x 6 foot modules and three standard chambers ranging from 19 cubic feet to 32 cubic feet in capacity. All chambers are capable of running 85/85 tests. Typically, we expose our modules to just the 85/85 environment (dark). The test is interrupted every 500 hours for electrical tests and visual inspection. We have also performed the 85/85 tests on specimens, with additional conditions. Some of these added conditions are described below.

85/85 with forward current

We have conducted several experiments in which we biased several of our own mini-modules under forward current and compared them to unbiased modules of the same construction. Current has ranged from the mA range to the 1 amp range. In all cases, the difference between the conditions was imperceptible. Since then, we do not bias the modules in the 85/85 test environment.

Schematic of module under forward current

85/85 with voltage

We recently conducted an 85/85 test where our modules and some of our competitors' modules were also subjected to a voltage of 500 volts applied from each module's source

circuit to its frame. Although our module and those of certain competitors were not affected, other competitors suffered immediate degradation. This will be discussed in more detail in the section entitled Temperature/Relative Humidity Observations.

Schematic of module under 500 volts from source circuit to frame

85/85 with Interim Thermal Cycling and "Humidity Freeze" Testing.

We have combined 85/85 testing with interim thermal cycling, (10 cycles every 500 hours of 85/85). We have also conducted humidity freeze testing of both the PVUSA cycle and JPL (soon to be adopted by the IEEE) cycle. Thus far, we have found that the interim thermal cycles and the humidity freeze test are no worse on our modules than the straight 85/85 test, both in terms of power degradation and insulation resistance values. In fact, we have found that the PVUSA cycle tends to be less severe than the JPL cycle and the straight 85/85 testing. We have found that the interim thermal cycling can adversely affect certain competitors.

Other Temperature and Humidity Testing

Perhaps our most significant work has been in our efforts to: a) find ways to further accelerate the test and reduce the test development times and b) gain a better understanding of the 85/85 test, as it relates to the actual operating conditions. Some examples of these are:

Autoclave Testing:

We have tailored autoclave test equipment and test techniques originally developed for the microelectronics industry to further accelerate the test results of the 85/85 test. After several years of work, we have found test conditions that adequately reproduce the results from 85/85 testing in about 1/4 the time. The advantages of this drastic reduction in test time are obvious. We are able to make changes and improvements to the processes and products in shorter time with confidence that the heat and moisture resistance of the module is not being compromised. However, these highly accelerated methods must be conducted with caution. These conditions may not be appropriate for certain materials and constructions.

Matrix Testing:

In an effort to draw correlation with the actual operating environments, we have conducted, "Matrix" tests at various temperatures and relative humidities which included the 85/85 environment. These tests are still in process. However, we have compared results attained thus far to a number of temperature/relative humidity models. Some of these models, including the one from JPL, have been dismissed based on our experimental findings to date.

Irradiance Testing

Mercury vapor

Upon our first observations of EVA browning at the Southwest Residential Station in New Mexico, we only had one form of UV testing in house, the Sunlighter. This unit used RS-4 mercury vapor lamps, (originally used for superfast suntans.). This unit had a rotating plate to attain uniform light exposure of the samples and blower to keep the samples cool. We found that we could approximate the failure mechanism if we disabled the blower and the rotating motor, and allowed the samples to exceed 60° C. Later, we made our own UV light boxes that could be placed in an oven or an environmental chamber so that we could attain higher temperatures and reduce test times. GE discontinued the RS-4 line, due to the reduced demand resulting from the ban on their use for suntanning purposes. We have since switched to another type of mercury vapor lamp, which has less energy in the UV and therefore requires longer exposure.

The mercury vapor lamps are effective in duplicating the particular mechanism that browns EVA, but we received several warnings from test labs and GE about using it for generic UV testing of any construction materials.

Q-Panel

Our next UV equipment purchase was a Q-Panel unit that uses UVA fluorescent bulbs. This unit does a much better job of approximating the UV spectrum of the sun. It also has a lower energy dosage rate below 300 nm than the mercury vapor lamps. Unfortunately, it took substantially longer than the mercury vapor lamps to achieve browning of the EVA. Furthermore, results were somewhat confusing, due, we suspect, to the non-uniform heating of the unit.

DSET EMMA

In search of other irradiance testing methods to test EVA degradation, we launched an experiment at the Desert Sunshine Environmental Test (DSET) Labs outside of Phoenix, Arizona. We placed special samples in one of their EMMA outdoor test systems. This system attains an approximately 5 to 7 X concentration of sunlight through the use of

mirrors. By providing samples constructed with 2 interconnected half cells, divided by a gap and covered with a clear backskin (as well as the front cover glass), we were able to make cell measurements as well as spectrophotometer measurements on the same samples. Our findings confirmed that construction and materials can delay the onset of "EVA browning" but nothing can prevent it.

DSET EMMAQUA

We have only recently launched testing that incorporates DSET's water spray with their EMMA test apparatus. So far, we have not observed any differences between the two environments.

Observations:

Temp/Relative Humidity Observations:

Almost all the modules (competitors' and our own) that we have exposed to the 85/85 test have degraded substantially in power within 3000 hours. All dry megger readings dropped eventually. Some dropped much earlier than others. Stabilized megger readings ranged from 500 Kohms to 300 megaohms. We have also observed that samples left in the dark at 85°C (irrespective of humidity) long enough (1500 to 3000 hours) will brown. We have not observed this browning in chambers at 45°C. All multi-laminate backskins are subject to delamination in this test, usually within 1000 hours. We have seen cases where single layer substrates delaminate from the encapsulant, but this is not true in all cases.

Results were further complicated when the samples were exposed to additional stresses. As stated above, neither forward current through the source circuit nor voltage applied from the source circuit to the frame nor interim thermal cycling appeared to affect our module one way or the other. We have not done much bias testing on competitors but we have found that added voltage testing and interim thermal cycling testing may have had an adverse affect on some of our competitor's product (see 1993 Round of Testing Chart above). Infrared (IR) scans of the failed competitor's modules subsequent to 85/85 with 500 volts indicate that one type may have a problem related to their interconnect system and the other type may have a problem whereby cells become shorted. It is important to note here that limited failure analysis was done on competitor's modules and these mechanisms were not confirmed.

Construction, materials and processes clearly play a large role in the performance in this test, but it is not a straightforward issue. Modules and samples that appear to achieve a "near" hermetic seal, in fact do worse than constructions that are breathable. Modules that look great are, in fact, "dead". Low insulation resistance readings show no correlation to performance. Mobil Solar has devoted significant efforts toward determining the relationships between these variables and 85/85 test results. We believe we understand many of the key impacting variables, but much more work is required.

Irradiance Testing Observations:

The observations from our own studies support many of NREL's findings. EVA browning always appears to be less around the edges of cells and modules, in addition to areas where bus bars run through the module. This is because acetic acid, generated during the degradation of EVA, escapes first from these areas, and therefore is less likely to make the degradation reaction turn auto catalytic. Experiments strongly indicate that specimens made with non-breathable backskins (foil, glass) will brown somewhat faster than specimens made with breathable (tedlar only) backskins.

The type of light and the ambient temperature of the test environment plays a significant role in the browning reaction rate. EVA browning does not seem to be dependent on particular wavelengths of the UV range as some other mechanisms are. It is very dependent on the temperature: the higher temperature, the sooner EVA browns.

Our experimentation has also found that the type of EVA and lamination process can affect the time onset of browning. Also, the type of metalization used in the cell or laminated in the EVA can affect the reaction rate. This is evidenced by the brown diffusion pattern around the copper-constantan thermocouples used in the construction of some of our samples.

Approach to Lifetime Predictions:

While we strive to make our product more resistant to accelerated tests, we also wage a battle on a second front; correlating the test results to operating conditions. We constantly endeavor to answer the question: are the tests applicable to field conditions? This question can actually be broken down into two lower level questions: 1) What are the true product operating conditions and 2) How do accelerated conditions correlate to these operating conditions? We approach the answers to these questions by mathematically modeling the environmental conditions and applying those conditions to the models that relate accelerated conditions to field conditions. The process iterates between modeling and confirming the model with additional testing and studies.

Operating Conditions

We have collected a fair amount of weather data and module temperature data. We do not have actual module relative humidity data. Instead, we used JPL's approach to calculating module relative humidity. The figure below is an example of the module operating condition at the Florida Solar Energy Center in Florida.

In the case of temperature and humidity, the information is averaged and aggregated in groups of 10°C and 10% RH. We can then employ the temperature/RH models based on our test findings and predict module lifetimes for various conditions throughout the country.

Temp/RH models

As previously mentioned, the 85/85 test for PV is not founded on observations in the field, rather it comes from other industries. Whether or not it can really be used as a method to forecast PV lifetime is still unknown. JPL, based on its tests and analyses, estimates that in calculating temp/RH acceleration factors, a 1 degree rise in temperature will result in the same acceleration as a 1% rise in RH. Using their model and the doubling of reaction rate for every 10°C rule of thumb, failure mechanisms in a constant environment of 40°C/60% RH will occur 128 times slower than in an 85/85 environment. In other words, 20 years of 40/60 is equal to 1360 hours in 85/85.

Our concerns about JPL's model led us to conduct "matrix tests". The graph below gives some indication of how module performances degraded under different environments. The precise details of this testing are currently confidential and cannot be presented in this paper. Furthermore, we are still in the midst of this testing, so the results are not complete.

We did learn that our test results, to date, did not agree with the JPL model. It appears that JPL's model places too heavy a weight on the relative humidity factor for the product and environments that we used in our test. This discrepancy prompted us to look at other temperature/RH models. We studied six models for various electrical components and configurations and found one that seems to fit reasonably well to the data collected so far

(see figure below). We must complete our testing to determine if this model holds true for all cases.

Irradiance model

Unlike the 85/85 test, our accelerated irradiance and UV testing was prompted by observations in the field. EVA browning appeared to visually manifest itself within 4 to 6 years in southern United States sites. We began measuring significant power degradation (on the order of 5%) in about 7 to 10 years. Our mercury vapor lamp testing in an oven at 90°C dramatically accelerated the process. Given that the spectrum of the mercury vapor lamp was so different from that of the sun, no attempt was made to correlate the results. Although the acceleration rate is much lower, testing in the DSET EMMA system appeared to correlate reasonably well with the actual product observations. As shown below, it appears that a line provides an adequate fit for the degradation, at least down to 10% power loss.

Combining Models

It is clear from our results that the southern United States is the area most likely to experience early module wearout. If the failure mechanisms associated with temperature/RH did not interact or depend on those associated with irradiance, it would be reasonable to simply add the results of the two models to obtain a lifetime forecast for this area. It is likely that there are interactions between failure mechanisms, particularly with respect to EVA. This "synergism" of environmental effects makes the simple addition of models either optimistic or pessimistic. The former is more probable.

Follow-up Work:

Aside from completing existing tests/analyses and continuing routine testing/analyses, our efforts will focus on eliminating or reducing uncertainties. Such uncertainties include: 1) the synergisms and interactions between environments and failure mechanisms, 2) the error between calculated module RH and actual module RH and 3) the dependency of the test results to various manufacturing steps.

Our basic approach to such uncertainties has always been to target the failure mechanism that causes degradation. By understanding the failure mechanisms at hand, a number of these uncertainties disappear. We continue to employ a vast number of techniques to determine failure mechanisms, including FTIR, spectroscopy and IR imaging. In the absence of understanding the mechanisms, we strive to combine environments and improve monitoring. We are currently conducting tests in our new weatherometer that can simultaneously provide high temperature, high humidity and xenon lamp irradiance as well as thermal cycling on specimens. We are also endeavoring to better comprehend the module RH through the use of an RH monitoring device that can be laminated into the module.

Of course all this work would be for naught, if it were not communicated to the designers and manufacturers of the product. Members from our group are intimately involved with the design and development of products, ensuring that our customers realize the benefits of these studies.

Conclusions:

The world of accelerated testing and forecasting product lifetimes is a world of assumptions, hypotheses and inaccuracy. It perhaps requires fewer assumptions and is more accurate than the world of market and financial forecasting, although that serves as little solace. Accelerated testing, if understood, does help to weed out weak designs and materials, while significantly reducing time-to-market and improving customer satisfaction and safety. Product lifetime forecasting serves to maintain the thread from test to actual operating conditions. Behind both of these activities must be an understanding of underlying failure mechanisms.

Although life testing and prediction may seem like a never ending, inconclusive activity, information that flows from it is an essential element to effective and enduring product improvements. Some of the primary conclusions that we have drawn from our program for this paper are:

EVA browns in the dark at 85°C

There is a wide variation in 85/85 performance between competitors

Irradiance test observations to date support NREL's EVA hypotheses

JPL Temp/RH model does not correlate with our temperature/RH testing

The EMMA test system provides reasonable test results to actual field operations.

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Performance and Stress Testing of CdTe PV Modules

Solar Cells, Inc.

**Dan W. Sandwisch
Manager of Manufacturing**

Performance and Stress Testing of CdTe PV Modules

Performance

- Efficiency**
- Manufacturing**
- Field exposure**

Stress Testing

- IQT failure analysis**
- Next steps**

Best Demonstrated Efficiencies

	NREL	SCI
Efficiencies	6.9%	8.2%
Max Power	47.5 W	56.0 W
Vmax	65.4 V	72.3 V
I_{max}	726 mA	774 mA
Voc	90.7 V	94.5 V
Isc	900 mA	879 mA
Aperture Area	6844 cm²	6844 cm²
Date	1/18/93	8/12/93

Total Area Efficiency vs. Number of Modules Produced
averaged in groups of 20

Manufacturing Variability Power Distribution

Solar Cells, Inc. 09/07/93

DAYS OF EXPOSURE:	87
INITIAL OUTPUT:	931 WATTS
CURRENT OUTPUT:	918 WATTS
PERCENT CHANGE:	-1.4%

- No Temperature Correction
- No Spectral Correction

Stress Testing

IQT Failure Analysis

- **Failure mode identification**
- **Manufacturing implications**

Next Steps

- **Accelerated testing**
- **Field exposure**

CdTe PV Module Testing

Percent Change vs. Test

1--Humidity Freeze

2--Hail Impact

3--Wet Insulation Resistance

4--150 thermal Cycles

5--Electrical Isolation

6--50 Thermal Cycles

7--Hot-Spot Endurance

8--Mechanical Loading

SCI CELL AND MODULE STRUCTURE

(FILM THICKNESS AND LASER SCRIBE DETAIL NOT TO SCALE)

Humidity-Freeze Modes of Failure

- **Internal "fingering"**
- **Edge delamination**

Superstrate Flatness Profile

Solar Cells, Inc.
09/07/93

Cover Flatness Profile

Solar Cells, Inc.
09/07/93

Humidity-Freeze Failure Analysis

Maximum Slope of Superstrate vs. Cycles

Manufacturing Implications

- **Sampling on-line for flatness of superstrates and cover sheets**
- **Quality control indicator based on severity of glass curvature**

Next Steps

- **Continue IQT Evaluations**
- **Accelerated Tests**
 - **Bias conditions**
 - **Ambient conditions**
 - **Insolation levels**
- **Field Exposure**
 - **SCI: 1-4kW**
 - **NREL: 1kW**
 - **Toledo Edison: 100kW**

Investigation of Lamination Induced Metastability in CIS-Based Modules

Dennis Willett

Siemens Solar Industries

Camarillo, CA

CIS-Based modules temporarily decrease power after lamination.

The largest changes is in the FF due to an increasing slope at the open circuit voltage point.

The Voc change is typically 1 to 5%.

The Jsc change is typically 0 to 2%.

A typical module will lose 15 to 25% of its Pmax during lamination. The module will then recover in one to four weeks to within 5% of its initial power.

Typical lamination with "green" float glass

Our small experimental modules are often laminated with an inexpensive untempered float glass.

This causes larger absorption loss in Jsc than seen with water white tempered glass used on our larger modules .

By measuring the module I-V characteristics as a function of light intensity the change in the fill factor is found to be due to an increase in the total series resistance. In this module the resistance increased 57%.

Tests were made to determine what component of the module and what part of the lamination step cause the change.

The lamination step includes:

Heat : 140°C for 30 to 40 minutes

Pressure : Vacuum and pressure to withdraw the air as the circuit, EVA and cover glass are pressed into a sandwich.

Chemicals : The EVA may release some agent harmful to the ZnO during the lamination and cure.

Test cells were put into heat and heat/pressure environments.

851 cells were split into two groups. The first group was oven annealed at 140°C for one hour; a second group received a "pseudo lamination" in which the glass/circuit /mylar/cover-sheet was subjected to the lamination cycle.

The average efficiency of each group was unchanged by the test.

The relative stability of this large group of cells to high temperatures is very encouraging.

However investigations of the light soaking effects seen in CIS-based cells showed that improvements due to light soaking quickly decayed at temperatures above 100°C in the dark.

A newer group of cells were laminated and shows the variable impact of the lamination process and partial recovery with light soaking.

Three groups of cells were laminated with EVA/Glass.

191

This newer group of cells shows the variable impact of the lamination process and a partial recovery with light soaking.

Pseudo laminations with mylar and oven anneals were also conducted on modules.

Many modules also show a rapid partial recovery if light soaked after lamination. A significant portion of the drop in performance may be due to the annealing (depopulation) of beneficial states at the lamination temperatures. These states are then regained (repopulated) with light soaking.

The change in the resistance of the ZnO was measured in laminated Glass/ZnO/EVA/Glass structures and was found to be negligible in a previous study.

194

However, interconnect contact resistance was found to be a significant contributor to the variability of initial module performance.

Interconnect test structures are made to evaluate the "via" quality and reliability

Measuring the voltage drop across each double interconnect allows the contact resistance to be calculated.

Lamination makes most interconnects better but some interconnects much worse. This method is used to evaluate new patterning techniques.

Interconnect test structures can show the sensitivity of the via to changes in glass, CIS formation process and sometimes heating and light soaking.

The interconnect test structure has allowed us to optimize a mechanical scribe that gives consistently low resistance and does not change during lamination.

Summary

Many CIS-Based modules suffer a temporary loss in power when exposed to the lamination process.

This loss is due to an increase in the series resistance.

Part of this effect may be due to a thermal decay or depopulation of beneficial states which can be reversed with light soaking.

Interconnect test structures show that the contact resistance of the "via" may change in the lamination process. Changes may also occur with light soaking or thermal annealing.

Alternate patterning methods are being evaluated to provide a more robust module interconnect.

TESTING FOR MODULE WARRANTIES

BY

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Introduction

The value of a Photovoltaic module depends upon the amount of electricity it can produce over time. The longer a module continues to produce electricity, the greater will be its value to the customer. Part of this value comes from the stated manufacturer's warranty that guarantees replacement for a specified period of time. Another part of this value comes from the history and testing of the product that went into establishing the warranty. Because PV modules are often the only source of electricity for the customer's application, the reliability as well as projected lifetime of the modules are important features.

On the other hand, a module manufacturer must have a great deal of confidence in the product and its projected lifetime before offering an extended warranty. Failure of a large number of modules while still under warranty, would impose a large financial burden on the manufacturer. Therefore, it is extremely important to perform long term testing on modules to assure that most of the modules will continue to meet the minimum specification for a much longer time than the term of the warranty requires. For the customer then, the value of the product is enhanced both by the longer warranty and by the assurance of reliability gained from the testing.

History

To understand the testing involved in establishing a PV module warranty, it is instructive to review the history of crystalline silicon module warranties at Solarex. Table 1 shows the dates when the warranty times were increased. It took Solarex 4 years to achieve a 1 year warranty, 6 years to offer a 5 year warranty, 12 years to reach a 10 year warranty and finally, 20 years to extend the warranty to 20 years. These numbers point out quite clearly that it takes a long time to assemble the test data necessary to provide the assurance for increasing the warranty period. The question to be answered in this talk is where does this data come from?

Testing Development

The first step in module testing is outdoor exposure. Since this is where the modules have to work, this is where they should be tested. However, there are 2 problems with outdoor testing. The first problem is the variation in outdoor conditions from site to site. A module deployed in Arizona will experience different conditions than one deployed in Maryland or Alaska. The second problem is the length of time required for outdoor exposure testing. You have to wait 10 years to see if a module can last 10 years at that specific site. If a change is made in process or materials you have to wait another 10 years to see the effect. This is certainly unacceptable, so to overcome these problems, accelerated environmental tests are developed.

In designing accelerated environmental tests extreme care must be taken to insure that the test relates to both acceleration of the environment that the product is to be exposed to as well as to the mechanisms by which the environmental stress causes failure in the product. In other words, the accelerated stress must

cause the module to fail in the same way as it does in the field or the accelerated test is not a valid test. For example, if in trying to accelerate the influence of temperature, the module were heated above the 180° C, the solder bonding the interconnects to the cells would likely melt, probably causing open circuit failures. However, melting of the solder is not the temperature induced failure mechanism seen in the field. Therefore, the stress, temperature in this case, has been accelerated too much, resulting in a different failure mechanism.

Much of the early work in this area was performed by JPL under the LSA Program¹⁻⁴. JPL developed a series of module qualification test sequences for the Block purchases. A summary of the sequences are given in Table 2. Each of the tests in this sequence was developed to evaluate module performance against specific stresses that were related to failures observed in the field. In these early days of the PV industry, these tests were extremely helpful and at times very painful for the manufacturers. Manufacturers used the accelerated qualification tests as quick feedback in the development of more reliable modules. By designing modules to pass the qualification tests, production modules no longer exhibited the early field failures caused by the failure mechanisms that the accelerated tests were designed to stress. The increased module reliability allowed PV companies like Solarex to offer module warranties for the first time.

The next step was field deployment of the modules that had successfully passed the early (Block I, II and III) qualification tests. Once again, field failures occurred, but this time the modules lasted for much longer periods before failures began. These new failures were analyzed, failure mechanisms identified and new (or modified) accelerated qualification tests were developed. For example, because a number of the early modules suffered from hail damage, a hail test was developed and added to the qualification sequence in Block IV. Module failures due to broken interconnects, especially in climates with large daily temperature extremes lead to increasing the number of thermal cycles from 50 to 200 in Block V.

It was during this time (late 70's and early 80's) that the reliability of crystalline silicon PV modules was established^{5,6}. The field data showed that modules qualified to at least the Block II and III sequences had very low failure rates and projected lifetimes well in excess of 5 years. By 1980 most of the crystalline Si module manufacturers were offering warranties of up to 5 years on their products. In most cases the warranty was based more on passing the qualification tests than on actual field experience with the products being manufactured, since product designs changed frequently to lower cost and increase efficiency.

Block V was the last qualification sequence published by JPL. A Block VI procedure was being prepared with the addition of a long term humidity test and a bypass diode test⁴, but it was never published due to reduced DOE funding. Government sponsored qualification efforts then shifted to development of procedures for thin film modules⁷. Work on crystalline silicon modules continued as the manufacturers continued to monitor field results and to develop their own accelerated testing programs. Once again the emphasis was on identification of field failures, determination of failure mechanisms, development of accelerated tests to simulate those failure mechanisms, redesign of modules and materials to overcome the identified failure mechanisms and finally testing via the accelerated test sequence to verify that the problem has been solved. One example of this process was the reported field failures of Ag paste cells with PVB encapsulant⁸. While Solarex never used PVB encapsulant, the corrosion mechanism can occur to some degree in any encapsulation system unless the module is permanently hermetically sealed. Therefore, Solarex used this experience on other manufacturer's modules to design an accelerated temperature humidity test to verify that our metallization and encapsulation systems were not susceptible to this failure mechanism. Development and periodic use of these accelerated tests as well as the excellent record of field performance lead Solarex and many other PV manufacturers to extend their module warranties to the range of 10 years in the mid 1980's. It was assumed that crystalline silicon modules qualified to a Block V sequence should last for at least 10 years in the field.

Lessons Learned from Carrisa Plains

Carrisa Plains was a 6 megawatt grid connected PV system using flat plate modules with mirror enhancement and tracking. The system began to experience major power loss in the first 5 years due to degradation of the modules. Since these modules also exhibited severe discoloration of the EVA encapsulant, EVA degradation was blamed for the power loss^{9,10}. Indeed it has now been conclusively shown that high temperature and high UV illumination will cause EVA to discolor¹¹. However, the Carrisa system had other problems in addition to the EVA discoloration that contributed significantly to the power loss. Recent reports have shown that hot spot failures due to poor system design with inadequate diode protection caused a significant portion of the power loss at Carrisa¹². Module hot spot testing is no substitute for good system design, especially in terms of diode protection via bypass and blocking diodes.

Reports of EVA discoloration at Carrisa lead to a survey of other EVA modules with reports of discoloration at a number of other sites in hot sunny environments. EVA discoloration depends on the site, the module mounting conditions, module construction and possibly even the properties and processing of the EVA used. The question of EVA discoloration is still under review (see the session scheduled for this conference). However, we do know that some EVA modules have been deployed for up to 12 years in the field without appreciable power loss¹². The only reported power loss mechanism associated with EVA discoloration is the loss of optical absorption, which in most cases results in a slow loss in current, but not a catastrophic failure¹¹. Development of an accelerated UV-thermal test is important for many crystalline silicon module manufacturers in terms of defining the "EVA lifetime" for their modules.

Recent Qualification Tests

Many of the lessons learned during the 80's were incorporated into an IEC (International Electrochemical Commission) crystalline silicon PV module qualification sequence that has now been approved by the international PV community and published as IEC-1215. This procedure was based on Block V and CEC-502 specifications. It includes all of the Block V tests as well as a damp heat test at 85° C/85% RH for 1000 hours, an outdoor exposure test, a UV test and a robustness of termination test. We have already seen that adding the UV test before thermal cycling and humidity freeze is able to accelerate a failure mechanism previously observed in the field where certain tapes (that have been used in modules to hold the cells in position before and during lamination) delaminate. Clearly UV weakens the adhesive bond which then fails during thermal cycling and humidity freeze.

Work is now underway to develop both IEEE and IEC qualification documents that cover all terrestrial PV modules. The difficulty with this task is the need to identify all of the potential failure mechanisms for all of the different type of modules and then to develop accelerated tests that test for these specific failure mechanisms. This means that for each new PV technology, a new set of failure mechanisms may be identified from field experience and accelerated tests have to be designed to test for these mechanisms. A good example is the wet high-pot test developed to test for a corrosion problem observed on some amorphous silicon modules. This procedure is now routinely used to test crystalline silicon modules to identify possible problems with liquid water penetration into the active circuit elements, representing a possible high voltage danger. So qualification tests will continue to improve as PV matures.

Testing Beyond Qualification

When module technologies were being developed, qualification tests were sufficient for establishing the length of module warranties. Now, however, module warranties have been extended for times considerable longer than the accelerated stress tests in the qualification sequences were designed to simulate. Some of the tests, like the hail test, are not time dependent, but rather just increase the severity

beyond that normally encountered in the field. However, most of the accelerated tests define a duration and/or number of cycles that were selected based on several years of field experience. These tests may have to have extended duration or increased cycles to evaluate product performance for long term operation.

Thermal cycling is an accelerated qualification test run for a specific number of cycles. The original thermal cycle test specified 50 cycles. However, module designs that had successfully passed 50 thermal cycles began failing in the field, especially desert environments, in 2 to 4 years due to interconnect failures. In response to these failures the number of thermal cycles in the qualification sequence was increased to 200. To better understand what field experience equates to 200 thermal cycles, we must estimate the acceleration factor associated with the specified cycles. Many thermally activated processes can be modeled by an activation rate that doubles for every 10°C increase in temperature¹³. The accelerated thermal cycle test cycles from -40°C to $+90^{\circ}\text{C}$, representing a ΔT of 130°C . In actual field experience the daily change in temperature varies from site to site as well as with the seasons. An estimate for daily module temperature change includes 15°C for the change in ambient and 25°C from the module increase in temperature above ambient, yielding an estimate of a ΔT of 40°C . Therefore the accelerated thermal cycle test increases the daily cycle by 90°C , representing an estimated acceleration factor of 18. As a check on this value, 50 cycles would represent 2.5 to 3 years, approximately the time required for observation of field failures in the early modules. This acceleration rate indicates that 200 thermal cycles represents approximately 10 years in the field. So the 200 thermal cycle test is valid for a 10 year module lifetime, probably carrying a 5 year manufacturer's warranty. However, to test for a 30 year module lifetime and warranty the module for 20 years, the thermal cycle test should be run for 600 cycles.

The damp heat test (85°C , 85% RH) is another test where the duration is important. Oth and Ross¹⁴ estimated that 200 hours at 85°C and 85% RH represented 20 years of exposure in Miami, Florida, one of the US warmest dampest climates. Ricaud and Petersen¹⁵ calculated a range of probable acceleration factors and concluded that a 20 year field exposure could be simulated with up to 400 hours of exposure at 85°C and 85% RH. So this appears to be a case where the 1000 hour qualification test in IEC-1215 is more than adequate to test for a 30 year life or 20 year warranty.

The UV test is a recent addition to qualification test sequences. The UV test is important because of the interaction between UV exposure and other stresses including high temperature, thermal cycling and humidity. The identification of UV and high temperature as the cause for discoloration and degradation of the EVA at Carrisa Plains^{9,10} lead to a greater interest in accelerated UV testing of modules. There is a UV test included in the IEC-1215 qualification test procedure, but the UV test procedure itself has not been approved for publication. In addition, the IEC test represents a UV exposure equivalent to only 325 hours of the UV component of the reference solar spectrum. This is clearly not enough UV and thermal stress to simulate the Carrisa problem. Solarex is using a mixture of long and short wavelength UV lamps to provide the appropriate spectrum with a UV acceleration factor of 5 as specified in the IEC UV draft document. Temperature can also be used as an acceleration factor during the UV test. By running the test continuously at 80 to 90°C an acceleration ratio of 50 to 100 can be achieved. However, at this acceleration rate it takes on the order of one-half a year to test for a 30 year module life. It is interesting to note that the Carrisa system, operating at 90°C with a UV acceleration rate of 2, had an acceleration factor of approximately 10 over a normal flat plate system that runs at 60 to 65°C . So we should be looking at the performance of the Carrisa system after 2 or 3 years to evaluate the effect of UV and temperature on flat plate modules after 20 or 30 years.

Most of the other tests in the qualification sequence (hot spot, mechanical load, twist, robustness of termination and cut susceptibility) are not time or duration dependent. They test for the modules ability to withstand a particular event. It is important that these tests be conducted after the long term stress tests to ensure that normal operation doesn't impair the modules ability to withstand these stresses. For example,

the ability to pass the hot spot test depends among other things on the number and quality of solder bonds. Therefore, modules should be subjected to the hot spot test after thermal cycling and/or damp heat to determine if the module can still pass the hot spot test.

The humidity-freeze test is a special case. It does have a particular duration and number of cycles, but the mechanism of pumping moisture into the encapsulant and then freezing it, is more a measure of the strength of the adhesive bonds in the module rather than the measure of the modules ability to withstand a particular long term process occurring in the field. Like the hot spot test, the humidity freeze test does not have to be extended, but should be utilized after applying the other accelerated stresses to determine how well the adhesive bonds stand up to long term exposure to humidity, thermal cycling and UV.

Summary

The development of a valid qualification test sequence for a particular module technology takes a long time (many years). It requires an iterative process of field observations, identification of failure mechanisms, development of accelerated tests to simulate the failure mechanisms and finally more field testing to show that modules that pass the accelerated test also do not exhibit the failure mechanism during normal operation. Qualification tests are designed to test for failure over a moderately long time frame (5 to 10 years). Testing for longer term reliability (for 20 year warranties and 30 year lifetimes) requires longer term field testing, longer duration accelerated testing and the use of various combinations of accelerated tests to better understand how they interact. With 20 years of field and accelerated test experience for crystalline silicon modules, we now produce highly reliable and long lifetime products. However, we won't know what the average module lifetime or what the ultimate life limiting failure mechanism will be until we have 30 or 40 years of field experience with these modules.

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TABLE 1
Solarex Module Warranty History

<u>Year</u>	<u>Warranty</u>
1973	First Solarex Crystalline Modules Manufactured - No Warranty
1977	1 Year Warranty
1979	5 Year Warranty
1985	10 Year Warranty
1993	20 Year Warranty

TABLE 2
JPL Block Qualification Tests

Test Year	I 1975	II 1976	III 1977	IV 1978	V 1981
Thermal Cycle	100 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	200 cycles -40 to +90
Humidity	70 C, 90%rh 68 hr.	5 cycles 40 C, 90%rh to 23 C	5 cycles 40 C, 90%rh to 23 C	5 cycles 54 C, 90%rh to 23 C	10 cycles 85 C, 85%rh to -40 C
Hot Spots	-	-	-	-	3 cells 100 hrs
Mechanical Load	-	100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 cycle ± 2400 Pa	10000 cycle ± 2400 Pa
Hail	-	-	-	9 impacts ¾" - 45 mph	10 impacts 1" - 52 mph
NOCT	-	-	-	Yes	Yes
High Pot	-	< 15 µA 1500 V	<50 µA 1500V	<50 µA 1500V	<50 µA 2*Vs+1000

Block I	JPL 5-342
Block II	JPL 5-342-1B
Block III	JPL 5-342-1C
Block IV	JPL 5101-16A and 5101-83
Block V	JPL 5101-161 and 5101-162

Field Wet Resistance Test Procedure and Results at PVUSA

**NREL PV Performance and Reliability Workshop
Denver, CO Sept. 1993**

Charles M. Whitaker Benjamin E. Valega

Endecon Engineering, San Ramon, CA

Description of PVUSA Systems

System	Description	Location	Rating	Installation Date
<u>EMT</u>				
Siemens Solar Industries (SSI)	Flat-plate Cz	Davis, CA	18.7 kWdc	Jan-89
Sovonics	Flat-plate a-Si	Davis, CA	17.3 kWdc	Jun-89
Utility Power Group	Flat-plate a-Si	Davis, CA	15.7 kWdc	Dec-89
Solarex	Bifacial Cz	Davis, CA	15.7 kWdc	Oct-90
ENTECH	Concentrator Cz	Davis, CA	16.5 kWdc	Mar-91
<u>US</u>				
Advanced Photovoltaic Systems (APS)	Flat-plate a-Si	Davis, CA	479 kWac	Sep-92
Siemens Solar Industries (SSI)	Flat-plate Cz	Kerman, CA	498 kWac*	Aug-93
Integrated Power Corporation (IPC)	Flat-plate EFG	Davis, CA	196 kWac*	Aug-93
Siemens Solar Industries (SSI)	Flat-plate Cz	Davis, CA	176 kWac*	???
<u>Host</u>				
Sovonics	Flat-plate a-Si	Maui, HI	18.5 kWdc	Oct-89
Integrated Power Corporation (IPC)	Flat-plate EFG	Austin, TX	17.5 kWac	Jul-92

* Anticipated rating

Wet Resistance Test History

- ❑ JPL-developed test to quantify module leakage current
- ❑ Pass/fail criteria need to address
 - Safety (1-5 mA)
 - Ground fault arcing ($\sim 50\mu\text{A}$)
 - Leakage current induced degradation: Corrosion ($1\text{-}5\mu\text{A}$)
- ❑ Safety and G.F. based on single incidents. Corrosion based on cumulative leakage over time
- ❑ TCO wrap around on thin film modules: $10^5\text{ M}\Omega$ dry, $0.1\text{ M}\Omega$ wet: Dry Hipot does not address adequately
- ❑ Incorporated in several module qualification tests:
 - PVUSA Module qual. test
 - NREL IQT
 - IEEE Module Qualification Test (draft)
 - IEC Thin-film Module Qualification Test (draft)

Field Wet Resistance Test Setup

Wet Resistance Test Criteria

- ❑ Cumulative charge transfer to module failure
- ❑ Initial JPL testing based on 4"x4" coupons
- ❑ Scaling dependant on type of failure mechanism:
 - Point defect (3 - 30 Coulombs for 30 yr life)
 - Perimeter dependant (0.1 - 1.0 Coulombs/cm)
 - Area dependant (0.03 - 0.3 Coulombs/cm²)
- ❑ For a 1'x4' module with perimeter-related leakage,
 $R_w^* = 129 \text{ M}\Omega \text{ to } 1314 \text{ M}\Omega$
- ❑ 100 M Ω suggested as indicative but not overly restrictive

Field Wet Resistance Test Issues

- ❑ Surfactant (Liquinox 1:516)
- ❑ Module temperature
- ❑ Module size
 - PVUSA: Resistance $\propto 12.5 \mu\text{A}/\text{ft}^2$ @ $2V_{\text{max}} + 1000\text{V}$
 - IEEE Proposing $40\text{M}\Omega\text{-m}^2$
- ❑ Array segment size ($R_w^* \geq 0.1\text{M}\Omega$)
- ❑ Array segment voltage
- ❑ Spray pressure
- ❑ Labor intensity ($\sim 0.1 \text{ mhr}/\text{m}^2$)
- ❑ Safety
- ❑ Frequency

Effect of PV Voltage on Megger Reading

$$R_{\text{MeggerReading}} = \frac{2 \times V_M \times \frac{R_{PVL}}{n \times m} - n \times V_{PV} \times R_M}{2 \times V_M + n \times V_{PV}}$$

PVUSA FWRT Results

	# of Modules	Array Area (m2)	Array Power (kW)	Harness	J-Box	Module	Unknown	Diode
EMT1 Totals	6988	1497	83.9	14	5	12	0	0
US-1 Totals	14668	15629	849	229	139	60	52	23
US-2 Totals	12240	5171	498	2	1	9	0	0

Conclusions

- ❑ Provides detailed information regarding location and extent of
 - Module and field wiring design, mfg., and QC flaws
 - Shipping damage
 - Installation damage
 - Insulation system degradation
- ❑ Labor intensive: can do samples on “large” systems
- ❑ May result in “tight” J-boxes
- ❑ Untested systems are very likely to have multiple failures

National Renewable Energy Laboratory

**Performance of a 1.8 kWac Dual-Junction
Amorphous Silicon System**

Presented by:

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Abstract:

On December 7, 1992 a 1.8 kWac utility-interconnect photovoltaic (PV) system was brought on-line at NREL. The system was deployed in order to evaluate the performance of a dual-junction amorphous PV array in a utility-interconnect application. The system is unique in that the manufacturer installed construction grade insulation on the back of each module in an attempt to elevate the operating temperature of the array. This presentation details system performance versus name-plate rating, interim results covering the in-situ module/array performance and the predominate system experiences encountered thus far.

Overview:

The name-plate rating of the system is 1.8 kWac. Early on it was determined that the system was operating below this rating. In an attempt to raise the system output 6 modules were added to the array changing the number of modules per string from 16 to 17 in series. This change took place on 4/19/93. The system output as of 8/24/93 meets the name-plate rating. Note: system monthly total AC and DC energy generated during the month of April was low due to the installation of the 6 new modules (system was down for approx. 51 hours).

The insulation was placed on the back of each module in the array to study the effect this might have on array degradation and performance. In-situ module performance characteristics were calculated based on temperature corrected/normalized data acquired using a portable IV curve tracer. This data showed as temperature dropped so did power and as temperature increased the power also increased. It was also seen that this trend deviated from that of the fill factor after 12/31/92. Isc and I_{max} also rose as temperature increased after 12/31/92. These changes are thought to be related to the increased module operating temperature, thus offsetting the effect of light induced degradation. However, seasonal changes in the solar spectrum may have played a prominent role here as well.

The degradation of the array was found to be about 20% based on the earliest measured array efficiency. This result is somewhat supported by the 21% module degradation determined from individual module IV data gathered 9/92 and 8/93.

National Renewable Energy Laboratory

Performance of a 1.8 kWac Dual-Junction Amorphous Silicon System

Presented by:
Troy Strand *(Staff Engineer)*
September 8, 1993

Acknowledgements:

This work was supported by the United States Department of Energy under contract #DE-AC02-83CH10093

Robert Hansen (NREL)

(major contributions to the successful installation of the system)

Steve Rummel and Yehoshua Caiyem (NREL)

(module baseline measurements)

Dave Waddington (formerly of NREL)

(technical discussions)

Dr. Robert Ross (United Solar Systems Corp.)

National Renewable Energy Laboratory

Objective:

Evaluate the performance of a dual-junction amorphous photovoltaic array in a utility-interconnect application.

ARRAY SPECIFICATIONS:

OPEN-CIRCUIT VOLTAGE (STC)	± 374 VOLTS
SHORT-CIRCUIT CURRENT (STC)	± 5.4 AMPERES
VOLTAGE @ MAX. POWER (STC)	± 265 VOLTS
CURRENT @ MAX. POWER (STC)	± 4.2 AMPERES
MAX. POWER (STC)	2.2 kW
SYSTEM VOLTAGE	748 VOLTS

SYSTEM SPECIFICATIONS:

NAME PLATE RATING	1.8 kWac @ 120 Vac
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National Renewable Energy Laboratory

ARRAY CONFIGURATION (4/20/93 to present):

POSITIVE SUBARRAY:

3 PARALLEL STRINGS OF 17 MODULES IN SERIES

NEGATIVE SUBARRAY:

3 PARALLEL STRINGS OF 17 MODULES IN SERIES

ARRAY CONFIGURATION (prior to 4/20/93):

POSITIVE SUBARRAY:

3 PARALLEL STRINGS OF 16 MODULES IN SERIES

NEGATIVE SUBARRAY:

3 PARALLEL STRINGS OF 16 MODULES IN SERIES

221

SYMBOL	DEFINITION
SW1	DC DISCONNECT
SW2	AC DISCONNECT
SW3	LOCKABLE UTILITY ACCESSIBLE DISCONNECT SWITCH
CB1	120V, 20A, 1P CIRCUIT BREAKER
CB2	120V, 50A, 1P CIRCUIT BREAKER
CB3	120V, 60A, 3P MAIN CIRCUIT BREAKER

SYMBOL	DEFINITION
T1	TRANSFORMER 09/60
S.A.	SURGE ARRESTER
PV	PV ARRAY: ± 265 Vpk, ± 4.2 Apk, 2.2 kW (STC)
PCU	120VAC, 2KW STATIC POWER CONVERTER
O/U	OVER/UNDER VOLTAGE MONITOR TIME MARK MODEL 268
K1	20 AMP POWER RELAY (NORMALY OPEN) A&B 700-PK-400-115-120

National Renewable Energy Laboratory

POWER QUALITY:

(as measured by PSCC on 2/5/93 @ 11:52am using a BMI 3030A Power Profiler)

IRRADIANCE AT TIME OF TEST WAS APPROX. 1017 W/m²

PARAMETER:	MEASURED VALUE:
VOLTAGE THD	7.1%
CURRENT THD	1.4%
POWER	1.732 kWac
CURRENT	13.7 Amps
VOLTAGE	127.7 Vrms
N-GND VOLTAGE	3.3 Vrms
POWER FACTOR	0.99 PF

SYSTEM MONTHLY TOTALS FOR:
DC ENERGY, AC ENERGY AND POA IRRADIANCE

1.8 kWac UTILITY INTERCONNECT PHOTOVOLTAIC SYSTEM PERFORMANCE **SYSTEM PERFORMANCE FOR APRIL 23, 1993 (BEST DAY)**

96 MODULE (3/24/93) AND 102 MODULE (8/24/93) AC RATINGS. BASED ON BEST DAY
PERFORMANCE (C.F.=28.7, 30.2% on 3/24 and 8/23)

**1.8 kWac DUAL-JUNCTION AMORPHOUS SILICON SYSTEM
POS. STRING MAX. POWER VERSUS TIME**

DAY OF EXPOSURE	0	1	11	25	45	107	143	186	205	233
CALENDAR DAY	12/1/92	12/7/92	12/17/92	12/31/92	1/20/93	3/23/93	4/28/93	6/10/93	6/29/93	7/27/93

1.8 kWac DUAL-JUNCTION AMORPHOUS SILICON SUBARRAY DEGRADATION TREND FOR APERTURE EFFICIENCY

POS STRING #1: IV CURVES NORMALIZED TO 1000W/sq. m
(NO TEMP.-CORRECTION)

7/27/93: I_{sc} =1.703, V_{oc} =317.578, I_{pk} =1.393, V_{pk} =225.147, P_{max} =313.568, FF =58.005, $TEMP.$ =71.6

12/7/92: I_{sc} =1.594, V_{oc} =327.393, I_{pk} =1.346, V_{pk} =253.125, P_{max} =340.702, FF =65.294, $TEMP.$ =47.6

IN-SITU MODULE MAX. POWER TREND: BASED ON POS. AND NEG. SUBARRAY IV DATA.
 (Vmax: TEMP.-CORRECTED USING MANUF.-SUPPLIED COEFF. OF -0.3%/DEG. C ABOVE 25
 DEG. C PER MODULE. Imax: NORMALIZED TO 1000 W/sq. m)

IN-SITU MODULE SHORT CIRCUIT CURRENT AND MAX. POWER CURRENT TRENDS: BASED ON
POS. AND NEG. SUBARRAY IV DATA.
(DATA NORMALIZED TO 1000 W/sq. m)

IN-SITU MODULE OPEN CIRCUIT VOLTAGE AND MAX POWER VOLTAGE TRENDS: BASED ON
POS. AND NEG. SUBARRAY IV DATA
(DATA TEMP.-CORRECTED USING MANUF.-SUPPLIED COEFF. OF -0.3% /DEG. C ABOVE 25
DEG. C PER MODULE)

**CHANGES IN MODULE PERFORMANCE CHARACTERISTICS
AFTER 246 DAYS OF EXPOSURE.
BASED ON 6 MODULES TESTED 8/23/93, NORMALIZED TO THE AVERAGE BASELINE DATA.**

SYSTEM EXPERIENCES:

Problem:

- Inverter would not start in the early morning (subarray voltages were being driven down to 195 V by the Control Board while attempting to start)
- Positive and negative array voltages differed by as much as 110 V and as little as 3 V

Fix:

- Replaced Control Board 1/4/93

1.8 kWac UTILITY INTERCONNECT PHOTOVOLTAIC SYSTEM PERFORMANCE FOR DEC. 14, 1992

SYSTEM EXPERIENCES:

Problem:

- **One module out of 108 exhibited a dip in its IV curve**

Fix:

- **Manufacturer supplied replacement module under warranty**

OUTDOOR TEST 92A45 RUN No. 2

CONCLUSIONS:

System performance:

- **System performance on 3/24/93 was approx. 8.6% (-148W) below system nameplate rating of 1.8 kWac. Addition of 6 modules (one per string) elevated system performance approx. 1.6% (+27W) above the nameplate rating as measured on 8/24/93.**
- **Positive and negative subarrays have degraded approx. 20% with respect to earliest measured subarray efficiencies.**
- **Voltage THD of 7.1% is outside of PSCC's acceptable limits. Most probable cause is line impedance as indicated by a 4 V voltage drop between the inverter and AC utility disconnect switch.**

CONCLUSIONS:

Module performance:

- **Module power, as measured on 7/27/93 in-situ, was determined to be within approx. 4.1% of manufacturer's rated power.**
- **Modules have exhibited approx. a 21% degradation in efficiency as determined by IV traces acquired during baseline measurements and on 8/23/93 (data gathered via a portable IV curve tracer).**
- **Average and maximum Capacity Factors for the period beginning 12/7/92 and ending 8/31/93 were 16.5% and 31.4% respectively.**

THE VIRGINIA

SOLAR PHOTOVOLTAIC MANUFACTURING INCENTIVE GRANT PROGRAM (SPMIGP)

Draft Guidelines

September 1, 1993

1. DEFINITIONS

- 1.1 ASTM American Society for Testing and Materials
- 1.2 Concentrating Collector A photovoltaic panel, environmentally protected, which consists of photovoltaic cells, a lens or device to focus light on the photovoltaic cells, an assembly to hold the lens or focusing device, and the photovoltaic cells in fixed positions relative to each other, a secondary concentrator to reflect off-center light rays onto the cells, and a means to dissipate excess heat produced by concentrated sunlight.
- 1.3 Environmentally Protected Covered and shielded from injury and destruction from outdoor climatic conditions including, but not limited to, rain, snow and wind.
- 1.4 Flat-Plate, Non-Concentrating Collector A photovoltaic panel which contains photovoltaic cells that are mounted on a rigid, flat surface beneath a transparent cover, and is environmentally protected.
- 1.5 Independent Testing Laboratory A testing laboratory not associated or affiliated with a photovoltaic panel manufacturer. A photovoltaic panel manufacturer, its parent companies or subsidiaries cannot have a financial interest in an independent testing laboratory, its parent companies or subsidiaries, employed to conduct tests for the SPMIGP.
- 1.6 Manufactured in Virginia A photovoltaic panel is considered as manufactured in Virginia when the following criteria are satisfied.
 - 1.6.1 The substances, materials, films, crystals, or devices which produce electricity directly from incident solar radiation, and photovoltaic cells and photovoltaic modules using these substances, materials, films, crystals, or devices, are made, fabricated, constructed, or processed in Virginia from raw materials.
 - 1.6.2 The photovoltaic cells and modules are assembled in Virginia with other components to form a complete photovoltaic panel which can produce electrical energy in a usable form, independent of any other

device, suitable for connection to an electrical load.

- 1.7 Maximum Power Output The electrical output of a photovoltaic cell, module, or panel when operated at a point of its current-voltage characteristic curve in the power-producing quadrant where the product of current and voltage is a maximum.
- 1.8 Photovoltaic Module An assembly of two or more photovoltaic cells which are interconnected electrically.
- 1.9 Photovoltaic Panel A complete, environmentally protected assembly of one or more photovoltaic modules, mechanically fastened together and electrically wired together, which is capable of independent production of usable electrical energy, suitable for connection to an electrical load. The assembly consists of photovoltaic cells, electrical circuitry, optics, and housings. The assembly does not include tracking equipment or panel mounting systems.
- 1.10 Photovoltaic Cell The basic device which can produce electricity directly from incident solar radiant energy.
- 1.11 Randomly Selected Selecting out or choosing on a chance basis, in a manner to ensure that an object chosen has had an equal probability of being chosen as had the other objects capable of being chosen.
- 1.12 Rated Wattage The rated wattage of a photovoltaic panel to be used in determining the amount of the grant for which the panel manufacturer is eligible under the SPMIGP is the maximum power output as measured at the time the photovoltaic panel is constructed multiplied by the Solar Radiation Exposure Factor.
- 1.13 Solar Radiation Exposure Factor A weighting factor ranging in value from 0.0 to 1.0 which characterizes the decrease in generation of electricity by a photovoltaic panel due to the effects of incident sunlight over a specified period of time.
- 1.14 Usable Electrical Energy Electricity convenient and practicable for doing work.

2. TEST PROTOCOLS

2.1 General Conditions

- 2.1.1 Each model of photovoltaic panel for which a grant is requested from the SPMIGP is to be tested in compliance with the procedures and standards published in these guidelines.

2.1.2 All costs associated with testing photovoltaic panels in accordance with these guidelines are the responsibility of the photovoltaic panel manufacturer.

2.1.3 The Commonwealth of Virginia reserves the right to require the retesting of photovoltaic panels in accordance with these guidelines at any time if the Commonwealth has reason to believe these guidelines are not being followed. All costs associated with the retests will be the responsibility of the photovoltaic panel manufacturer.

2.2 Solar Radiation Exposure Factor

2.2.1 The Solar Radiation Exposure Factor of a photovoltaic panel which uses crystalline silicon to produce electricity from incident solar radiation is 1.0.

2.2.2 The Solar Radiation Exposure Factor of a photovoltaic panel which uses amorphous silicon to produce electricity from incident solar radiation will be 0.85 unless the panel manufacturer chooses to have the Solar Radiation Exposure Factor determined experimentally by an independent testing laboratory, in accordance with the procedures described in section 2.2.4.

2.2.3 The Solar Radiation Exposure Factor of a photovoltaic panel which uses a material other than crystalline silicon or amorphous silicon to produce electricity from incident solar radiation will be determined experimentally by an independent testing laboratory, in accordance with the procedures described in section 2.2.4.

2.2.4 Experimental Testing Procedures

2.2.4.1 Selection of Test Samples

- a. A minimum of six (6) photovoltaic panels will be tested.
- b. The photovoltaic panels are to be randomly chosen by a representative of the independent testing laboratory from among all of the panels manufactured during the twelve (12) month period prior to the beginning of the tests.
- c. After a photovoltaic panel has been selected for testing, the panel is not to leave the control of a representative of the independent testing laboratory.

- d. A photovoltaic panel selected for testing is not to be pretested, modified, improved, or altered in any manner after its selection for testing.
- e. Prototype panels cannot be used for testing.
- f. Solar Radiation Exposure Testing must be performed after any major change in the design or construction of a photovoltaic panel or after a major change in the photovoltaic panel manufacturing process that will affect the rated wattage of the photovoltaic panel.

2.2.4.2 Test Procedures

- a. Before a photovoltaic panel is exposed to direct solar radiation, the electrical performance of the panel is to be measured in accordance with the procedures presented in section 2.4.2 of these guidelines.
- b. Each photovoltaic panel will be exposed to direct solar energy for a sixty (60) day period.
 - 1) Mount each photovoltaic panel so that it faces due south.
 - 2) Mount each photovoltaic panel with a slope so that the panel surface is normal to direct solar radiation at solar noon on day thirty (30) of the sixty (60) day test.
 - 3) The photovoltaic panels will be operational and generate electricity throughout the duration of the sixty (60) day test period.
 - 4) The average daily incident solar radiation throughout the duration of the test will be a minimum of 750 Watts per square meter.
- c. Beginning on day thirty-one (31) of the test period, the electrical performance of the photovoltaic panel is to be measured daily in accordance with the procedures presented in section 2.4.2 of these guidelines.
- d. The Solar Radiation Exposure Factor for a photovoltaic panel is the maximum power output of the panel measured immediately after the day sixty (60) test period

has been completed divided by the maximum power output of the panel measured before exposure to direct solar radiation.

- e. The Solar Radiation Exposure Factor to be used in calculating the rated wattage of photovoltaic panels is the arithmetic average of the Solar Radiation Exposure Factors for the six (6) test panels.

2.2.4.3 Reporting of Test Results

- a. Report test results in accordance with Section 3 of these guidelines.

2.2.3.4 Certification of Test Results

- a. The test results are to include the name, address, and telephone number of the independent testing laboratory employee responsible for testing the photovoltaic panels.
- b. The test results will have an original signature by the independent testing laboratory employee responsible for testing the photovoltaic panels.

2.3 Electrical Performance Testing

- 2.3.1 The electrical performance of each photovoltaic panel shall be measured by the manufacturer at the time the panel is constructed in accordance with the applicable methods which follow.

- 2.3.2 Electrical Performance Test Standards Photovoltaic panels are to be tested in accordance with one of the following test procedures and comply with each of the standards published in the procedure.

- 2.3.2.1 Non-Concentrating Collectors The electrical performance test is to be performed in accordance with ASTM Standard E1036, "Standard Methods of Testing, Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells", reference 1.

- 2.3.2.2 Concentrating Collectors The electrical performance test is to be performed in accordance with ASTM Standard E1036, "Standard Methods of Testing, Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells", reference 1, with the following changes in rated output conditions to those published in Table 1,

paragraph 5.3 of reference 1.

- a. Irradiance: 850 Watts per square meter

2.3.3 Test Equipment Calibration

2.3.3.1 Test equipment used by the photovoltaic panel manufacturer to determine the electrical performance of the panels is to be recalibrated on the schedule recommended by the test equipment manufacturers and by the standards referenced in 2.3.2.

2.3.4 Reporting of Test Results

2.3.4.1 Report test results in accordance with Section 3 of these guidelines.

2.3.5 Certification of Test Results

2.3.5.1 The test results are to include the name, address, and telephone number of the photovoltaic panel manufacturer's employee responsible for testing the photovoltaic panels.

- a. The test results will have an original signature by the photovoltaic panel manufacturer's employee responsible for testing the photovoltaic panels.

2.4 Electrical Performance Verification Testing

2.4.1 The electrical performance of photovoltaic panels is to be measured periodically by an independent testing laboratory.

2.4.2 Electrical Performance Verification Test Standards Photovoltaic panels are to be tested in accordance with one of the following test procedures and comply with each of the standards published in the procedure.

2.4.2.1 Non-Concentrating Collectors The electrical performance test is to be performed in accordance with ASTM Standard E1036, "Standard Methods of Testing, Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells", reference 1.

2.4.2.2 Concentrating Collectors The electrical performance test is to be performed in accordance with ASTM Standard E1036, "Standard Methods of Testing, Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays

Using Reference Cells", reference 1, with the following changes in rated output conditions to those published in Table 1, paragraph 5.3 of reference 1.

- a. Irradiance: 850 Watts per square meter

2.4.3 Selection of Test Samples

2.4.3.1 A minimum of one (1) photovoltaic panel is to be tested for every 200,000 Watts of production or every six (6) months of production, whichever is more frequent.

2.4.3.2 Photovoltaic panels are to be selected for testing randomly from among all the photovoltaic panels manufactured since the preceding Electrical Performance Verification Test, or if there has been no preceding Electrical Performance Verification Test, from among all the photovoltaic panels manufactured since the start of production.

2.4.3.3 Photovoltaic panels are to be chosen by a representative of the independent testing laboratory conducting the Electrical Performance Verification Tests.

2.4.3.4 After a photovoltaic panel has been selected for Electrical Performance Verification Testing, the panel is not to leave the control of a representative of the independent testing laboratory.

2.4.3.5 A photovoltaic panel selected for Electrical Performance Verification Testing is not to be pretested, modified, improved, or altered in any manner after its selection for testing.

2.4.4 Test Equipment Calibration

2.4.4.1 Test equipment used by the photovoltaic panel manufacturer to determine the electrical performance of the panels is to be recalibrated on the schedule recommended by the test equipment manufacturers and by the standards referenced in 2.4.2.

2.4.5 Certification of Test Results

2.4.5.1 The test results are to include the name, address, and telephone number of the independent testing laboratory employee responsible for testing the photovoltaic panels.

2.4.5.2 The test results will have an original signature by the

independent testing laboratory employee responsible for testing the photovoltaic panels.

2.4.6 Reporting of Test Results

2.4.6.1 Report the test results in accordance with Section 3 of these guidelines.

2.4.7 If the maximum power output value obtained during the Electrical Performance Verification Test is more than 10% lower than the arithmetic average of the maximum power output values obtained by the photovoltaic panel manufacturer for all panels manufactured since the preceding Electrical Performance Verification Test, the maximum power output value obtained during the Electrical Performance Verification Test will be used to calculate the rated wattage of all panels manufactured since the preceding Electrical Performance Verification Test.

2.4.7.1 In the event that the maximum power output value obtained during the Electrical Performance Verification Test is more than 10% lower than the arithmetic average of the maximum power output values obtained by the photovoltaic panel manufacturer for all panels manufactured since the preceding Electrical Performance Verification Test, the photovoltaic panel manufacturer may choose to have additional panels undergo Electrical Performance Verification Testing. The arithmetic average of the maximum power output values obtained from the Electrical Performance Verification Testing of all panels, including the first test panel, will be used to calculate the rated wattage of all panels manufactured since the preceding Electrical Performance Verification Test.

2.4.8 If there has been no preceding Electrical Performance Verification Test, and if the maximum power output of the Electrical Performance Verification Test is more than 10% lower than the arithmetic average of the maximum power output values obtained by the photovoltaic manufacturer for all panels manufactured since the start of production, the maximum power output value obtained during the Electrical Performance Verification Test will be used to calculate the rated wattage of all panels manufactured since the start of production.

2.4.8.1 In the event that the maximum power output value obtained during the Electrical Performance Verification Test is more than 10% lower than the arithmetic average of the maximum power output values obtained by the photovoltaic panel manufacturer for all panels manufactured since the start of production, the

photovoltaic panel manufacturer may choose to have additional panels undergo Electrical Performance Verification Testing. The arithmetic average of the maximum power output values obtained from the Electrical Performance Verification Testing of all panels, including the first test panel, will be used to calculate the rated wattage of all panels manufactured since the start of production.

3. REPORTING OF TEST RESULTS

3.1 A report summarizing all photovoltaic panel test results and test equipment calibrations for the preceding twelve month period will be submitted to the Director of the Virginia Department of Mines, Minerals, and Energy as part of the annual report of manufacturing and sales.

3.1.1 The summary report is to be divided into the following three sections.

3.1.1.1 Solar Radiation Exposure Tests

a. Solar Radiation Exposure Test results need to be submitted only in years during which testing takes place.

3.1.1.2 Electrical Performance Testing

3.1.1.3 Electrical Performance Verification Testing

3.2 The summary report will contain the following information.

3.2.1 Manufacturer information

3.2.1.1 name

3.2.1.2 address

3.2.1.3 telephone number

3.2.1.4 Virginia incorporation number or State Corporation Commission registration number (only if the manufacturer is a corporation)

3.2.1.5 Federal tax identification number

3.2.1.6 name of contact at manufacturer, with address and telephone number

3.2.2 Photovoltaic panel information

3.2.2.1 model name and number

3.2.2.2 panel serial number

3.2.2.3 nameplate ratings assigned by manufacturer

3.2.2.4 location of plant where photovoltaic panel was manufactured

3.2.2.5 Report data for each photovoltaic panel tested

3.2.3 Independent testing laboratory information

3.2.3.1 name of laboratory

3.2.3.2 address

3.2.3.3 telephone number

3.2.3.4 name of individual responsible for testing, with address and telephone number

3.2.4 Test procedures

3.2.4.1 date(s) of tests

3.2.4.2 equipment used to perform tests

3.2.4.3 date of most recent calibration of test equipment, method of calibration, and results of calibration

3.2.4.4 statement of test procedures used

3.2.5 Test results

3.2.5.1 Information and data as required by the standards cited in sections 2.3.2 and 2.4.2 of these guidelines.

3.2.5.2 Test result certifications

REFERENCES

1. Electrical Performance of Non-concentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells, ASTM Standard E1036, Philadelphia, PA, 1985.

DURABILITY AND RELIABILITY

**Contact Corrosion on CdS/CdTe Solar Cells:
a photoemission study of the formation
of the CdS/SnO₂ interface**

by

David Niles, Dennis Rioux, Rajesh Patel, and Hartmut Höchst

special thanks to

**Kannan Ramanathan, Ramesh Dhere, Sally Asher,
Amy Swartzlander, Art Nelson, Helio Moutinho
and Al Czanderna**

David W. Niles

Application of Synchrotron Radiation UPS to CdS/CdTe contact formation

- reason for studying the SnO_2/CdS interface with synchrotron radiation UPS
- overview of synchrotron radiation UPS
- describe analysis of formation and electronic structure of the SnO_2/CdS interface
- show band lineup at SnO_2/CdS interface
- future work on problematic metal/CdTe interface

Synchrotron Radiation Photoemission Spectroscopy

Photon Energy Range $8 \leq h\nu \leq 200$ eV
 loose many core levels, but . . .

- several decades increase in flux
- five fold increase in resolution
- 1000 fold increase in cross section of valence bands

Experimental Procedure:

1. measure cleaned SnO_2 surface
2. deposit thin (several Å) CdS layer
3. measure CdS/ SnO_2 interface
4. deposit thick (100Å) CdS layer
5. measure CdS surface

Band Diagram for a CdS/CdTe heterojunction solar cell

262

Summary of CdS/SnO₂ interface

- CdS agglomerates on SnO₂ when deposited at RT
- no heat-driven chemical interaction between CdS and SnO₂
- moderate heat (400°C) enhances agglomeration
- band lineup favorable for electron flow from CdS to SnO₂ – perfect for photovoltaics
- future work focuses on the back contact – more susceptible to corrosion than the SnO₂

THERMAL BOND AGING OF THICK FILM SILVER METALLIZED SOLAR CELLS

by

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Presentation at the NATIONAL RENEWABLE ENERGY LABORATORY
Photovoltaic Workshop
Sept 9, 1993

LIST OF TABLES AND FIGURES:

TABLE 1.0	FIRST INDICATOR OF THERMAL AGING IN SOLDERED CONTACTS TO THICK FILM SILVER SOLAR CELLS
FIG 1.0	THERMAL AGING OF ALTERNATE SOLDERS TO FERRO CONDUCTROX 3349, METALLIZED CELLS
FIG 2.0	POWER LOSS VS BOND YIELD
FIG. 3.0	SN96 SOLDER TO FERRO 3349 BOND YIELD vs AGING TEMPERATURE
FIG 4.0	MEAN TIME TO FAILURE OF Sn 96/FERRO 3349 SYSTEM BOND SYSTEM
FIG. 5.0	BOND AGING PEEL STRENGTH OF Sn96: TO SPHERICAL VS FLAKE+SPHERICAL SILVER INK
FIG. 6.0	BOND AGING YIELD OF Sn96 SOLDER TO SPHERICAL SILVER VS FLAKE+SPHERICAL SILVER INK
FIG. 7.0	MEAN TIME TO FAILURE OF Sn96 SOLDER TO SPHERICAL SILVER VS SPHERICAL+FLAKE SILVER INK

THERMAL BOND AGING OF THICK FILM SILVER METALLIZED SOLAR CELLS

by

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INTRODUCTION

Accelerated testing studies determined that thermal bond aging of soldered contacts to thick film silver metallization (TFSM) of silicon solar cells is an operative failure mechanism that can result in reduced photovoltaic product lifetime. The composition of the solder and the structure of the silver thick film material are primary factors that influence the rate of bond aging and the related extrapolated product lifetime. The MSEC patents entitled PHOTOVOLTAIC CELLS WITH IMPROVED THERMAL STABILITY (US 5,074,920) and METHOD FOR FORMING SOLAR CELL CONTACTS AND INTERCONNECTING SOLAR CELLS (US 5,178,685) define improved embodiments of these key factors which we project to substantially improve potential product lifetime.

FIRST INDICATOR OF OPERATIVE THERMAL BOND AGING:

In the course of preparing single cell mini-coupons in a laminated construction of: Glass/EVA/Cell/EVA+3 layer backskin, for accelerated reliability testing we often observed cell fill factor degradation. The solar cells metallized with thick film silver were at that time dip coated with 62Sn/36Pb/2Ag solder and reflow solder bonded with flattened copper wire tabbing that was coated with Sn/Pb.

Among the battery of subsequent tests to address the fill factor degradation was a simulation of the thermal process of lamination which produced a strong signal or indication of significant metallurgical alteration of the solder:silver system. The simulation of the thermal effects of the lamination process was conducted on electrically characterized discrete silver metallized solar cells that were overcoated with solder. The lamination simulation conducted at the EVA curing temperature of 150° C included extended exposure of 80 minutes. A summary of the results of that simulated lamination process is given in table 1.0 but without the results of control cells that were not overcoated with solder. The control cells without a solder were thoroughly stable to the lamination simulation which is important to the interpretation of the results.

Subsequent thermal aging of reflowed solder paste with a composition of 62Sn/36Pb/2Ag to affect local bonds of tabbing to a number of sites along the silver busbar revealed rapid deterioration of the mechanical peel strength. The early aging tests conducted at 150° C were of 20 to 120 minute duration. Cells thermally aged without solder and subsequently bonded to tabbing by the above process had consistently strong peel strength thereby strengthening the belief of a solder:silver thermal interaction as opposed to a silver:silicon

interaction. Additionally, microanalytical analysis indicated the accumulation of tin at the failed interface of only the thermally aged solder:Ag bonds which heightened the belief that the Ag_6Sn intermetallic compound was being formed.

A search of existing literature on this topic conducted by my colleague J. Borenstein uncovered a wealth of information. The information was largely on silver thick film hybrid circuit technology of the 1970's that indicated brittle and swollen intermetallic compound formation on thermal aging at 150°C that was related to the solder composition. Thermal bond aging terminology was liberally used in describing this problem.

THERMAL BOND AGING DEGRADATION OF ALTERNATE SOLDER SYSTEMS:

The effects of solder composition to the resistance of thermal aging degradation in the solder:thick film silver solar cell system were systematically conducted. The solder composition was certified by the suppliers and provided in the form of solder paste/cream. This study used nickel coated copper tabbing to avoid confounding material interactions and a specific and reproduceable regiment of solder reflow to effect a tab/solder/silver bond. The response was measured by destructive peel strength measurements that represented the mean of 40 bond sites collected on 8 sites per cell for each data point plotted in the summarized results of figure 1.0. For the Sn 96.5/Ag 3.5 eutectic system it was necessary to increase the sample size due to the apparently higher activation energy.

ARRHENIUS PLOTTING OF SOLDER BOND WEAKENING:

To determine meaningful Arrhenius plotting of bond strength weakening it was necessary to first define the limiting lower limit that would constitute a representation of substantial product failure. For a representation of a severely weakened bond we modeled that at a strength of < 0.1 lbs the bond was not likely to survive temperature cycling without separation from the solar cell and therefore constituted a failed bond. From this position it was necessary to model the sensitivity of a module product's performance vs the yield or population of good bonds. Figure 2.0 summarizes the results of this modeling exercise for the stated specific boundary conditions. From this model, represented over a full range of bond yield (bonds > 0.1 lb), there is a threshold at the 25% to 30% bond yield region where the product essentially fails by excessive power loss.

From this information it was necessary to collect the experimental data that defined this 25% failed bond level for the solders of interest, as influenced by thermal bond aging at 3 or more temperatures, for this Arrhenius plotting objective. This exercise involved hundreds of cells to test the one(1) Sn 96 solder system, with 2 methods of solder reflow bonding of the tab: silver system. The tabbing for this portion of the study was Sn coated flattened copper. While the bond peel strength was a direct measured response the effective bond yield from this response over time at the temperatures of 150°C , 135°C and 120°C was the critical parameter of interest to this program. Figure 3.0 summarizes the experimental results for the B method of reflow solder bonding. The A method was similarly plotted but omitted in this presentation. Each data point represents the mean bond yield of 40 destructively tested bonds. The point of failure for the purpose of this study is the 75 % bond yield point at the 3 tested aging temperature conditions.

The points of failure mentioned above were plotted as a log of time vs the inverse of absolute temperature (K) in figure 4.0 for bonding (reflow heating) methods A and B. The solid lines represent the experimental data and the dotted line extensions represent their extrapolation to real product environmental thermal conditions. Figure 4.0 predicts a potential mean time to failure for Bond method A that is 1.5 orders of magnitude lower than method B which in a location providing a temperature of 60°C for 6 hours a day will resist product performance degradation due to failed bonds for a minimum of 5 years. The area under the time-temperature solder reflow process curve for method A is significantly higher in magnitude than method B but the details of the specific bonding methods which are beyond the scope of this presentation, will not be discussed here.

IMPROVED THERMAL STABILITY OF SPHERICAL Ag vs SPHERICAL + FLAKE Ag IN THE Sn 96 SOLDER BOND SYSTEM:

Subsequent to the completion of the aforementioned studies and the related patent filing, pilot manufacturing adopted the Sn 96.5/Ag 3.5 solder composition. As expected due to the higher activation energy of the new solder:silver system compared to the former Sn 62/Pb36/Ag2 system there was a positive overall impact to conventional (85/85) accelerated endurance testing but numerous manufacturing improvements obscure quantification of a specific reason.

In the course of engineering manufacturing improvements, an investigation was conducted in an alternate structure of the silver particles composing the thick film Ferro 3349, Conductox silver ink material. The earliest experiments were an immediate success regarding further limitation of the thermal aging degradation of the solder:silver bond system. For manufacturability the alternate ink system was applied to only the busbar regions of the the solar cell electrode system. At a later date the alternate silver ink material was applied to the P⁺ electrode regions to provide equivalent reliability to both electrode solder bond regions. The alternate silver material only effected a change that excluded flake shaped silver particles, thereby leaving a 100% spherical silver system.

The fully spherical system, we reasoned would pack more densely and thus limit surface diffusion of the solder system (solid or liquid phase). The preferred spherical silver particle size is in the range of 0.5 to 2.0 microns although a 0.5 to 10 micron range is expected to be satisfactory. Additionally, there was no sensitivity seen of bond aging degradation to the fired film thickness over the tested range of 5 to 30 microns nor was there an operable sacrifice of cell efficiency seen in this study of the fully spherical silver applied to busses and P⁺ electrode regions.

Figure 5.0 summarizes the comparison of peel strength of the Sn 96 solder bond system to the silver systems of spherical+flake vs fully spherical. Figure 6.0 summarizes the effective mean bond yield of these systems above the 0.1 lb lower limit discussed previously. Lastly, figure 7.0 transposes the data in figure 6 to a log of time vs the inverse of absolute temperature for the purpose of extrapolating the effective mean time to failure at appropriate boundary conditions. The activation energy of the fully spherical system increased to the extent that the 75% bond yield or product failure point could not be experimentally defined; therefore the more conservative 95% bond yield point (technically more difficult) was used for this case. The dotted lines in figure 7 are the extrapolations of the experimental data marked in solid lines.

The effect of the fully spherical silver system vs the spherical+flake silver each using the Sn 96 solder and bonding (reflow) method A was to extend the mean time to failure in excess of 3 orders of magnitude.

CONCLUSION:

A potential limitation of photovoltaic lifetime has been identified and an engineering/materials solution has been defined and implemented at MSEC. The goal of 25 year PV product life has been uplifted by this and other related achievements.

ACKNOWLEDGEMENTS:

For conducting the experimental processing and data collection I would like to thank Dick Billings. For their substantial contributions as co-inventors of the patents related to this program I thank J. Borenstein and M. Kardauskas. And to J. Amick, retired, I wish to express my appreciation for all his support and invaluable consultation.

FIRST INDICATOR OF THERMAL BOND AGING

TIME @150 C (Minutes)	0	20	40	80
Rbb (milliohms)	70	83	97	113
CELL FILL FACTOR	.734	.725	.720	.705

Rbb = Inter Busbar Resistance

Table 1.0

THERMAL AGING OF ALTERNATE SOLDERS FERRO CONDUCTROX 3349 METALLIZED CELLS

SOLDER

--- 62Sn/36Pb/2Ag	-+- 108Sn/88Pb/2Ag	* 43Sn/43Pb/14Bi
-■- 50In/50Pb	-*- 25In/75Pb	-+ 96.5Sn/3.5Ag

FIG 1.0 --MSEC/RCG--1990

MODULE POWER LOSS vs BOND YIELD

FIG10.MSEC.FEB.1990

Sn96 SOLDER BOND YIELD TO FERRO 3349 AG vs AGING TEMPERATURE

FIG. 3.0,MSEC,4/90

MEAN TIME TO FAILURE OF Sn96 SOLDER BONDS TO FERRO 3349 SILVER METALLIZATION

FIG. 4.0, MSEC, 5/90

BOND AGING PEEL STRENGTH OF Sn96 SOLDER TO SPHERICAL AG vs SPHERICAL+FLAKE Ag

Ag TYPE/TEMP

—□— SPHERICAL/165 C	—×— SPHERICAL/150 C	—◇— SPHERICAL/135 C
—■— SPHER'L +FLAKE/165 C	—●— SPHER'L +FLAKE/150 C	—○— SPHER'L +FLAKE/135 C

FIG.5....MSEC/2/91

BOND AGING YIELD OF SN96 SOLDER TO SPHERICAL Ag vs SPHERICAL+FLAKE Ag

Ag TYPE/TEMPERATURE

* SPHERICAL/165 C	□ SPHERICAL/150 C	× SPHERICAL/135 C
* SPHER'L+FLAKE/165 C	□ SPHER'L+FLAKE/150 C	× SPHER'L+FLAKE/135 C

FIG. 6.0...MSEC-2/91

MEAN TIME TO FAILURE OF Sn 96 SOLDER BONDS TO SPHERICAL Ag vs SPHERICAL+FLAKE Ag INK SYSTEMS

FIG.7.0,MSEC,2/91

**OUTDOOR AND INDOOR
ACCELERATED UV EXPOSURE TESTING**

**WILLIAM J. PUTMAN
Heraeus DSET Laboratories, Inc.
45601 N. 47th Avenue
Phoenix, Arizona 85027-7042**

When designing accelerated tests the following elements must be considered:

- **Ultraviolet radiation**
- **Visible and near-IR radiation**
- **Application of moisture to specimens**
- **Enclosure boundary conditions**
- **Proper and accurate measurements of light, temperature and moisture**

ULTRAVIOLET SPECTRAL ABSORPTION COEFFICIENT FOR OZONE

Adapted from Vigroux

FACTORS THAT CONTRIBUTE TO ACTION SPECTRA

- ▶ **Spectral energy distribution of the light source (i.e., its spectrum)**
- ▶ **Spectral energy absorption by the material of interest (i.e., its transmittance)**
- ▶ **Spectral quantum efficiency of the absorbed light**
- ▶ **Degradation response measured**

**ACTIVATION SPECTRA OF SEVERAL POLYMERS WHOSE
PHOTO-OXIDATION CAN BE FOLLOWED BY
ULTRAVIOLET AND VISIBLE SPECTROSCOPY**

Polymer	Activation Spectra (nm)
Polyethylene	300
Polystyrene	318.5
Polypropylene	390
Polyester	325
PVC/Vinyl Acetate	327/364
Polyvinyl Acetate	280
Cellulose Acetate Butyrate	295/298
Styrene Acrylonitrile (Film)	290/325
Polycarbonate	285/305
	330/360
Polyvinyl Chloride	320

EFFECT OF HIGH RADIANT INTENSITIES OF VERY LOW-WAVELENGTH ULTRAVIOLET

UV in 285 to 295nm Region

- ▶ **Un-natural photochemistry, particularly if a polymer's action spectrum peaks near 300 nm wavelength, and is strong in the 290 nm region.**
- ▶ **Effects may be intense and confined to the outer surface layers of a polymer. This can result in subsequent filtering of more penetrating, longer-wavelength ultraviolet radiation (thus passivating the surface)**

ACCELERATED TESTING

Test Philosophy

- ▶ Accurately simulate multiple element environment
- ▶ Highly aggressive, worst case

Methodology

- ▶ Deterministic approach
- ▶ Probabilistic approach

FACTORS NECESSARY FOR CORRELATION BETWEEN ACCELERATED AND NATURAL TESTS

Single Material

- ▶ **Difference in property retention between two tests independent of stress level**
- ▶ **Agreement in property retention at more than one stress level**
- ▶ **Agreement with respect to more than one property**

FACTORS NECESSARY FOR CORRELATION BETWEEN ACCELERATED AND NATURAL TESTS

Groups, or Set, of Materials

- ▶ Results should exhibit few, if any, reversals between indoor accelerated and natural outdoor tests
- ▶ General agreement in property retention values at equal stress levels
- ▶ General agreement in more than one property of interest highly desirable

FAILURE TO CORRELATE ACCELERATED WITH NATURAL EXPOSURE TESTS

Equipment/Design Considerations

- ▶ Significant mismatch between UV source and sunlight below 300nm wavelength
- ▶ Mismatch between source spectra and a plastic's action spectra
- ▶ Ultraviolet burner, or lamp deterioration
- ▶ Solarization of spectrum-modifying filters
- ▶ Inadequate control of specimen temperatures
- ▶ Lack of uniformity of test conditions within the test chamber
- ▶ Reciprocity failures in devices exhibiting high-intensity ultraviolet irradiance

FAILURE TO CORRELATE ACCELERATED WITH NATURAL EXPOSURE TESTS

- ▶ **Incorrect choice of property measurements**
- ▶ **Inaccurate property measurements**
- ▶ **Insufficient frequency of property measurements**
- ▶ **Inaccurate measurement, control or monitoring of environmental parameters**
- ▶ **Inadequate or incorrect analysis of otherwise satisfactory data**

**Analysis and Measurement Techniques Used
to Evaluate Weathering Effects**

Category I Analytical, Diagnostic Techniques	Category II Engineering Property Tests
<ul style="list-style-type: none"> • Spectroscopic <ul style="list-style-type: none"> - Infrared - UV-VIS-NIR - NMR - ESR - ESCA - MS - ATR - Transmittance - Reflectance 	<ul style="list-style-type: none"> • Colorimetric/Appearance <ul style="list-style-type: none"> - Gloss - Color Difference - Spectrocolorimetry - Yellowness - Haze - Chalk
<ul style="list-style-type: none"> • Chromatographic <ul style="list-style-type: none"> - Gas - Liquid 	<ul style="list-style-type: none"> • Mechanical <ul style="list-style-type: none"> - Tensile - Flexural - Impact - Abrasion - Craze - Tear
<ul style="list-style-type: none"> • Thermal Analysis <ul style="list-style-type: none"> - TGA - DSC - DTA - TMA - DMA 	<ul style="list-style-type: none"> • Spectral Optical <ul style="list-style-type: none"> - Absorbance - Transmittance - Reflectance
<ul style="list-style-type: none"> • Microscopic <ul style="list-style-type: none"> - TEM - SEM/EDX - Optical 	

Application of Analytical and Diagnostic Techniques

Technique/Instrument	Application	Sample Requirements
Spectroscopic		
Infrared	Surface Chemical Structure Bulk Chemical Structure	Thin Film Thin Film or Solution
UV/VIS/NIR	Surface Properties Bulk Composition	Thin Film or Sheet Thin Film or Solution
NMR	Molecular Structure	Solution
ESR	Chemical Structure	Solution or Solid
ESCA	Surface Chemical Composition	Thin Film
MS	Chemical Structure Molecular Structure Chemical Composition	Liquid, Gas, or Solid
Chromatographic	Chemical Composition	Liquid or Gas
Thermal Analysis		
TGA	Chemical Composition	Powder or Granule
DSC	Molecular Structure	Powder or Granule
DTA	Molecular Structure	Powder or Granule
TMA	Molecular Structure	Thin or Thick Film
DMA	Molecular Structure	Thin or Thick Film
Microscopic		
SEM/EDX	Surface Structure	Film or Powder
TEM	Surface Composition	Film or Powder
Optical	Surface Structure	Thick or Thin Film

ACCEPTABLE DEGRADATION

**DIFFICULT TO DISCERN BETWEEN THIS CONDITION AND THE
LONG INDUCTION CATASTROPHIC FAILURE CONDITION**

LM Xenon Weathering Device

EMMAQUA®+ Test Field

SCHMATIC OF EMMAQUA[®] OUTDOOR ACCELERATED WEATHERING DEVICE

Super-Maq® Accelerated Outdoor Exposure Device

Xenotest® LM Xenon Weathering Device

"Mini" PV Modules Exposed on Super-Maq®

Xenotest® LM Test Chamber

A Spectral Comparison of Natural Sunlight vs. EMMAQUA®

Suntest® CPS Tabletop Xenon Weathering Device

- XENON-Strahler
- 2 UV-Spiegel
- 3 Licht-Spiegel
- 4 Quarzglasschale mit selektiv-reflektierender Schicht
- 5 Zusatzfilter aus UV-Spezialglas oder Spezial-Fensterglas
- 6 Parabolreflektor
- 7 Probenebene

- 1 XENON burner
- 2 Ultra-violet mirror
- 3 Light mirror
- 4 Quartz glass dish with selective reflecting coating
- 5 Supplementary filter made of special ultra-violet glass or special window glass
- 6 Parabolic reflector
- 7 Specimen plane

Cross Section of the Suntest® Optical System

Control Panel for the EMMAQUA®+

EMMAQUA®+ Spray Cycle

- 1 Filter system
- 2 Absorber
- 3 Xenon long-arc light source

Cross Section of the Xenotest® LM Optical

SystemXenotest® LM Spectral Energy Distribution

**Xenotest® Alpha HE High Irradiance
Exposure Device**

Chamber of ALPHA HIGH ENERGY

Heraeus
INSTRUMENTS

Principle of the XENOCHROME filter system in ALPHA HIGH ENERGY

Heraeus
INSTRUMENTS

Absorber

Filter

Xenon Ω -lamp

UV + VIS radiation

IR radiation

Absorber

Filter

dielectric
filter coating

Xenon Ω -lamp

Filter System: XENOCHROME 300

***Irradiance in XENOTEST® ALPHA HE
for various filters***

EVA DEGRADATION MECHANISMS: REVIEW OF WHAT IS AND IS NOT KNOWN

A.W. CZANDERNA

**Measurements and Characterization Branch
National Renewable Energy Laboratory
Golden, Colorado**

**PV Performance and Reliability Workshop
Golden, Colorado**

September 8-10, 1993

OUTLINE

Introduction/Background

- What is EVA? (A9918 and 15295)
- What is the Problem?

What is Known About EVA Degradation?

- Before 1987 and Now

What is Not Known About EVA Degradation

MAJOR POINTS

- **Module durability is more than an EVA problem**
- **EVA degradation is not new -- what is known**
- **What is not known about EVA degradation**

PURPOSE -- MATERIALS SYSTEMS

- Provide mechanical support for solar cells
- Facilitate maximum optical coupling -- sun/cells
- Isolate cells from degrading environmental factors (reactive elements/compounds, soiling, hail, etc.)
- Provide electrical isolation for solar cells
- Provide ancillary electrical circuitry for cells
- Emphasize low cost -- Maintain function for 30 YEARS
- i. e., All necessary functions except that of cell itself.

FAILURE MODES -- EARLY WORK

- R • Delamination at interfaces
- R • Penetration of liquid water
- R • Short circuit -- arcing
- R • Cracking of solar cells -- T_{EXP}
- R • Cell interconnect failures -- $T_{CYCLING}$
- R • Charring and melting of solder -- High T
- D • Soiling
- D • Weathering and physical degradation

REACTIONS/PROCESSES THAT LIMIT ENCAPSULANT DURABILITY (Not Including Edge Seals)

POLYMERS AS A PV MODULE ENCAPSULANT

- The Reality!

ENCAPSULATION STABILITY

- Multilayer stack on either side of active device material
- Extremely complex to predict -- large number of variables
 - T effects including cyclic T
 - UV degradation -- Photothermal
 - Concentration of H₂O, O₂, and other gases
 - Interface reactions/interdiffusion
 - Compositional effects --- impurities
 - Electric field influences
 - Slow time-dependent effects (requires ALT)

SIMPLIFIED SCHEMATIC OF THE MECHANISM OF PHOTOTHERMAL DEGRADATION

R = Polymer

- UV - wavelength? Intensity (W/m²)
- Catalytic effect of degradation products.
- Exposure time for permanent damage?
- Synergistic influences from UV, T, ΔT , H₂O, gases, impurities?
- Distribution of copolymer blocks.

PHOTOOXIDATION USUALLY RESULTS IN:

- Deterioration of optical properties
- Deterioration of mechanical properties
- Reduction in tensile strength (TS)
- Reduction in elongation (e), i.e., more brittle
- Reduction in transparency (Willis, 1986, VII-1).

POLYMER DEGRADATION CAN BE MEASURED BY CHANGES IN PROPERTIES

- **Mechanical:** tensile strength, elongation, gel content, modules
- **Optical:** UV-vis (300 to 1100 nm), fluorescence
- **Chemical:** [stabilizer]. [outgassing products]. interconnect corrosion
- **Dielectric:** E field stress, leakage current, electrical isolation

CONSEQUENCE OF PHOTODEGRADATION OF EVA

- Scission: decrease polymer chain length/molecular weight
- Cross-linking: increase networking of polymer chains
 - => change mechanical properties
- Formation of long polyconjugated C=C bonds
 - => increased light absorption
 - => reduced optical transmission
 - => luminescence
 - => cross-linking

GENERAL FACTORS AFFECTING PERFORMANCE OF EVA STABILITY

- Polymer/cover interface degradation
- Bulk polymer degradation
- Polymer/cell interfacial degradation

POTTANT/INTERFACES STABILITY

- Thermodynamically unstable -- always in higher G state
- Always want a lower energy surface
- "Stability" depends on kinetic processes: composition
- At any T (or set of degradation parameters), ONE reaction usually predominates
- Typically, many reaction paths with different E_A .

EVA: WHAT IS THE PROBLEM?

- **Observed Degradation in the Field?**
- **Locations of Observed Degradation?**
- **Observed Degradation in the Laboratory?**

EFFECTS OF EVA YELLOWING

- Reduced optical transmission on EVA
- Reduced power output of PV modules
- Acidic corrosion of metallic circuits
- Acidic corrosion of solar cells
- Enhanced M^{n+} -catalyzed photodegradation
- Reduced service life of PV modules

DEGRADATION IN THE FIELD

- **Color changes - Yellow to Brown**
- **No color changes - Areas remain clear**
- **Evidence for Gas Bubbles**
- **Metalization Corrosion - Acetates**
- **Location Specific Degradation/Stability (Apparent)**
- **Massive Disaster - Rare**

OVERALL STRATEGY -- SOLVING THE EVA PROBLEM

- Understand why EVA is degrading
- Use/develop analytical capabilities
- Develop collaboration/cooperation with PV Manufacturers
- Expand effort for securing a better pottant and more stable encapsulated PV module systems

RECENT HISTORY – YELLOWING OF EVA COPOLYMER

- 1984, SWRES, light yellow, 4 years after installation, one mfg.
- 1988, Carrisa Plains, 2.5 years after installation, mirrors; Schaefer
- 1990, (Feb.), Meeting at SERI to discuss EVA "crisis"; many
- 1990, (Oct.), EVA degradation at Carrisa; Rosenthal/Lane
- 1991, Less but increased browning of Segment 10, Carrisa; Schaefer
- 1992, SMUD, Phoenix, Albuquerque, Cape Canaveral, Morocco, Australia, Namibia, Saudi Arabia, Israel in addition to the above, Pern/Czanderna
- 1993, More examples continue to be reported

WHAT IS EVA?

- Copolymer with 33% Vinyl Acetate
- Added ingredients?

DU PONT ELVAX 150; SPRINGBORN A - 9918; EVA

NORRISH MECHANISMS

PREDOMINANT (II)

CHROMOPHORE

Acetic Acid

(III)

CHROMOPHORE

ACETALDEHYDE

(I) UV/T

Acetaldehyde

Methane

POLYENE, $m = 3$, LIGHT YELLOW, 3 DEACETYLATIONS

$\downarrow O_2$ POLYENE OXIDATION

PEROXIDE

$\downarrow -H_2O$

CHROMOPHORE (UNSATURATED CARBONYL)

PHOTOOXIDATION
WILL REDUCE
MW OF
POLYMER

FORMULATION/STABILIZATION OF ELVAX 150 (EVA COPOLYMER) AND COMMENTS

- UV absorber [Cyasorb UV 531] – ~ 90% effective as UV absorber
- Anti-photo oxidant [Tinuvin 770] – Important to lifetime of UV 531
- Anti-thermal oxidant [Naugard P]
- Curing agent [A9918-Lupersol 101] — "slow cure," ~ 50 min.
[15295 -Lupersol TBEC] – "fast cure," ~ 7 min.
(Cure time, of course, is T dependent)
- UV screen between cover/EVA – rarely used since early 1980s

WHAT IS KNOWN ABOUT EVA DEGRADATION AS OF DECEMBER 1992?

- Degradation in the Field-Yellowing
- Laboratory Studies/Mechanisms
 - Thermal (EVA)
 - Photothermal (EVA)
 - Acetic Acid Catalyzed (EVA)
 - Cyasorb Loss
 - Photobleaching (Photo-Oxidation)
 - Metal Ion Catalyzed

Glass		
yellow clear clear	yellow yellow clear	yellow-brown yellow-brown yellow-brown
		E V A
Grid	And	Cell Material

Reference 8

EVA DEGRADATION: LABORATORY STUDIES

- **Fluorescence Analysis**
- **UV-vis**
- **Gel Content**
- **HPLC (Now in Process)**
- **Colorimeter Studies (Future)**
- **Electrical Performance (Minimodules)**
- **FT-IR**
- **Simulation**

BA-G0703003

SINGLE CELL

FA

Reference 8

Fluorescence Analysis of EVA and other Polymers

NREL has demonstrated the broad-based scientific and applications potential of using fluorescence analysis (FA) of encapsulant polymers for PV modules. The most useful mode of FA is to excite a polymer with radiation (typically 350 nm) and scan the emitted radiation from 350 to 700 nm. The FA detects chromophores, which result from structural changes in polymers that may be visibly discernible (e.g., yellowed or yellow-brown EVA) or may not be detectable to the eye (e.g., during processing steps). The accompanying figure shows the marked changes in emission spectra from clear to severely degraded EVA. The potential for using the noninvasive, nondestructive FA for measuring the extent of EVA degradation with a simple portable unit is obvious (i.e., excite at 350 nm, detect at 550 nm). NREL scientists have also shown that FA can be applied to discolored PVF as well as EVA and that the similar degradation mechanisms occur in both polymers. They have also shown that the various EVA processing steps of compounding, extruding, curing, and laminating can produce a different number of residual chromophores. The latter undoubtedly serve as the first stages of subsequent UV-induced degradation. Thus, FA has obvious potential for optimizing the EVA processing sequence (to yield a minimum number of undesired residual chromophores) as well as for being used for on-line quality control of the final PV laminated modules. The scientific value of FA for understanding the structural changes in EVA during degradation and

polyene formation was addressed in a recent paper in *Polymer Degradation and Stability* by F.J. Pern (NREL/TP-213-4605). A copy of this paper, its implications as given above, and an offer to PV manufacturers to send samples to NREL for analysis was sent to Solarex, Mobil Solar, Siemens, USSC, Solar Cells, Inc., and UPG in December, 1992, by A.W. Czanderna.

Reference 9

Synchronous fluorescence spectra of EVA in solar cells simulation-degraded at 85C
for 198 days

Percent changes of solar cell performance parameters after treatments

Treatment at 85+-2C	Cell Type	Days	Voc	Isc	FF	Effi.	EVA Color
OVEN	1"x4" c-Si	198	0.4	-2.2	-0.7	-2.5	light-yellow
	4"x4" c-Si	198	-0.2	-3.5	0.7	-3.1	light-yellow
	2"x4" pc-Si	198	-0.3	-0.5	-2.4	-3.1	light-yellow
	2"x2" a-Si	136	-1.7	1.2	1.0	0.4	light-yellow
	2"x2" a-Si	155	(cell breakdown)				light-yellow
RS4-UV	1"x4" c-Si/oc	198	-1.1	-9.3	0.2	-10.1	brown
	2"x4" pc-Si/sc	198	-1.7	-8.6	-5.6	-15.2	brown
	2"x4" pc-Si/oc	198	-1.5	-13.2	-2.8	-19.3	brown
	2"x2" a-Si/oc	136	-4.1	-33.8	-1.7	-37.6	yellow-brown
		155	(cell breakdown)				yellow-brown
IR Lamp	4"x4" c-Si	208	7.6	-1.8	3.0	8.8	clear
Measurement Error Range (+ -)			2	1	2	2	

oc: open circuit sc: shorted circuit

File: c:\Excel\Tests\Set1-Sum.XLS 9/13/92 John Pern

Reference 3

What happened to the EVA during degradation:

Photothermal oxidation ==> Loss of UV absorber and Gel% increase

==> Deacetylation ==> Formation of long polyenes ==> Discoloration

Luminescent chromophores in degraded EVA:

	$-(C=C)_m-C=O + -(C=C)_n-$		Color
Extent of	$m > 3 \sim 6$	$n > 3 \sim 6$	light yellow
Discoloration (Degradation)	$m > 6 \sim 13$	$n > 6 \sim 13$	dark brown

DEGRADATION STRESSES

- Thermal (T aging) both in air and inert atmospheres and hot spot Ts
- UV (the UV insolation should match the solar spectrum)
- Hydrolytic (water vapor)
- Catalytic (metal ion catalyzed)
- Reaction products (increased concentrations may catalyze)
- Combined, all of the above

SIGNIFICANT QUOTES FROM THE LITERATURE

- "For Elvax 150, the onset of acetic acid loss is also affected by the presence of air oxidation and proceeds at lower temperatures than in an inert atmosphere." [Willis, 1986, VII-10]
- -[HOAc] at 200°C in air but 340°C in nitrogen
- -[HOAc] for EVA A9918 is the same as for Elvax 150
- "If the EVA was sustained continuously at 85-90°C for 20 years in the absence of oxygen and water vapor, this would correspond to a net conversion of only 0.006% of the acetate groups into acetic acid."
- "A hermetic design would isolate the EVA from ...oxygen and water..."
- "A problem associated with acetic acid generation over 30 years appears remote". [Willis, 1986, VII-14]

Conclusions from all results obtained up to date:

A competition exists between the formation and bleaching of yellow EVA (i.e., polyenes) in field-deployed PV modules. Increase in the degree of cross-linking appears to be favored by exposure to the light at higher temperatures. Depletion or loss of Cyasorb UV 531 may be effected by photodecomposition and thermal diffusion via temperature gradient (over the solar cells) and is enhanced by the increased cross-linking. Acetic acid and other organic components are generated by exposure to the light and heating. Formation of polyenes will exceed bleaching when depletion of [Cyasorb] and accumulation of [acetic acid] are substantial. Yellowing of the EVA appears to be favored by higher operating temperatures of PV modules.

EVA DEGRADATION MECHANISMS THAT ARE KNOWN

- Deacetylation of vinyl acetate pendant group results from T or UV
- Photothermal (T and UV) produces acetic acid and polyenes $\text{--}(\text{--C=C--})_m\text{--}$ (Higher T, UV flux and more energetic UV gives yellow to dark brown)
- Increased [acetic acid] catalyzes the photothermal degradation
- Oxidation of polyenes produces keto-chromophores (photobleaching)
- Cyasorb UV 531 photodecomposes (but details are not known)
- Degradation products are HOAc, CH₃CHO, CO₂, CO, CH₄, H₂O, etc.

EVA DEGRADATION – WHAT IS KNOWN FROM FIELD EXPOSURE AND/OR LAB TESTING

- UV >> Temperature alone
- Loss in performance results from discoloration (yellow to brown).
- Metallization and bus lines corrode; acetates and oxides identified (no mechanistic details)
- Some metal cations catalyze an increased rate of photothermal degradation near interfaces (Cu^{++} >> anything else, Willis)
- Qualitative (and some quantitative) data support KNOWN mechanisms.

WHAT IS KNOWN ABOUT EVA STABILITY/ DEGRADATION

- Molecular composition assures degradation will occur in the sun or in the dark at higher temperatures (UV/T synergism)
- Stability depends on location and climate although details are not known
- Degradation fastest @ high T, high UV flux, short wavelengths (e.g., hot, dry climates in the southwest USA and Africa)
- Degradation slowest @ lower T, lower UV flux, less short wavelengths (e.g., cool, wet or dry climates in the northeast and central USA)
- Thus, rate of degradation depends on season and time of day
- Thicker films take longer to yellow throughout
- Closed module design permits an increase [acetic acid], an accelerator
- Unfortunately, stability is poorest at locations where economics is best

EVA DEGRADATION MECHANISMS

Variables		Mechanism or Possible Mechanism	
1.	T, [O ₂ , H ₂ O]	Thermal oxidative degradation	Well-studied
2.	UV, T, []	Photothermal oxidative degradation	Few studies
3.	M ⁺ , T, []	Metal-ion-catalyzed thermal oxidative degradation	Not studied*
4.	M ⁺ , UV, T, []	Metal-ion-catalyzed photothermal oxidative degradation	Not studied*
5.	M _g ⁺ , UV, T, []	Surface-M ⁺ -catalyzed thermal of PT oxidative degradation	Not studied
6.	i flow in M plus 1-5	i induced migration or e ⁻ injection plus other mechanisms 1-5	Not studied
7.	[O ₂ , H ₂ O] effects	1.-6 but [] dependence	Minimal in 1. and 2.
8.	[Original formulation]	1.-7 but [] additives	Minimal in 1. and 2.
9.	Electrochemical processes plus 1-6	Related to 6. and [H ₂ O]	Not studied
10.	As 1. 2. but Hot T	Any part of 1.-6. but initiated at hot spots	Isolated studies
11.	Effect of pin-holes or areas of high resistance		

WHAT IS NOT KNOWN – EVA DEGRADATION MECHANISMS RESULTING FROM:

- Different magnitudes of UV (and energies) and temperature (any changes?)
- Different concentrations of O₂, H₂O, other gases, plus the above (PA)
- Different additive, residual chromophores or initiators (Lupersol),
- Poor adhesion at interfaces (role of adhesion primer)
- Metal cations from (oxide) interfaces in the modules PA
- Contact with different metal (oxide) surfaces PA
- E field induced migration or e- injection PA
- Electrochemical processes at metallization interfaces PA
- Residual Damage from hot spots PA

INFLUENCES ON EVA STABILITY WHAT IS NOT KNOWN – RAW MATERIALS AND FABRICATION OF PV MODULES

- Supplier of the raw materials (kind and composition – impurities)
- Variations in distribution of vinyl acetate blocks in Elvax 150
- Variations in formulations ([Cyasorb], Lupersol 101, (TBEC), primer)
- Processing variables used (Manufacturer Sensitive) during cure
- Cell design (grid pattern, metallization, bus line, and interconnects)
- Module design (glass/polymer superstrate, edge seal, hermetic?)
- Flaws during fabrication that cause long term problems (hot spots)
- Mounting (does it cause T increase?)

EVA STABILITY

WHAT IS NOT KNOWN – REAL TIME TESTING OF PV MODULES (FIELD EXPOSURE)

- UV insolation data, both W/m^2 and wavelength distribution
- Accurate module operating temperatures (T_s) and time at T_s
- Quantitative measures of degradation (degree of yellowing as well as degradation that occurs without yellowing)
- Time to yellow (see above), and proof the yellow is from polyenes
- Time to failure (how is "failure defined?"; i.e., what efficiency loss?)
- Correlation between yellowing, degradation, and power loss?
- Effects of degradation products on module performance **other than optical** (e.g., bus lines, metalization, interconnects, balance of systems)
- Degradation on mechanical, electrical, and other physical properties
- Influence of property changes in EVA on the RATE of further degradation.

TABLE 1. Data Set: Photooxidation Reaction
Scheme and Activation Parameters

Reaction matrix		A	E kcal/mol
1.	Ketone $\longrightarrow$ KET [*]	0.70×10^{-9}	0
2.	KET [*] $\longrightarrow$ SMRO ₂ + SMRCO	0.00×10^0	0.0
3.	SMRCO $\longrightarrow$ SMRO ₂ + CO	0.00×10^{17}	15
4.	KET [*] $\longrightarrow$ Alkene + SMKetone	0.04×10^0	2.0
5.	SMKetone $\longrightarrow$ SMKET [*]	0.70×10^{-9}	0
6.	SMKET [*] $\longrightarrow$ SMHO ₂ + CH ₃ CO	0.32×10^{13}	0.8
7.	SMKET [*] $\longrightarrow$ Alkene + Acetone	0.04×10^0	2.0
8.	ROOH $\longrightarrow$ RO + OH	0.12×10^0	0
9.	RO ₂ + RH $\longrightarrow$ ROOH + RO ₂	0.10×10^{10}	17.0
10.	SMHO ₂ + RH $\longrightarrow$ SMROOH + RO ₂	0.10×10^{10}	17.0
11.	SMROOH $\longrightarrow$ SMRO + OH	0.13×10^{-9}	0
12.	SMRO + RH $\longrightarrow$ SMROH + RO ₂	0.10×10^{10}	0.2
13.	RO + RH $\longrightarrow$ ROH + RO ₂	0.16×10^{10}	0.2
14.	RO $\longrightarrow$ SMHO ₂ + Aldehyde	0.32×10^{16}	17.4
15.	KET [*] + ROOH $\longrightarrow$ Ketone + RO + OH	0.25×10^{10}	11.0
16.	SMKET [*] + RCOH $\longrightarrow$ SMKetone + RO + OH	0.25×10^{10}	11.0
17.	SMHCO + O ₂ $\longrightarrow$ SMHCOOO	0.00×10^{14}	0.0
18.	SMRCO + RH $\longrightarrow$ RO ₂ + Aldehyde	0.10×10^{10}	7.3
19.	SMHCOOO + RH $\longrightarrow$ SMHCOOOH + RO ₂	0.10×10^{10}	17.0
20.	SMHCOOOH $\longrightarrow$ SMHCOO + OH	0.13×10^{-9}	0
21.	SMHCOO $\longrightarrow$ SMHO ₂ + CO ₂	0.10×10^{10}	0.0
22.	SMHCOO + HII $\longrightarrow$ Acid + H ₂	0.10×10^{10}	17.0
23.	OH + RH $\longrightarrow$ RO ₂ + Water	0.10×10^{10}	0.0
24.	CH ₃ CO + RH $\longrightarrow$ RO ₂ + CH ₃ CHO	0.10×10^{10}	7.3
25.	CH ₃ CO + O ₂ $\longrightarrow$ CH ₃ COOO	0.00×10^{14}	0.0
26.	CH ₃ COOO + RH $\longrightarrow$ CH ₃ COOOH + RO ₂	0.10×10^{10}	17.0
27.	CH ₃ COO + RH $\longrightarrow$ CH ₃ COOH + RO ₂	0.10×10^{10}	17.0
28.	KET [*] $\longrightarrow$ Ketone	0.10×10^0	0
29.	SMKET [*] $\longrightarrow$ SMKetone	0.10×10^0	0
30.	KET [*] + O ₂ $\longrightarrow$ Ketone + SO ₂	0.00×10^{10}	0.0
31.	SMKET [*] + O ₂ $\longrightarrow$ SMKetone + SO ₂	0.00×10^{10}	0.0
32.	RO ₂ + RO ₂ $\longrightarrow$ ROH + Ketone + SO ₂	0.25×10^{10}	11.0
33.	RO ₂ + ROH $\longrightarrow$ ROOH + Ketone + HOO	0.10×10^{10}	15.3
34.	HOO + RH $\longrightarrow$ ROOH + H ₂	0.32×10^0	15.0
35.	HOO + RO ₂ $\longrightarrow$ ROOH + SO ₂	0.32×10^0	2.1
36.	RO ₂ + Ketone $\longrightarrow$ ROOH + PeroxyCO	0.13×10^0	0.0
37.	PeroxyCO + RH $\longrightarrow$ PEROOH + H ₂	0.10×10^{10}	17.0
38.	PEROOH $\longrightarrow$ PERO + OH	0.13×10^{-9}	0
39.	PERO + RO ₂ $\longrightarrow$ DKetone + ROOH	0.25×10^{10}	11.0
40.	RO ₂ + ROOH $\longrightarrow$ ROH + Ketone + OH	0.25×10^0	11.0
41.	RO ₂ + SMROH $\longrightarrow$ ROH + Aldehyde + HOO	0.10×10^{10}	15.3
42.	RO ₂ + Aldehyde $\longrightarrow$ ROH + SMRCO	0.25×10^{10}	11.0
43.	RO ₂ + RO ₂ $\longrightarrow$ ROH + SO ₂	0.36×10^{13}	10.0
44.	SO ₂ $\longrightarrow$ O ₂	0.02×10^0	0
45.	SO ₂ + Alkene $\longrightarrow$ ROOH	0.20×10^{14}	10.0
46.	RO ₂ + Alkene $\longrightarrow$ Branch	0.10×10^0	11.0
47.	SMRO ₂ + Alkene $\longrightarrow$ ROOH	0.10×10^0	11.0
48.	RO ₂ + QH $\longrightarrow$ ROOH + Q	0.10×10^0	5.2
49.	KET [*] + QI $\longrightarrow$ Ketone + Heat	0.00×10^{13}	0.0
50.	ROOH + QU $\longrightarrow$ PHOUS	0.00×10^{13}	0.0
51.	ROOH $\longrightarrow$ H ₂ O + OH [*]	0.02×10^{15}	25
52.	SMROOH $\longrightarrow$ SMRO + OH	0.02×10^{15}	25
53.	SMHCOOH $\longrightarrow$ SMHCOO + OH	0.02×10^{15}	25
54.	CH ₃ COOOH $\longrightarrow$ CH ₃ COO + OH	0.02×10^{15}	25

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HOW SHOULD "FAILURE" BE DEFINED FOR A PV MODULE

- What loss in efficiency is tolerable?
- Over what period of time in years?

IS THERE A FUTURE FOR EVA?

- For what module lifetime?
- For what module performance efficiency after x years?

TO ASSURE SUCCESSFUL LIFETIME PREDICTIONS, WHAT IS NEEDED FROM

- Fundamental understanding?
- Mechanisms of degradative reactions?
- Testing of components, materials only, complete minimodules, complete modules, and complete systems?
- Characterization and analysis? Before, during, and after testing?
- Time-dependent power loss from degradative reactions

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Modification of EVA Formulation For Improved Stability

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Golden, Colorado**

Objectives

1. To investigate the photothermal stability of UV absorbers and determine the stabilization effectiveness of individual stabilizer
2. To identify the good candidates of stabilizers, polymer materials, and superstrates for modified EVA formulations, new formulations, and encapsulation.
3. To compare normal (~ 1 sun) exposure and accelerated exposure

EPMA Composition Analysis for the New and Exposed Buses

Sample Source PV module #	Solar cell Location	Side of Bus-line	EVA Color	Normalized Atom%			
				Pb-M	Sn-L	Cu-L	O-K
New bus				39.52	60.48		
Carrizo 1B	L9,R2	EVA	light yellow	10.96	68.57	5.35	15.12
Carrizo 309259	L9,R2	EVA	brown	41.13	5.80	13.27	39.80
Carrizo 309262	L9,R2	EVA	dark brown	15.91	30.60	20.41	33.08
Carrizo 309262	L7,R3	EVA	dark brown	46.56	4.62	8.08	40.74

Auger Depth Profile Analysis

361

5. $\text{PO}_2\cdot + \text{PO}_2\cdot \text{----> POOP} + \text{O}_2$ **Chain Termination**
 $\text{----> PO}\cdot + \text{PO}\cdot + \text{O}_2$
 $\text{----> Inactive Products} + \text{O}_2$
 $\text{P}\cdot + \text{PO}_2\cdot \text{----> POOP}$
 $\text{P}\cdot + \text{P}\cdot \text{----> P-P}$

Principles of Stabilization

Chemical Methods

1. To reduce/block the Rate of Chain Initiation

- => reduce UV excitation of chromophores
- => deactivate excitation states

use UV screens or absorbers
use quenchers

2. To reduce/block the Rate of Chain Propagation

- => intercept/neutralize free radicals

(Primary/Chain-breaking antioxidants)

use free radical scavengers

3. To reduce/block the Rate of Chain Branching

- => reduce the formation of free radicals

(Secondary/Preventive antioxidants)

use hydroperoxide decomposers

Stabilizers used in EVA Formulations (A9918 & 15295):

Cyasorb UV 531	(0.3 wt%)	UV absorber & Quencher
Naugard P	(0.2 wt%)	Hydroperoxide decomposer (Processing anti-oxidant)
Tinuvin 770	(0.1 wt%)	Free radical scavenger (UV light stabilizer)
Lupersol 101 or TBEC	(1.5 wt%)	Peroxide, thermal cross-linking agent
Typical thickness of laminated/cured EVA films:		~0.46 mm

Design of Experiments

Investigate the photostability of UV absorbers (UVA) as an indication of free radical-induced degradation mechanism and the stabilization effectiveness of individual stabilizer.

Samples:

1. Solution phase (cyclohexane)
2. Thin film phase (in Elvax 150)

Compositions:

UVA (e.g., Cyasorb UV 531)

UVA + anti-oxidant (e.g., Naugard P)

UVA + free radical scavenger (e.g., Tinuvin 770)

UVA + anti-oxidant + free radical scanvenger

Compounds studied:

UV absorbers:

Cyasorb UV 531, Ciba-Geigy's Tinuvin family

Free radical scavengers:

Ciba-Geigy's Tinuvin, Irganox, and Chimassorb families

Anti-oxidants:

Naugard P, Ethanox 398, Irganfos 168

Sample Preparation

1. Cyclohexane solutions of Elvax 150 mixed with various stabilizers of pre-determined concentrations
2. Thin films in cuvettes made from cyclohexane solutions in (1)
3. Oven-treated at $\sim 75^{\circ}\text{C}$ for ~ 30 min to settle the films before exposure

Exposure Conditions (UV ≥ 290 nm):

- a). DSET Suntest CPS tabletop system: ~ 1-Sun Exposure
(for many thin film samples per run) UV-filtered 1.8-KW Xe arc lamp light,
~ 770 W/M² (300 nm - 800 nm),
55-60°C BPT (black panel temperature)
- b). Oriel 1-KW Xe light source: Accelerated Exposure
(for one solution sample per run) UV-filtered with aq. CuSO₄ and a LP 305 nm,
light beam was condensed to ~ 1" diameter,
Very intense light, 55-60°C BPT

Analysis:

UV-vis absorption to monitor [UVA] as a function of exposure
Methanol and/or THF solvent extraction after exposure
Spectral data analysis

Photodecomposition of [Cyasorb] = 4.50×10^{-5} M, [Elvax] = 0.56 mg/mL

in cyclohexane solution exposed to a concentrated 1KW Xe

(filtered with aq. CuSO_4 /LP 305nm) for 7.25 h

Stabilization Mechanism of Cyasorb UV 531

Photodecomposition of Cyasorb UV 531

UV, O₂

Substituted benzene compounds
(structure unidentified)

Photodecomposition of Cyasorb in cyclohexane solutions by a condensed, (CuSO₄ + LP305nm) filtered 1KW Xe light at 55-60C

Photodecomposition of Cyasorb in Elvax film by a concentrated 1-KW Xe light at 55-60C

Photodecomposition of Cyasorb in Elvax 150 Film by DSET's 1.8-KW Xe light at 55-60°C

Photodecomposition of Cyasorb in Elvax film by DSET's 1.8-KW Xe light at 55-60C
 $[\text{Tin-770}]/[\text{Cyasorb}]=R$, $[\text{Naugard}]/[\text{Cyasorb}]=K$

Photostabilization of Benzophenone-type UV absorber in Elvax Thin Films
Exposure: DSET 1.8-KW Xe, 55-60°C, 1200 h

Photodecomposition of Benzotriazole-type UV Absorbers in Elvax Thin Films
Exposure: DSET 1.8-KW Xe, 55-60°C, 1200 h

Conclusions:

- A. Photodecomposition of Cyasorb UV 531 (UV absorber) in cyclohexane solutions and Elvax 150 films is significant, resulting in substituted-benzene compounds.

All UV absorbers including Cyasorb promotes large gel formation (cross-linking) of Elvax 150 when used alone.

Tinuvin 770 (free radical scavenger) stabilizes Cyasorb effectively and prevent gel formation. But Tinuvin 770 at high concentration will not stabilize Cyasorb.

Naugard P delays but does not stabilize Cyasorb from photodecomposition.

Stabilization effect of Tinuvin 770 and Naugard P on Cyasorb is synergistic.

- B. Improved photothermal stability of current EVA formulations can be achieved by using the three key stabilizers with their concentrations properly balanced.

Similar improvement can be obtained by using other stabilizers with Cyasorb UV 531.

Benzophenone-type (e.g., Cyasorb) UVA is better than benzotriazole-type UVA for EVA.

- C. Accelerated exposure is useful to determine the photostability of a trial formulation in a relatively short period of time.

Whether a well-correlated acceleration factor can be established remains to be determined, although for thin film samples studied here, somehow similar photodegradation profiles of Cyasorb are obtained under normal and accelerated exposure conditions.

- D. **Future work:** (1) Test the photostability of thick films made with modified formulations, (2) Determine by HPLC analysis if Tinuvin 770 and Naugard P are also photodegraded.

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DOE contract no.: DE-AC02-83CH1009

Durability of Photovoltaic Modules at the Southwest Region Experiment Station Las Cruces, New Mexico

Andrew L. Rosenthal

September 1993

*Southwest Technology
Development Institute*

Southwest Region Experiment Station

- **Established by DOE funding in 1980**
- **3-acre test and evaluation facility located on the campus of New Mexico State University**
- **11 Prototype PV structures
30 kW of PV installed**
- **Operated by the Southwest Technology Development Institute (TDI)**

*Southwest Technology
Development Institute*

NREL/TDI Long-Term Module Evaluation Program

- **Part of NREL's Module Reliability Research Task**
- **Test program begun in May 1992**
- **Test program to run for 2 1/2 years**
- **Field work to be performed by TDI engineers**
- **Laboratory analyses to be performed by NREL scientists**
- **Goal:**
Help define the mechanisms and rates of module performance decline

*Southwest Technology
Development Institute*

Long-Term Module Evaluation Program

Selection Criteria

- **EVA encapsulated, Block V modules**
- **Diversity of PV materials: crystalline, polycrystalline, amorphous silicon**
- **Preference for modules with the longest cumulative solar exposure**
- **Preference for modules having documented history**
- **Modules Selected:** 1 crystalline
1 polycrystalline
2 amorphous silicon

*Southwest Technology
Development Institute*

Long-Term Module Evaluation Program

Test Plan

- **Select 12 modules from each array under test**
- **Develop dedicated hardware, establish test procedures**
- **Collect baseline performance data during May/June 1992**
- **Remove 2 modules from each array:**
 - 1 module returned to NREL for destructive analysis**
 - 1 module placed in storage**

*Southwest Technology
Development Institute*

Long-Term Module Evaluation Program

Test Plan (continued)

- **Collect IV curves of all modules every 2 weeks:
Archive the data**
- **Prepare quarterly reports of module IV data**
- **Remove modules for postmortem testing at NREL
(as required)**

IV Curve Data Limits of Error and Accuracy

	<u>Accuracy</u>	<u>Repeatability</u>
LiCor Pyranometer	$\pm 3\%$ (typ)	$\pm 1\%$
Current Shunt	$\pm 1\%$	$\pm 1\%$
Voltage Transducer	$\pm 1\%$	$\pm 1\%$
Thermocouple (type T)	$\pm 1^\circ\text{C}$	$\pm 2\%$
A/D Converter (14 bit)	$\pm 1\text{LSB}$ (1/16k)	$\pm 1\text{LSB}$ (1/16k)
	<hr/>	<hr/>
	$<\pm 5\%$	$<\pm 2\%$
<hr/>		
ASTM 1036	$\pm 3\% - 5\%$

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Module 42 -- Historical Data

Southwest Technology Development Institute

Module 33 -- Historical Data

Southwest Technology Development Institute

Module 6 -- Seasonal Comparisons

Module 6 -- Historical Data

Southwest Technology Development Institute

Module Performance/Reliability Discussion

Who needs module performance and reliability information?

- **Industry**
 - characterize their product
 - assess effects of design changes
 - warranty considerations
- **Research**
 - further the state of the technology
 - assist industry to provide better products
- **System Designers**
 - meet the needs of prudent system design
 - provide for worst case operating conditions
- **General Public**

TEAMED RESEARCH AND DEVELOPMENT ON
PVMaT, PHASE 3A - SHARED PROCESS ISSUES

Improved Non-discoloring Encapsulant for Flat Plate PV

JANUARY 1993 - DECEMBER 1995

For

NATIONAL RENEWABLE ENERGY LABORATORY
Under Subcontract ZAG-3-11219-02-105661

By

SPRINGBORN LABORATORIES, INC.

Enfield, Connecticut

SPECIFIC OBJECTIVES

- * BETTER DEFINE CAUSES OF EVA DISCOLORATION THRU STUDY
OF LITERATURE AND CASE HISTORIES IN THE FIELD
- * USING LAB STUDIES, DETERMINE PROBABLE MECHANISM(S) AND
ROLE OF HEAT, U.V., EVA GRADE, MODULE CONSTRUCTION, ETC.
- * DEVELOP "STABILIZATION STRATEGIES" FOR PROTECTING PV
ENCAPSULANT FROM DISCOLORATION
- * CONDUCT LAB. AND FIELD TESTING OF SMALL LAMINATES AND FULL MODULES
TO DEMONSTRATE "FUNCTIONAL ADEQUACY" OF IMPROVED ENCAPSULANTS
- * IMPLEMENT SUCCESSFUL STABILIZATION STRATEGIES BY INFORMATION
EXCHANGE AND MAKING IMPROVED ENCAPSULANT AVAILABLE TO INDUSTRY

PROGRAM SCOPE

YEAR ONE

- TASK 1 - SURVEY CASE HISTORIES OF EVA DISCOLORATION
- TASK 2 - FURTHER DEFINE PROBLEM THRU CONTROLLED LAB STUDIES
- TASK 3 - DEFINE DISCOLORATION MECHANISMS THRU ANALYSIS

YEAR TWO

- TASK 4 - DEVELOP STABILIZATION STRATEGIES TO REDUCE DISCOLORATION
- TASK 5 - CONDUCT ACCELERATED TESTING OF LAB-SIZE LAMINATES
- TASK 6 - EXTRUDE PILOT QUANTITIES OF PROMISING ENCAPSULANT SHEET

YEAR THREE

- TASK 7 - TEST MODULE-MFG.-PREPARED LAB-SIZE MINI-MODULES
- TASK 8 - INTERIM QUALIFICATION TESTING OF FULL-SIZE MODULES
- TASK 9 - MODULES FIELD TESTING WITH DATA ACQUISITION

History of Fielded, EVA- Encapsulated PV Modules

<u>Location</u>	<u>Module Mfg</u>	<u>Formulation</u>	<u>Color</u>	<u>Approx. Max. (1) Temperature</u>	<u>Time of Observed Color (Years)</u>	<u>Construction (2)</u>
Davis, CA	D	A9918	clear	-	3	Z
SWRES Las Cruces, NM	A	A9918	brown	-	3-4	-
Hawaii	B	A9918P	clear	-	4	X
Detroit	B	A9918P	clear	-	4	X
California	B	A9918P	clear	-	4	X
San Ramon, CA	A	-	light amber	64°C ⁽³⁾	-	W
San Ramon, CA	B	A9918P	faint yellow	64°C ⁽³⁾	4-5	X
San Ramon, CA	C	other	light amber	64°C ⁽³⁾	4-5	X
San Ramon, CA	D	A9918	light amber	64°C ⁽³⁾	-	X
Davis, CA	C	other	clear	-	4.5	X
China Lake, CA	A	A9918	discolored	-	5	W?
China Lake, CA	E	A9918	brown	-	5	-
Sells, AZ	C	other	80% brown	-	6-8	X
City of Austin, TX	C	other	slight brown	60-71°C ^{(3),(4)}	7	X
SMUD, CA	D	A9918	light amber	65°C ⁽⁵⁾	7	X
Caples Lake, CA	C	other	clear	52°C ⁽⁶⁾	> 7	X
Carissa Plains, CA	C	other	slight brown	-	8	X,Z
John Long, Phoenix, AZ	C	other	moderate	77°C ⁽³⁾	8	X
Sandia, Albuquerque, NM	D	A9918	light amber	-	8	X
SMUD, CA	C	other	slight brown	77°C ⁽³⁾	9	X
San Ramon, CA	F	A9918P	clear	-	9-10	X
Carissa Plains, CA ⁽⁷⁾	C	other	dark brown	80-90°C ⁽⁷⁾	10	X,Z
Costa Rica	G	A9918	clear	-	10	X,Y
Mohavi Desert	E	A9918	clear	-	10	X
"Around the World"	E	A9918	clear	-	10	X
Cape Canaveral, FL	A	A9918	discolored	-	10	W
SWRES Las Cruces, NM	D	A9918	light amber	75°C ⁽⁶⁾	10	X

(1) Estimated, no "hard" data available, (summer) measurements taken mostly from back-side of module

(2) W- Glass/EVA/Cell/EVA/Foil, X- Glass/EVA/Cell/EVA/Film laminate, Y- Tefzel/EVA/Cell/EVA/Film laminate, Z- Bifacial

(3) Average ambient temperature plus 30°C

(4) High and low mounted racks

(5) Manufacturer's data

(6) Estimated based on high wind velocity (ambient temperature plus 20°C)

(7) Modules operated at approximately 2 suns (mirror enhanced)

AVERAGE DAILY DIRECT NORMAL SOLAR RADIATION (MJ/m²)

OVERVIEW OF SURVEY ON CASE HISTORIES OF EVA DISCOLORATION

- * NO CASES OF EVA DISCOLORATION HAVE BEEN UNCOVERED FROM EASTERN AND
CENTRAL U.S. OR WESTERN EUROPE.
- * GENERALLY, THE TIME FOR ONSET OF EVA DISCOLORATION IS NOT WELL KNOWN.
DISCOLORATION OFTEN WAS NOT DOCUMENTED UNTIL FAIRLY ADVANCED.
- * GENERALLY, EVA DISCOLORATION WAS NOT A FOCUS OF MODULE FIELD TESTING PROGRAMS.
- * CONSEQUENTLY, INFORMATION ON DISCOLORATION IS QUALITATIVE RATHER THAN QUAN.
- * IN GENERAL, HARD DATA ON OPERATING TEMP. AND SOLAR INSOLATION WAS UNAVAILABLE.
- * MOST CASES OF EVA DISCOLORATION APPEAR MILD IN COMPARISON TO THAT AT CARISSA.
- * SAN RAMON, SMUD, AND PVUSA REPORT NO MEASURABLE LOSS IN POWER OUTPUT DUE TO
DISCOLORATION OF THE EVA ENCAPSULANT.
- * WHILE THERE HAVE BEEN REPORTS OF MODULES FROM ONE MANUFACTURER DISCOLORING
MORE QUICKLY THAN OTHERS, WE SAW LITTLE EVIDENCE AT SMUD, SAN RAMON, AND
PVUSA TO SUPPORT THIS, OR TO INDICATE A GREATER DEGREE OF DISCOLORATION
FROM ONE MANUFACTURER'S MODULES TO ANOTHER.

GENERAL CONCLUSIONS FROM CASE HISTORIES

- * EVA DISCOLORATION IS NOT LIMITED TO THE MODULES OF ANY ONE MANUFACTURER.
MODULES OF ALL MAJOR MFG. USING CRYSTALLINE OR SEMI-CRYSTALLINE CELL
TECHNOLOGY HAVE BEEN REPORTED TO DISCOLOR.
- * DISCOLORATION IS NOT LIMITED TO THE EVA ENCAPSULANT OF ANY ONE SUPPLIER.
- * IN GENERAL, DATA WAS INSUFFICIENT TO DRAW HARD CORRELATIONS
- * HOWEVER, SOLAR INSOLATION IN COMBINATION WITH MODULE OPERATING TEMPERATURE
APPEAR TO BE PRIMARY FACTORS IN EVA ENCAPSULANT DISCOLORATION, WITH
ALL REPORTED CASES APPEARING IN THE WEST AND SOUTH WHERE BOTH ARE HIGH

STABILITY OF EVA IN PV MODULES

BY

JOHN H. WOHLGEMUTH
SOLAREX CORPORATION
FREDERICK, MARYLAND 21701

Introduction

Yellowing and darkening of the EVA encapsulant in PV modules was first reported for the modules deployed at Carrisa Plains¹⁻³. The energy production efficiency of the array declined linearly at a rate of 8 to 12% per year from 1986 to 1989². The two facts were then equated and EVA degradation was blamed for the major power loss at Carrisa. However, subsequent analysis has shown that a significant portion of the power degradation of the Carrisa modules was a result of other loss mechanisms not related to EVA discoloration⁴. Nevertheless, after the Carrisa observations, EVA yellowing and discoloration on modules deployed at other sites in hot sunny climates was reported⁵.

The National Renewable Energy Laboratory (NREL) has been studying the behavior of EVA modules⁶⁻⁸. They have reported on EVA degradation of modules with field exposure as well as modules that underwent accelerated UV/temperature exposure in the laboratory⁸. UV/temperature induced degradation of EVA was reported, producing byproducts, including acetic acid, that lead to EVA discoloration.

While the NREL and Carrisa Plains data show that EVA will discolor under accelerated stress conditions, neither study provides guidance on the expected performance under normal one sun application. In this paper a summary of field results for Solarex modules will be presented. The field and accelerated test results will be utilized to evaluate the expected continuing performance of these modules. Finally, recommendation will be made for the direction of future work on the EVA encapsulation system.

Field Tests

Solarex has now been manufacturing EVA modules for more than 13 years. Modules from a number of sites are being monitored on a continuing basis. Module data is now available from a number of sites as detailed in Table 1. The Solarex modules at Sede Boqer, Israel have been exposed to a similar environment as the Arco modules were at Carrisa⁹. These Solarex modules have experienced much less discoloration and power loss than the Arco modules did in their first 6 years of deployment at Carrisa Plains. Field data on Solarex EVA modules indicates that high temperature, high irradiance conditions do cause measurable degradation and observable discoloration, but the degradation and discoloration rates are low in comparison to some other field reports.

At sites with low to moderate insolation levels and moderate temperatures like the mid-Atlantic or Northeastern US there is no evidence of EVA discoloration. At sites with high insolation levels, but moderate temperatures (i.e. high altitudes) like at NREL there is still little observed discoloration of the EVA. The sites with appreciable degradation are those with high insolation levels and hot temperatures for most of the year, like the US Southwest. These conditions are exaggerated by mounting schemes that result in higher module temperatures and of course by concentrating more sun light onto the modules.

Degradation Mechanisms

Reviewing the data and observations on the performance of EVA under UV and thermal stress can tell a great deal about the degradation mechanism. The worst case discoloration occurs in regions that are enclosed. Around the edges of cells and near cracks in cells or glass, the EVA remains clear. Modules with hermetically sealed backs (double glass or Al foil backsheets) experience more severe discoloration than those modules with a plastic (Tedlar) backsheet. Something either must diffuse into or out of the EVA to keep it from discoloring. A likely candidate for diffusing out of the EVA is acetic acid produced by the photothermal breakdown of EVA. The EVA would then be clearer in the regions where the acetic acid is gone and will be darker where the acetic acid builds up accelerating further degradation⁸. Another possible mechanism is the diffusion of oxygen into the EVA leading to a photobleaching process in the EVA⁸.

The fact that both clear and discolored EVA occur on the front of the same module, results from a balance of 2 competing mechanisms. In the clear areas the diffusion in (or out) of the crucial species is sufficient to minimize the photothermal degradation with the EVA remaining clear. In the areas over cells the rate of generation of the light absorbing species or creation of light absorbing bonds is greater than the diffusion out of the light absorbing or reaction catalyzing species (or photobleaching from diffusion in). Therefore, the EVA over the cells discolors. A slow rate of degradation or discoloration means the reactions are close to equilibrium and therefore, the degradation reaction will continue to be slow unless the reaction rates are changed by changing the external environment or until the Cyasorb, UV stabilizer, is lost. However, it has been found that the extent of discoloration is closely related to the decrease in Cyasorb concentration¹⁰. There is very little Cyasorb lost from the clear areas of modules even when the areas over the center of the cell has discolored appreciably with a major loss of Cyasorb. So in modules with no discoloration or a minor degree of discoloration the Cyasorb concentration is expected to remain high and the degradation rate will remain low. This is an extremely encouraging result, leading to the conclusion that, since Solarex modules have already proven that they only experience minor discoloration in more than 10 years of exposure in some of the worst one sun conditions, the degradation rate of the EVA is low and is expected to remain low. Therefore, Solarex EVA modules should have service lives much longer than the 10 to 13 years of already demonstrated life.

EVA Cure

Discoloration and degradation of EVA has been linked to increased gel content in the material⁶. While the initial gel content in new modules is approximately 70%, Pern and Czanderna measured a gel content of 82 to 88% in the clear areas and 90 to 92% in the discolored areas from degraded EVA modules¹⁰. This fact was used to indicate that even the clear EVA in these modules is degraded. It should not be surprising that the gel content of EVA has increased in modules that have experienced high operating temperatures. While curing of EVA is usually performed at temperatures above 120° C for short times, curing will occur at 80 to 90° C over long periods of time. There is nothing wrong or potentially degrading about this increase in gel content.

The gel content measurement does not measure the degree of cross-linking of the EVA. It measures the percentage of EVA that is cross-linked. EVA that has 100 % gel content may still have many additional bond site available for continued cross-linking. Such EVA still has adequate physical and chemical properties to continue serving as an encapsulant. Eventually the EVA could become so cross-linked that it would embrittle and stop serving as a good encapsulant. However, we have never observed brittle EVA either from modules that have been exposed in the field, from modules that have undergone long term accelerated thermal tests (for example 1000 thermal cycles), nor from modules that have been inadvertently over cured during production. Specially prepared test samples of EVA with 100 % gel content are still flexible and pliable.

Future Work

It is very important that the careful field monitoring of EVA modules continues. Solarex will continue to monitor the performance of modules from a variety of sites. We are also cooperating with NREL and the Ben-Gurion University to monitor the mirror enhanced system at Sede Boquer. This site is especially interesting because of the similarity with the operating conditions at Carrisa Plains, but with very different degrees of module degradation.

It is also important to establish accelerated testing procedures for the EVA degradation mechanism¹¹. Because of the presence of competing mechanisms, it may not be possible to accelerate this process by a great deal without changing the nature of the failure mechanism. Even accelerated tests may take the better part of a year to test for a 20 or 30 year module lifetime.

Work on understanding the chemical reactions that are occurring in the EVA due to photothermal stress and the competing reaction(s) that keep some of the EVA clear is also important. This effort must precede the development of an improved EVA formulation that maintains the many desirable properties of EVA, while eliminating the photothermal degradation from occurring under normal flat plate terrestrial operating conditions.

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TABLE 1
SUMMARY OF FIELD TEST RESULTS
FOR
SOLAREX EVA MODULES

Location	Type of Array	Years of Exposure	Evidence of EVA discoloration	Power Loss (%)
Solarex Frederick, MD	rack mounted	10	no	0
Southwest Res Las Cruces, NM	roof mounted	13	yes	0
Sandia Albuquerque, NM	rack mounted	8	no	0
SMUD Sacramento, CA	rack mounted	6	slight	2-3
Sede Boqer Israel	mirror enhanced	6	yes	6-7

Highlights from the Panel Discussion at the Durability and Reliability Session, Photovoltaics Performance and Reliability Workshop September 9, 1993, Golden, Colorado

A. W. Czanderna, Session Chairman and Panel Members: Niles, Gonsiorawski, Putman, Pern, Rosenthal, Holley, and Wohlgemuth)

Widely varying opinions that were expressed by the panel members and workshop participants about EVA discoloration in which the opinion expressed by utilities (U), PV manufacturers (I), and NREL (N) are identified are as follows:

- Why be concerned if loss is only 1%/year-- it is only economics (U)
- Lifetime prediction is not possible at this time because many potential degradation mechanisms are not known and too little information about the initial starting materials, processes, etc., results in too much uncertainty about the value of presently field deployed modules (N,I)
- Slow long term loss may become catastrophic by a mechanism not identified as yet (DSET)
- It is only a problem in some hot sunny areas of high UV intensity and in which mirror enhancement has been an "overuse" (I)
- Why accept any loss in performance when the problem can probably be solved by using a polymer with a different pendant group at a cost of 20 to 30 M\$ over 5 to 7 years? (I,N)
- If up-front economics can justify accepting a 20% decrease in efficiency over 20 years, then losses are OK and aesthetics is not an issue (U)
- Aesthetics do matter and discoloration is repulsive (U)
- Degradation in performance is a problem, aesthetics are important, and both should be corrected (I,N)
- EVA needs to be improved because it is a problem and industry will probably accept a better or "super-EVA" more readily than a new copolymer formulation (I)
- EVA, even optimally stabilized, will always be subject to producing acetic acid, acetaldehyde, and other degradation products. Who wants acetic acid, a known catalyst for further degradation, present in PV modules? A super-EVA might be an appropriate transition material for the near term. However, a copolymer that will not discolor or produce aggressive degradation products needs to be identified, tested, and established as a 30-year PV module material (N)

SYSTEM FIELD EXPERIENCES

PSCO
RENEWABLE ENERGY INVOLVEMENT
TO DATE:

by Chris Thompson, Engineer
Public Service Company of Colorado

Presentation to NREL
PV Performance and Reliability Workshop
September 9, 1993

Although we are here today to talk about PSCO's field experience with photovoltaics, we must acknowledge that PSCO's history of involvement has also included other renewable energy technologies.

In 1984, 1985, and part of 1986, PSCO Generation Engineering Division monitored three wind sites in Colorado and Wyoming that looked promising according to existing national wind data. These were: Harriman, Wyoming (located approximately 30 miles NW of Cheyenne, along the Colorado/Wyoming border); Burlington, Colorado (located in East-Central, Colorado along I-70 approximately 13 miles west of the Colorado/Kansas border); and Petes, Colorado (located in Northeastern Colorado, approximately 30 miles north of Sterling, along the Colorado/Nebraska border). The most promising site of the three was Harriman, Wyoming, which showed a rating of a Wind Power Class 7 site.

In 1988, a Waste-to-Energy Feasibility Study was conducted as a joint effort between PSCO and the City and County of Denver. The purpose of the study was to determine the feasibility of constructing a waste-to-energy facility in the City and County of Denver. The basic finding of the Study was that the economic realities currently surrounding solid waste disposal in the Denver area did not support the construction and operation of a waste-to-energy facility at that time. Environmental issues were also addressed during the Study. Since Denver is a non-attainment area for a number of air pollutants, the introduction of a new emission source into the City would not be easily accomplished or accepted.

Over the last ten years, there have been more than 60 cost-effective Photovoltaic (PV) (Solar) powered systems installed for remote monitoring and cathodic protection of PSCO's WestGas's transmission system. All of these units were smaller than 200 watts. It is not uncommon for solar units to be installed because in many cases Gas transmission lines are located in remote locations. The cost of installing an electric distribution line may be more expensive and/or it may be impractical to install the electric distribution line.

Last year it was found to be more economical to cathodically protect an underground PSCo Boulder Division electric transmission line that crosses the median strip of Hwy 119 between Gunbarrel and Niwot Substations with a PV-powered system than to extend a distribution line to the site. The cost of this PV system was approximately \$1500.

In effect since March 3, 1991, Rule 31 (Section X) required utilities to provide new customers, in certain circumstances, with a comparison of the cost of an electric line extension with the cost of installing a photovoltaic system. Application of Section X required that the utility receive an estimate of an applicant's monthly kilowatt-hour usage and distance from the nearest feeder line. If the ratio of monthly kilowatt-hour usage to line extension mileage is 1000 or less, the utility will supply a cost comparison between a line extension and photovoltaics. On May 11, 1992, the Commission held a hearing to evaluate the rule's effectiveness and to determine if any modifications should be made. The outcome of that hearing was a change in the rule as requested by PSCo that eliminated a great deal of PSCo paperwork and helped to maintain PSCo's credibility with its customers.

Only about 1.5% of the over 5,000 requests received in the last 29 months have fallen in to the category where a cost comparison was required. This may mean there really aren't many cost-effective applications for photovoltaics or it may mean that the correct audience may not be targeted as yet.

Three sites have been targeted for investigation of solar potential:

- 1) Ft. St. Vrain: As part of the repowering of Ft. St. Vrain, a proposal was initially suggested that 14 MW of PV power (roughly the equivalent house power of the plant) would be installed incrementally at the repowered Ft. St. Vrain. Further investigation of this technology revealed that more benefits could be experienced if this generating capacity was moved closer to the loads--a distributed generation scheme. Since that time, PSCo and NREL have been negotiating to have a 50 kW Amorphorous Silicon photovoltaics system belonging to NREL installed and to provide the interconnection to the Ft. St. Vrain 480 volt house power bus.

- 2) Initial indications show that the Valmont Plant in Boulder might be a much better place to install photovoltaics, and rather than install the APS system at the repowered Ft. St. Vrain, Valmont might be a better site. Boulder's solar insolation has been well monitored over the years because of the many different laboratories that reside there. NREL is now helping PSCo determine whether further monitoring at Valmont will be necessary.

- 3) The small mountain community of White Pine in the Mtn. Division is served by a single-phase distribution line that goes over the continental divide. Obviously, by this slide, this line can be a challenge to maintain. There are approximately 25

PSCo customers out of approximately 35 residents, the majority of which live there only during the Summer months. The cost to rebuild PSCo's line to this town has been estimated at approximately \$132K. The cost to serve this town from a hybrid PV-propane generator system (approximately 35kW of PV) has been estimated at between \$500K-\$700K. PSCo would pay the avoided cost of this line and is continuing to search for cost-sharing partners in this endeavor. The information gathered from such an installation would be useful to the PV community, other utilities, as well as PSCo.

PSCo has completed a preliminary investigation of its feeders and substations in conjunction with the Utilities Renewable Energy Forum group's inquiry. The purpose of this investigation was to determine if there were any situations in which installation of a distributed generation 500 kW PV system could be a cost-effective delay of a substation bank or feeder upgrade. Analysis of a similarly-sized PV system by PG&E (for their Kerman Substation) indicated that this was the case. PSCo's present worth analysis showed that this was not the case (by a factor of 10) for its most promising site. In addition, most of PSCo's feeders had a peaking period which was after sundown--thus requiring storage and additional costs.

PSCo is involved in the following renewable energy organizations:

a) Photovoltaics for Utility Scale Applications (PVUSA) is a national public-private partnership that is assessing and demonstrating the viability of utility-scale photovoltaic (PV) electric generating systems. PVUSA participants include Pacific Gas & Electric (PG&E), the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), the California Energy Commission (CEC), and eight+ utilities and other agencies. PVUSA offers utilities hands-on experience needed to evaluate and utilize maturing PV technology. The project also provides manufacturers a test bed for their products, encourages technology improvement and cost reductions in PV modules and other system components, and establishes communication channels between utilities and the PV industry. The project consists of two types of demonstrations: Emerging Module Technology (EMT) arrays, which are unproven but promising state-of-the art PV technologies in 20 kW arrays; and Utility Scale (US) systems, which represent more mature PV technologies in 200- to 500kW turnkey systems. One additional advantage of PVUSA is the ability to use EPRI tailored collaboration funds.

b) The Utility Renewable Energy Forum (UREF) is a Colorado coalition of utilities, regulatory agencies, suppliers and manufacturers, and other groups interested in renewable energy technology. The major purpose of UREF is to exchange technical information and experience in order to encourage the use of these renewable technologies in Colorado. Since its first meeting at

NREL in Jan 1992, information on PV, Wind, and Thermal Solar technologies have been shared.

c) The Utility PV Group (UPVG) is a chartered organization with 28+ utility members representing investor-owned utility companies, publically owned, and rural electric cooperatives. This utility-driven effort has a two-fold thrust: 1) to accelerate the use of PV in cost-effective applications and 2) to accelerate the commercialization of PV.

PSCo has not been required to own, operate, or maintain renewable technologies. However, in order to learn firsthand about the O&M requirements of photovoltaics, PSCo become involved in four PV projects:

a. PSCo was a host utility for an EPRI/Sandia National Laboratories-sponsored photovoltaic-powered stockwatering project. This small PV pumping system (100W) is located in a PSCo customer's well in Brush, Colorado and is used in the summer to water cattle. PSCo has coordinated the design, contract, installation and maintenance of this system and has provided reports to Sandia National Laboratories, EPRI, and NEOS corporation. We completed final testing of the system this summer. We encountered a few problems with this installation and we've learned a great deal from our experience. (although the PV panels gave us no problem, we did have a pump failure and our contracted vendor went through a complete reorganization during this time period.) And for all of our systems, we've learned that one of the more frustrating facts is that a great majority of the time, the Sun does not always shine when you have the people and time to test the systems. We learned that there is a great need for an adequate maintenance infrastructure that does not exist today. We will continue to follow-up with the customer in order to determine if there is a market for this type of system. We've learned that customer satisfaction is extremely important. The cost of the system including installation was \$3400.

b. PSCo, in conjunction with NREL, DOE, and the South Suburban Parks and Recreation District installed a photovoltaic-powered pumping system and a photovoltaic power supply for an irrigation system in the South Platte Park northwest of Santa Fe and Mineral Avenue in April of 1992. This total system is designed to pump approximately 9500 gallons of water a day in the summer from Cooley Lake to irrigate approximately 1400 trees, part of the 10,000 Trees urban reforestation project along the Platte River. PSCo has been a part of the design, procurement, and installation process and had plans to monitor the operation and maintenance experience of this total system for only two years after installation (April 1992), but have been requested by the Parks Depart to come back next year for further testing. PSCo owns this 2.5kW system and the Parks and Recreation District is contracted to maintain it. The total cost of this system was approximately \$43,000.

The system has performed very well during the last two years, and overall the Parks Department is pleased with the system. I was surprised and yet not surprised that the Parks Department is still wary of this system and asked that PSCo and the PV contractor both be present when the system was turned on this Spring. This is a good example that customer satisfaction is imperative. I foresee that a little "hand-holding" with our customers will be necessary until their confidence is built up--not unlike our relationship with NREL. Unfortunately, the Parks Department has had irrigation subcontractor problems and delays and we've had to do without a main flowmeter this summer and without a main pressure meter once the flowmeter was finally replaced. In addition, about 3 weeks ago 2 of the 42 panels were stolen from the site. The locknuts that were using proved worthless and we've since secured the panels to the frames by spotwelding. We will be replacing the panels and plan a meeting of the project participants in September to open up the discussion of security for not only this installation but future projects that PSCo is involved with. This is a serious subject that really hasn't been dealt with to date.

c. PSCo is working with NREL and the University of Colorado at Denver on a project to gather data and test commercially-available stand-alone PV lighting systems. PSCo provided one of the area lighting systems and has also had recent field experience with three PV-powered area lights placed at the World Youth Organization headquarters at the Cherry Creek Reservoir during the Papal visit.

d. PSCo has begun to assist NREL in testing their 5kW PV grid tie in Golden. We are assisting with harmonics testing on the existing 2kW system and will be doing the same for the new NREL SERF building when it comes on line.

Where do we go from here?

I'm proud to answer that question. On August 19, 1993, PSCo began our Voluntary Renewable Energy Program (VREP). Our Market Research has shown that our customers want to play a major part in our involvement with renewable energy. This VREP is a customer-driven program designed to accelerate the development of renewable energy sources in PSCo's territory. We are in the beginning stages of forming a Citizen's Advisory Panel (CAP) that will help PSCo encourage funding participation among our customers and will help us to direct those funds to the renewable technologies and projects that our customers desire. Members of PSCo's Renewable Energy Strategy Team (REST) have been working on some of the initial projects that we will be presenting to the CAP. PV technology projects will be among these initial and future proposals.

PHOTOVOLTAIC SYSTEM EXPERIENCE
AT ARIZONA PUBLIC SERVICE COMPANY

PETE ECKERT
ARIZONA PUBLIC SERVICE COMPANY
SEPTEMBER 9, 1993

INTRODUCTION

APS has used cost-effective applications of PV since the mid-70's

APS has been involved in PV system testing and demos for many years

- ◆ **Sky Harbor concentrator PV project (1982)**
- ◆ **Yuma residential system (1982)**
- ◆ **STAR Center (1988)**
- ◆ **EPA/DSM projects (1993)**

Valuable experience will help to design and implement future PV

HISTORICAL PROJECTS

COST-EFFECTIVE PV APPLICATIONS

- ◆ **Gas telemetering**
- ◆ **Telecommunications applications**
- ◆ **Sectionalizer switches**
- ◆ **Communications trailer**
- ◆ **Flume control**
- ◆ **Water pumping**
- ◆ **Warning sirens**

SKY HARBOR CONCENTRATOR PV SYSTEM

- ◆ **1980 Martin Marietta design**
- ◆ **200 kW_{ac} (80 2-Axis tracking arrays)**
- ◆ **Experimental design - Largest in US at that time**
- ◆ **First 300 kW inverter failed - Replacement very reliable**
- ◆ **Expensive system improvements**
- ◆ **O&M costs decreased and reliability increased over time**

HISTORICAL PROJECTS (CONTINUED)

YUMA RESIDENTIAL PV SYSTEM

- ◆ **Installed in 1982**
- ◆ **4 kW_{ac}, 132 Photowatt modules**
- ◆ **PCU 95% Efficiency, THD: 1.8%**
- ◆ **Produces 6000 kWh per year**
- ◆ **\$61,000 or \$15 / Watt**
- ◆ **Customer savings over 10 years: \$4,473 or \$.079 per kWh**
- ◆ **O&M cost over 10 years: \$519 or \$.009 per kWh**
- ◆ **99.5% availability**
- ◆ **Required maintenance:**

Replace 2 muffin fans

Replace DC disconnect (original not DC rated)

Replace 1 Blocking Diode.

STAR CENTER ACTIVITIES

MODULE TESTING

- ◆ **Capacity to test 60 modules, dynamically loaded**
- ◆ **32 under test**
 - **9 Crystalline**
 - **13 Thin Film**
 - **10 Concentrators**
- ◆ **Results**
 - **Thin Film less reliable than crystalline**
 - **Solarex - Internal junction failure (no longer used)**
 - **2 Chronar - Efficiency decreased to 2% - 1 finally died**
 - **Advanced Photovoltaic Systems - DOA**
 - **2 Wattsun - Concentrator modules literally fell apart**
 - **Some manufacturers are better than others at rating their modules**

STAR CENTER ACTIVITIES (CONTINUED)

GRID-CONNECTED SYSTEM TESTING

- ◆ 28 Sky Harbor modules configured as a 2 kW array
- ◆ 24 Intersol modules configured as a 2 kW array
- ◆ Three 2 kW Mobil/Omnion systems
- ◆ 12 kW Siemens/Dickerson system (State-owned)

Results

- ◆ Acrylic concentrator lenses have held up since 1982
- ◆ Drive mechanisms have been reliable at STAR
- ◆ ECU signal cables have failed several times
- ◆ One array blew past limit switch
- ◆ Array tracking comparison:

Fixed position	2245 kWh/m ² -yr	Reference
One-axis tracking	2720	+ 21.2%
Two-axis tracking	3090	+ 37.6%

- ◆ One-axis only 3% lower than 2-axis during summer months

STAR CENTER ACTIVITIES (CONTINUED)

POWER CONDITIONING UNIT TESTING

Installed 3 Omnion and 2 Pacific Inverters in 1988

- ◆ **Interaction between PCU's**
- ◆ **Both manufacturers worked to solve problem**
- ◆ **Both manufacturers made revisions to ALL of their units**
- ◆ **Upgraded units were compatible**
- ◆ **Omnion unit had software glitch - hung at 400 watts**
- ◆ **All 5 units have been very reliable over past 3 years**

Installed Dickerson inverter in 1992

- ◆ **Unit susceptible to VSD noise in adjacent power plant**
- ◆ **Still evaluating unit performance**

STAR CENTER ACTIVITIES (CONTINUED)

ARRAY TRACKING METHODS

SPATS - Solar Panel Array Tracking System - Stone & Webster

- ◆ **Very reliable - Economical**
- ◆ **Accuracy / versatility compatible with Flat Plate systems**
- ◆ **Open loop control**

Martin Marietta Electronic Control Unit (ECU)

- ◆ **Reliability improved with time**
- ◆ **Tendency to track clouds on partly cloudy days**
- ◆ **Signal cabling failed due to repeated flexing**

STAR CENTER ACTIVITIES (CONTINUED)

ARRAY TRACKING METHODS

Prime Industries - Stand alone intelligent array controller (1986-87)

- ◆ **Extremely complex design**
- ◆ **Closed loop design**
- ◆ **Reliability decreased over 3 years**
- ◆ **Expensive**

Solar Technologies International (Sandia design)

- ◆ **1st generation design**
- ◆ **Relatively economical**
- ◆ **Rough start due to hardware problems**
- ◆ **Initial software setup was difficult**
- ◆ **Still evaluating unit performance**

STAR CENTER ACTIVITIES (CONTINUED)

PORTABLE PV GENSET

- ◆ Owned by State of Arizona
- ◆ 48 ARCO M55 at 55 deg tilt - 2.54 kW
- ◆ 1375 AH battery bank
- ◆ 6 kW LP Generator w/250 Gal tank
- ◆ Generator powers battery charger (not AC loads)
- ◆ 24 Vdc to 240 Vac
- ◆ Heliotrope "Quasi" Sinewave inverter

Comments

- ◆ Needed 240/120 transformer
- ◆ Mismatched Hardware
 - Battery capacity reduced by 15%
- ◆ PCU not suited for some loads
 - e.g. some inductive & electronic loads
- ◆ Generator ran more often than anticipated
- ◆ PCU THD 45-49%

EPA DSM PROJECTS

4 kW residential system in Peoria

8 kW commercial system in Scottsdale (hospital outpatient clinic)

4 kW commercial system in Flagstaff (high school)

Areas of Concern

- ◆ **PCU operating in hot garage**
- ◆ **1 String is grounded**
- ◆ **High cell temperatures**
- ◆ **Potential PCU problems at low temperatures**
- ◆ **Low system output**

OVERALL CONCLUSIONS

- ◆ **PV system costs have decreased by 50% since 1982**
- ◆ **Well designed / installed systems are reliable**
- ◆ **Balance of System has been the cause of most difficulty with PV systems**
- ◆ **EVA browning starting to appear on several modules**

Performance of Maspeth a-Si PV System

presented by Byron Stafford

PV Performance and Reliability Workshop
September 8-10, 1993
Golden, Colorado

Subcontract with Integrated Power Corporation using United Solar System Corporation's UPM-880 modules

Phase 1 Goals

- Demonstrate 22 W modules after 600 hours illumination at 1000 W/m², 50C, and under load
- Demonstrate passage of Interim Qualification Tests (IQT)
- Design and approval of PV system

Results From Phase 1

- NREL measured 21.5 W average stabilized power after 600 hours of illumination at 1000 W/m², 50C, and under load
- NREL accepted USSC's IQT Certification
- System design accepted by Review Team (NREL, Sandia, PVUSA)

Phase 2 Goals

- Deploy the modules in a utility interconnected PV system
- Performance greater than 15 kW(ac)
- System rating determined after 60 days of operation

Maspeth a-Si PV System Facts

- PV system is installed on the roof of a New York City Transit Authority warehouse in Maspeth, NY (Queens).
- System is utility interconnected in cooperation with New York Power Authority connected to Consolidated Edison.
- System contains 1008 USSC UPM-880 a-Si modules.
- 24 modules are connected in series, 3 parallel groups per row, 7 rows per monopole, 2 monopoles.
- Modules are tilted at 10 degrees and face south.
- System uses a 20 kW Omnion Series 3200 inverter for 3-phase, 480 V(ac).
- System has been operating since June 18, 1993.
- After 60 days, system operates around 17 kW(ac).
- IPC's innovative BOS uses ballast weights for roof mounting with no penetrations.

- DC performance of individual rows.
- Each row contains 72 modules.

	18-Jun-93	26-Aug-93
ROW	Power (W)	Power (W)
Row 1	1497	1437
Row 2	1504	1414
Row 3	1533	1429
Row 4	1532	1471
Row 5	1522	1462
Row 6	1527	1460
Row 7	1518	1444
Row 8	1522	1453
Row 9	1511	1433
Row 10	1546	1472
Row 11	1528	1446
Row 12	1531	1441
Row 13	1532	1442
Row 14	1533	1444
Average dc Power per Row	1524	1446
Average Power per Module	21.2	20.1
(includes diode & wiring losses)		

System Performance

- Selected data from 8/21-26/93
- POA irradiance $> 750 \text{ W/m}^2$ and wind speed $< 4 \text{ m/s}$

SMUD PV1 & PV2 FACT SHEET

		PV1	PV2
PLANT RATING (AC)		1 Megawatt	1 Megawatt
DATE OF OPERATION		August 1984	February 1986
COST	SMUD	\$3.2 Million	\$3.2 Million
	DOE	\$6.8 Million	\$6.8 Million
	CEC	<u>\$2.0 Million</u>	<u>\$0.0</u>
	TOTAL	\$12.0 Million	\$10.0 Million
	PV Cost/Watt	\$5.60/Watt	\$4.80/Watt
INVERTER	Rating	1 Megawatt	1 Megawatt
	Manufacturer	Omnion	Toshiba
	Type	Line Commutation	Self Commutation
	Efficiency	96.5%	96%
PV CELL MANUFACTURER		ARCO	ARCO
TECHNOLOGY		Single Crystal	Single Crystal
CAPACITY (AT S.T.C)		1.17 Megawatt	900 Kilowatts
PV CELL EFFICIENCY		10%	12%
			SOLAREX Poly Crystalline 200 Kilowatts 10%
			MOBIL Ribbon 35 Kilowatts 8%
TRACKING	Type	Single Axis	Single Axis
	Motor Rating	1/20hp	1/50hp
	Panel Rotation	Clock Driven	Clock Driven
CONTROL COMPUTER		Analog Device	Analog Device
DESIGN A&E		Acurex	Acurex

PV1 & PV2 Power Generation

1985-August 1993

PV1 & PV2 1991 GENERATION

Total 1991 Generation:
PV1 = 1,699,185 kWh
PV2 = 1,578,286 kWh

Photovoltaic Electric Vehicle Charging Station

SMUD's ELECTRIC VEHICLE SOLAR CHARGING STATION

On August 5, 1992, the Sacramento Municipal Utility District (SMUD) unveiled the first Solar Powered Electric Vehicle Charging Station in the western United States. By utilizing advanced photovoltaic (PV) panels, energy from the sun will now be used to provide power for up to sixteen non-polluting electric vehicles. This bold step further underscores SMUD's commitment to cleaner air and renewable sources of energy production.

General Information

- The free standing structure, measuring 8 feet by 130 feet, provides 16 shaded parking spots specifically reserved for Electric Vehicles.
- Automated rotation of the array optimizes the sun angle, providing maximum power at all times - even on cloudy days.
- Peak output from the array is 12 kW. Average daily energy production is 68.4 kWh AC.
- The 1,000 square foot array provides enough energy to drive:
 - 1 Compact Pickup 30 miles, AND
 - 4 Compact Sedans 30 miles each, AND
 - 10 Neighborhood EVs 25 miles each.

August 1992

SYNOPSIS OF SMUD'S 1993 PV PROGRAM

SMUD is a leader in utility grid-connected applications of PVs with the world's largest operating PV power plant (SMUD PV1/PV2, 2 MW), the first PV electric vehicle recharge station in the West, residential grid-connected PV installations, and numerous remote power and sensor applications. In 1993, SMUD is installing 640 kW of grid-connected PV systems. These systems will include 100 3 to 4 kW residential, roof-mounted PV systems; a 40 kW commercial building sited, concentrating PV system and a 200 kW substation sited, distribution support PV system.

⚙ The 1993 Residential PV Pioneers Project

Siemens Solar Industries

Partnership with our customers - PV Pioneers

100 4 kW residential PV systems

Demonstration project- grid-connected, residential-sited
distribution generation using photovoltaics

\$7.07/watt (1992 residential PV systems were over \$12/W)

Fixed array mounted on residential sloped rooftops

400 square feet of roof area

installed by the contractor in 1993.

PV PIONEERS - "green pricing" - 15% premium on existing rate for PV generated energy, held constant until the general rate reaches the same level at which point the PV rate will be kept the same as the general rate. Over 300 customers have volunteered to participate in this program.

⚙ 1993 Commercial Sited Photovoltaic Project

Solar Energy Applications Corp. (SEA)

One 40 kW Commercial Building Sited PV system

Innovative, concentrating PV system

Uniquely adaptable to roof-top applications

Substantial potential for significant cost reduction

On a SMUD owned building (Headquarters Building)

Demonstration project - grid-connected, commercial building sited,
distributed generation using photovoltaics

\$9.11/watt

Roof mounted, single axis tracking, concentrating PV system

4000 square feet of roof area

Installed by the contractor in 1993.

⚙ 1993 Substation Photovoltaic Generation Project

Utility Power Group (UPG)

One 200kW ground mount PV system at a SMUD substation site

Demonstrate the ability and versatility of placing medium size PV systems for District distributed
generation benefits

\$7.70/watt compared to \$8.90/watt for the PG&E 500kW Kermin PV plant completed in Spring 1993

Ground mount, single axis tracking system utilizing Siemens solar modules

Installed in 1993.

THE SMUD PV PIONEER PROGRAM

At dawn this morning, the sun went to work for SMUD customers. A solar power plant near Rancho Seco generated enough electricity for hundreds of customers... rooftop solar water heaters lowered many residential electric bills... and scores of photovoltaic panels turned some Sacramento homes into mini power plants.

These are just some of the ways SMUD is putting the sun to work. In so doing, Sacramento's customer-owned electric utility is drawing on diverse energy sources that include hydroelectric and geothermal power. In the near future SMUD will add cogeneration, wind power and other renewable sources of energy. This clean and reliable energy mix will work in concert with SMUD's conservation programs to power Sacramento well into the 21st century.

SMUD Solar Power Brochure, 1993

The Sacramento Municipal Utility District (SMUD) is the fifth largest public utility in the nation and serves a 900 square mile area in and near Sacramento County, California. Under the leadership of SMUD General Manager S. David Freeman and its publicly elected Board of Directors, SMUD is committed to a 800 Megawatt (MW) "Conservation Power Plant" and 400 MW of renewable and advanced energy projects by the year 2000. Solar energy will provide an important part of both the "Conservation Power Plant" and renewable resource technologies. Investments made in solar power today will provide the customer-owners of SMUD with enormous long-term energy and community benefits.

The 1993 SMUD PV Pioneer Project establishes a partnership with customers willing to assist in the early adoption of photovoltaic (PV) technology. This year SMUD will purchase, own, install and operate about 100 3 to 4 kilowatt (kW) residential rooftop PV systems. Customers participating in this project (the PV Pioneers) are volunteering to share in this effort through a form of "green pricing" and by providing the roof area to place the environmentally friendly, solar electric generation PV systems. In doing so, the PV Pioneers will have the satisfaction of generating clean, renewable energy on their own rooftops! SMUD will gain experience in the installation, operation, maintenance, pricing strategies and other aspects of residential PV systems. This joint effort will help advance the development of the solar technology and accelerate the commercialization of PV through a process of

sustained, orderly development. SMUD is also installing a 200 kW single-axis tracking PV system at the Hedge Substation for grid support and a 40 kW concentrating PV system on one of the SMUD buildings.

The use of solar energy has many benefits to SMUD, the Sacramento community and the United States in general. Solar technology reduces the use of non-renewable resources. It is a renewable and sustainable energy source and helps improve air quality. Solar technology is environmentally benign.

It is up to local communities, states, the utilities and the public at-large to take the lead in demanding and providing the extensive use of solar energy. The following recent survey shows that the people of Sacramento are interested in helping to lead the way to a cleaner, sustainable future. The survey, taken this Spring, showed that 26% of the general population and 57% of the "green" population in Sacramento would be willing to pay a premium price (15%) for PV generated electricity from their own rooftops. Further, 49% of the general population and 77% of the "green" population would be willing to pay the premium (15%) for "rooftop PV" with rate stabilization of the PV portion. Finally, the support for general investment in a clean, renewable energy future was overwhelming with 70% of the general population and 88% of the "green" population willing to participate in a general "green pricing" utility effort to establish a "Clean Energy" program to add renewables, such as PVs, to the District's

system (not necessarily on their own roof).

Due to SMUD's commitment to advancing the use of this clean, renewable energy source—for only a 15% premium, mere dollars a month, PV Pioneers can enjoy the satisfaction of generating their own clean, renewable PV power on their own rooftop. In addition, this premium will protect them from future rate increases until the general rate exceeds the special "PV Pioneer" rate.

Among the added benefits PV Pioneers will receive are:

- ❖ Membership in the SMUD PV Pioneer Club
- ❖ The Solar Pioneer News
- ❖ Updates on new SMUD Energy Efficiency and Solar Programs
- ❖ Priority processing and participation in new SMUD Energy Efficiency programs

There are only a limited number of systems that will be installed each year and there are particular rooftop requirements. They include:

- Roof orientation: sloped, south to south west exposure
- Roofing material: Composition shingle in good condition
- Roof size: Approx 400 square feet of shade free area where the PV panels will be installed

Solar energy is here today. Working together, SMUD and its customer-owners can put the sun to work for a better and cleaner Sacramento. The PV Pioneers are on the cutting edge of bringing environmentally benign, sustainable energy to Sacramento by demonstrating their commitment to a clean and safe environment. If you are interested in becoming a PV Pioneer call SMUD at 455-2020.

When the sun rises in Sacramento, electricity begins flowing on the roof of John Harvey Carter's 80-year-old converted firehouse. PV panels collect enough power to meet the average annual energy needs of Carter's office.

THE SACRAMENTO UNION / MONDAY, JUNE 7, 1993

SMUD harnesses sun power

The Sacramento Municipal Utility District installed its first "rooftop power plant" on an 80-year-old converted firehouse at 417 20th St. The installation, for building owner John Harvey Carter, is the first in a \$4.9 million SMUD pilot project designed to provide information on the cost and effectiveness of a SMUD investment in solar energy. SMUD is seeking another 100 volunteers to test the rooftop system, which is installed and maintained by the utility, although volunteers pay a 15 percent premium for the clean, renewable energy. The rooftop power plant uses photovoltaic panels to absorb the sun's rays and create direct-current electricity, which is then converted to alternating current by means of an inverter. For more information on becoming a volunteer, call 455-2020.

SMUD 4KW RESIDENTIAL SYSTEM

Siemens Solar Ind.,
APRIL 1993

POWERGRID 1000®

One-Kilowatt Concentrating Photovoltaic Array For Low-Cost PV Power

Until now, the widespread use of photovoltaic power (PV) has been hampered by high cost. Now SEA Corporation, working under DOE funding*, has designed a unique PV concentrating system which, when manufactured at a production rate of 100 MW/yr, can supply D.C. power for under \$1.00/Watt. At this price, the system will produce AC busbar power at less than 6¢/KW-hr.

The **POWERGRID 1000®** is a one-kilowatt array utilizing 10 concentrating modules supported on a fixed frame. The 100 Watt modules are linked to a single-axis tracking system which operates automatically and unattended, requiring no batteries or external power source. Single axis tracking allows the **POWERGRID 1000®** to produce 30% more power than equivalent fixed flat-plate systems.

The light weight construction makes the array suitable for roof top or field installations. It can be mounted independently or linked in groups for any electrical application; from charging battery banks to addressing utility loads.

- ***Lowest cost per watt installed***
- ***Wide acceptance angle***
- ***30 year design life***
- ***Roof or Earth mount installation***
- ***Independent or linked applications***
- ***Simple, Reliable, Single-axis tracking***
- ***30% more power than equivalent non-tracking flat plate systems***
- ***No additional support structure required***

*This effort is supported in part by United States Department of Energy contracts 05-4239C and 40-8941C

THE POWERGRID 1000® IS DESIGNED FOR MANUFACTURABILITY AND LOW COST

From its inception, the *POWERGRID 1000®* was designed as a commercial product using cost-effective, currently available components and high volume manufacturing processes.

The *POWERGRID 1000®* modules use a minimum number of simple parts resulting in an inexpensive and reliable system. It was designed for high speed automated manufacturing. Cells are adhesive bonded to an anodized aluminum heat sink, formed from inexpensive sheet material. Integrated lens and module sides are formed by extrusion and then bonded to molded plastic endcaps with integral bearings. When the assembly is joined, it becomes a rigid, self-supporting structural element (module). This is far simpler, and less expensive than any other photovoltaic system available today.

The combination of the 10-inch wide extruded acrylic Fresnel lens and reflecting module sides creates primary and secondary elements of a unique optical system which has a wide acceptance angle. The wide acceptance angle allows more efficient operation in diffuse sunlight and larger tracking window. The SEA lens can be produced for one-fourth the cost of competing technologies.

SEA's 10-sun photovoltaic cells were designed to be manufactured using one-sun technology. This allows the cost benefit of concentration (less cell area per Watt output) without the usual high cost of concentrator cells.

A WIDE VARIETY OF APPLICATIONS

The *POWERGRID 1000®* can be configured for many power requirements. Single arrays can deliver output from 18 volts (ideal for charging 12 volt batteries) to 180 volts. Multiple arrays can be linked in series to working voltages as high as 650 volts.

SEA's engineering team has a reputation of technical excellence and many years of experience in the photovoltaic industry. We have the capability to configure a *POWERGRID* system for a wide variety of applications.

Current (Typical @ Load)	53 Amps
Voltage (Typical @ Load)	18.9 VDC
Short Circuit Current	59 Amps
Open Circuit Voltage	24 VDC
Maximum Working Voltage	650 VDC

Measured at 1000 W/m² direct normal insolation, 20°C ambient temperature, and 1 m/s wind speed.

Building Integrated Photovoltaic Systems NEES's Gardner & EPA's PV-DSM Projects

Edward C. Kern, Jr.
Ascension Technology, Inc.

NREL Photovoltaic Performance and Reliability Workshop
Golden, Colorado
September 8-10, 1993

Building Integrated PV Systems

Experience from 1979 through 1993

- John F. Long Properties - ARCO Solar "batten-seam"
- Hawaii Natural Energy Institute - ARCO Solar stand-off
- NE, SW & SE Regional Experiment Stations
- Carlisle, "Impact 2000", "Solar One" homes
- New England Electric / Mobil Solar Gardner homes
- San Diego Gas & Electric / ARCO Solar Laguna del Mar condos
- Massachusetts Energy Office Nantucket School Project
- Environmental Protection Agency PV DSM Demonstrations
- Sacramento Utility / Siemens Solar 100 home project

Performance and Reliability

Gradual and catastrophic effects

- Most PV modules have exceptional reliability
- Roof-mounting methods have proven durable
- Most static power converters have problems
- DC wiring and switchgear have minor problems
- Simple performance models yield reasonable agreement with measured system performance

SEVEN YEARS OF EXPERIENCE WITH AUSTIN'S 300 KILOWATT SINGLE-CRYSTAL PHOTOVOLTAIC ARRAY

City of Austin Electric Utility Department

OVERVIEW

- **Plant Design**
- **Seven-Year Performance (1987-1993)**
- **Plant Power Rating**
- **Tracking Actuators**
- **Laminates (Modules)**
- **Conclusions**

FACT SHEET

- **Start-up date:** July 29, 1987
- **Plant cost:** \$3 Million
- **Operation:** Utility line tied
- **Cells:** Siemens, single crystal silicon
- **Tracking:** 1-axis, passive
- **Inverter:** Toshiba, self-commutated

- **Rating in 1987:** 283 kW at STC
- **Array Field:** 6160 Laminates
- **Aperture area:** 2620 m²

DC POWER *vs.* CELL TEMPERATURE

DC POWER RATING ON AN ANNUAL BASIS

VARIATION IN SOLAR RADIATION

VARIATION IN ANNUAL ENERGY PRODUCTION

ANNUAL CAPACITY FACTORS

VARIATION IN DC EFFICIENCY

ACTUATOR FAILURES

(Total field includes 42 tracking actuators)

LAMINATE FAILURES

(Total array field = 6160 laminates)

ANNUAL PLANT AVAILABILITY

CONCLUSIONS

- Plant reliability has been high.
 - Average annual availability was 99%.
 - Average annual capacity factor was 21%.
- Inverter reliability has been high with only two component failures in seven years.
- Leaks in tracking actuator seals tend to occur at a rate of 6 per year.

CONCLUSIONS cont'd

- **Data indicate that the full power rating has declined since start-up.**
- **Factors that are believed to contribute to the power loss are:**
 - corrosion and shearing of laminate ribbons;
 - tracking actuator failures;
 - delamination;
 - reduction in EVA transmissivity.

The Performance of PV Systems

Marjorie L. Whipple

PV Reliability Workshop
Sept. 8-10, 1993

Sandia National Laboratories
For the Department of Energy

I Will Present Several Pieces Of the Reliability Puzzle

- ▶ **Background**
- ▶ **Changes in Systems Performance Over Time**
- ▶ **Charge Controller and Battery Issues**
- ▶ **What Needs to be Done Next?**

93 NPRL 2

Pre Block V

Non-producing Modules 10,143

Southwest Technology Development Institute

Total number of modules tested: 19,956

Block V

Non-producing Modules 4,463

Southwest Technology Development Institute

Total number of modules tested: 68,739

Keywords:
Photovoltaic power generation
Solar power plants
Maintenance costs
Field testing

Field Experience With Photovoltaic Systems: Ten-Year Assessment

Prepared by
Southwest Technology Development Institute
Las Cruces, New Mexico

EPRI
Electric Power
Research Institute

Module Performance Has Been Documented

(by Rosenthal, Thomas and Durand)

Pre-Block V

Post-Block V

► Modules

45% Failure Rate

< 0.1% Failure Rate

► Systems

5% of Modules Not
Producing Due To
BOS, Wiring,
& Mismatch

6% of Modules Not
Producing Due To
BOS, Wiring,
& Mismatch

►► Module Failures Are Less Significant Than
Other Systems Reliability Issues

Ten-Year Systems Performance Data Are Also Documented

- ▶ More Than 10 Different Systems Studied
- ▶ Mostly Crystalline Silicon Modules
- ▶ Geographic Locations Across the U.S. & Puerto Rico
- ▶▶ 1-3% Per Year DC Power Performance Degradation is the Trend

CONFIDENTIAL

We Formulated a Hypothesis About This Change in Systems Performance

HYPOTHESIS

Performance degradation is due to
optical absorption and reflection by the encapsulant,
solder bond failures, and
changing Balance of Systems components.

Lab & Industry Staff Examined Over 30 Modules From 8 Sites

2019.01.11

We Have Drawn 3 Conclusions From These Data

- ▶ Approximately 1/2 of the Degradation is Due to "EVA Browning"
- ▶ Mismatch & BOS Issues are Equally Significant
- ▶ "Delamination" & Module Solder Bond Failures are Secondary Factors
- ▶▶ Improved BOS Reliability Is Needed

2019.01.11

BOS Component Reliability Issues Are Numerous

- ▶ Power Conditioner Problems
- ▶ Failures of Contactors, Wiring Connectors, Switches, Bypass Diodes, and Fuses
- ▶ Charge Controller and Battery Design, Selection, and Operation

93 NRE_03

Battery & Charge Controller Reliability Is One Critical Issue

BATTERIES

Based on a Survey of PV Systems & Integrators ...

- ▶ Approximately 50% of New Batteries are not Conditioned Properly, Allowing Degradation to Begin
- ▶ Less than 50% of Batteries are Operating at the Recommended Temperature (77°F)
- ▶ ▶ Lack of Information About Batteries in PV Application Results in Reliability Problems

93 NRE_03

CHARGE CONTROLLERS

- ▶ 80% of Systems Employ ON/OFF Regulation
(Not Generally Understood, No Standardized Set Points)
- ▶ Many Systems Operate With Excessive ($> C/25$)
Charge Rates (C/20 - C/15 is recommended)
- ▶ ▶ Information Exchange Between Manufacturers
& Systems Designers Reduces These Problems

95 NREL 9

What Needs to be Done Next?

DOE's PV Program is Supporting...

- ▶ Solutions to Module Degradation Through NREL Staff
& PVMaT Contractors
- ▶ Reduced Costs and Increased Reliability of BOS
Components Through Sandia Systems Activities

Other Suggestions...

- ▶ New "Tests" to Help Identify BOS Reliability Issues
Prior to Fielding Hardware
- ▶ **Your Ideas Welcome!**

95 NREL 10

PV Systems Performance and Reliability Issues are Connected

- ▶ **Module Failure Rates are Low**
(< 0.1% Per Year)

- ▶ **Systems Degradation is a Serious Issue**
(1-3% Per Year)

- ▶ **BOS Component Reliability Needs More Work**
(BOS Issues are of Greater Magnitude than Module Issues)

- ▶ **Please Provide Your Input on "Next Steps"**

STANDARDS AND CODES

Report on 1993 PV Standards & Codes Forum

Carl R. Osterwald

National Renewable Energy Laboratory

Purpose:

- To provide information and status of current photovoltaic standards and codes development activities in the U.S.
- To provide a forum where all U.S. PV standards organizations meet together for discussions and work

Outline

- Standards & Codes Forum
- ASTM E44.09 subcommittee meeting
- IEEE SCC21 meeting
- IEC TC82 US TAG meeting
- Working groups
- Major topics

Standards & Codes Forum

(1/2 day)

- Introductory, organizational, and status of committees presented by representatives of:
 - IEEE SCC21
 - ASTM E44.09
 - Proposed changes to National Electric Code for non-utility PV systems
 - IEC TC82 US TAG
- Open panel discussion

ASTM E44.09 meeting (1/2 day)

- Ballot results:
 - New draft standard for module solar weathering passed subcommittee ballot
 - New draft standard for module salt water endurance passed subcommittee ballot
 - Revision of module insulation integrity and ground-path continuity testing amended and sent for reballot

ASTM E44.09 (cont.)

- Status of interlaboratory comparison discussed
- Module wet insulation integrity draft standard discussed and revised
- Working group formed to develop draft standard for multijunction device performance testing

IEEE SCC21 meeting (1/2 day)

- Approved two new Project Authorization Requests
 - Infield Test Methods and Procedures for Grid-Connected Photovoltaic Systems
 - Guidelines for Terrestrial PV Power System Safety

IEC TC82 US TAG meeting (1/2 day)

- Results of May 1993 meeting of TC82 in Ischia, Italy presented and discussed

Working groups of SCC21 (1 day)

- PAR 1262 Recommended Practice for Qualification of Photovoltaic (PV) Modules
- Battery and charge controller group
- New PAR — Guidelines for Terrestrial PV Power System Safety

Major topics

- How can the National Electric Code be changed to be more accommodating to non-utility PV systems?
- Is wet insulation breakdown (hi-pot) testing needed for module qualification?
- Should wet insulation resistance and hi-pot testing be performed with full immersion of the module?
 - Consensus—yes

INTERNATIONAL PV PERFORMANCE STANDARDS

INTERNATIONAL ELECTROTECHNICAL COMMISSION TECHNICAL COMMITTEE 82 SOLAR PHOTOVOLTAIC ENERGY SYSTEMS

BY

**Robert Klein
SEIA, NREL and DOE**

Whether we address PV performance standards or standards of any other technology, society is impelled to acknowledge the global impact that international standards have upon the world marketplace today. International standards are the key that helps create a thriving world economy. Today the world stands on the threshold of a major breakthrough. Once closed doors are now opening and can become a lucrative market to United States industry. However, it is important that we build a well-managed standards program that can strengthen the United States position in this new global economy. To achieve our goal we must financially support the process, build an industry government working relationship and make certain that any produced standards meet the users needs.

CLOSED DOORS NOW OPEN

- **Build a well managed international standards program.**
- **Financially support the program.**
- **Build and promote an industry government working relationship.**
- **Produce standards that meet user needs worldwide.**
- **Financially assist and permit United States experts to participate in the international standards writing process.**

Within the European Community (EC) efforts are underway to link the computer systems of a number of the EC governments into an overall program, termed the European Nervous System (ENS). This system is one part of the EC move toward an open market.

A world standards day has been announced for October 14 each year. The 1993 theme will be *Information Management - Faster and Better with Global Standards*. The International Electrotechnical Commission (IEC) and the International Organization for Standards (ISO) are encouraging their member organizations such as the American National Standards Institute (ANSI) to celebrate *World Standards Day*. The event will recognize thousands of volunteers, world wide, who help to advance international standardization.

In view of the EC movement towards a more open world market, IEC Technical Committee 82, Photovoltaic Energy Systems, is striving to produce PV standards that meet the user needs world wide. In the United States we have built an international PV standards program. However, we are yet lacking

**Photovoltaic Performance and Reliability Workshop
NREL - Sept. 1993**

adequate financial support and are yet in need of a stronger total PV industry-government working relationship. A strong internal bond is necessary for any nation in this new global economy.

Working Group 1, Glossary

In 1993, IEC/TC82 reactivated working group 1, Glossary, Terms and Symbols that pertain to PV technology. At present the group is compiling previously approved TC82 terms and symbols so that they can be printed as a TC82 Glossary Publication.

Joint Battery Working Group (JWG)

Experts from Working Group 4, Storage Systems, have been participating in a Joint Working Group of TC21, Accumulators and TC82. This group is presently in the process of writing a standard that will address a *Test Procedure to Determine Suitability for a Battery to be Cycled in a Photovoltaic System*. This standard will describe a test method to determine the number of discharge/recharge cycles that a secondary battery can provide in a simulated PV regime.

Working Group 3, Systems

Working Group 3, Systems, should commence work on drafts that address a "Reference Solar Day", "Efficiency of Power Conditioners", "PV Array I-V Characteristics - Translation Procedures", and "On-Site I-V Characteristics Measurement Procedures for PV Arrays". A draft document entitled "Characteristics of Utility Interface" has been circulated for voting as a Draft International Standard (DIS). The bulk of the input to this standard was supplied by the United States. This standard addresses the interface requirements between the PV system and the utility. These requirements include power quality, flicker, harmonics and power factor. Working Group 3 continues to work towards producing a draft on "Safety Guidelines for Grid-connected PV Systems Mounted on Buildings".

Working Group 2, Modules

Subsequent to the 1992 Tokyo meeting of TC82, Working Group 2, Modules, prepared a draft on "Requirements for Reference Solar Modules" that has been circulated for voting as a DIS. This standard gives requirements for the selection, packaging, calibration, marking and care of reference solar modules. It is intended to be a supplement to the printed IEC Publication 904-2, "Requirements for Reference Solar Cells".

Working Group 2 is preparing a "Design Qualification and Type Approval of Terrestrial Thin-film Photovoltaic Modules" draft. This standard is a parallel standard to the recently published IEC Publication 1215, "Design Qualification and Type Approval of Crystalline Silicon Terrestrial Photovoltaic (PV) Modules". The thin-film document will give the IEC requirements for the design qualification and type approval of terrestrial thin-film PV modules suitable for long term operation in moderate open-air climates, as defined in IEC Publication 721-2-1. The thin-film document will present a qualification test sequence that contains such tests as visual inspection, wet leakage, light soaking, UV, annealing, thermal cycling, humidity freeze, twist, etc.

WORKING GROUP 1 GLOSSARY

- **Reactivated in 1993.**
- **In process of compiling previously approved TC82 terms and symbols for printing as a separate publication.**
- **Will assist all other TC82 working groups in defining terms applicable to all future TC82 publications.**

JOINT (BATTERY) WORKING GROUP (JWG)

IEC/TC21, Accumulators

IEC/TC82, Solar Photovoltaic Energy Systems

- **Comprised of experts from both technical committees.**
- **Preparing a test procedure to determine suitability for a battery to be cycled in a photovoltaic system.**

WORKING GROUP 3 SYSTEMS

- **"Characteristics of Utility Interface" Draft International Standard (DIS)
Out for vote.**
- **In the process of preparing a draft document on:
"Safety guidelines for grid-connected PV systems mounted on buildings"**

WORKING GROUP 2 MODULES

- **"Requirements for reference solar modules"
Ready for circulation as a Draft International Standard (DIS) for voting.**
- **In the process of preparing a draft document on:
"Design Qualification and type approval of terrestrial thin-film photovoltaic modules"**

**Photovoltaic Performance and Reliability Workshop
NREL - Sept 1993**

**IEC/TC82 DOCUMENTS PRINTED
SINCE MAY, 1992**

- **IEC Publication 1215,**
Design qualification and type approval of crystalline silicon terrestrial photovoltaic (PV) modules.
- **IEC Publication 1194,**
Characteristic parameters of stand-alone photovoltaic (PV) systems.
- **IEC Publication 1173,**
Guide -overvoltage protection for photovoltaic (PV) power generating systems.
- **IEC Publication 891 - An amendment to take into account thin-film devices.**
Document 891 gives procedures that should be followed for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices.

All published IEC standards are available from:

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Fax #: 212+398-0023**

ACKNOWLEDGMENTS

On behalf of the Solar Energy Industries Association (SEIA), I thank DOE and NREL for their support in the international photovoltaic standards program.

Further, I wish to thank each company and each individual expert for their invested time and participation at various TC82 and its working group meetings.

CLOSED DOORS NOW OPEN

- . Build a well managed international standards program.**
- . Financially support the program.**
- . Build and promote an industry government working relationship.**
- . Produce standards that meet user needs worldwide.**
- . Financially assist and permit United States experts to participate in the international standards writing process.**

WORKING GROUP 1 GLOSSARY

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JOINT (BATTERY) WORKING GROUP(JWG)

IEC/TC21, Accumulators

**IEC/TC82, Solar Photovoltaic Energy
Systems**

- . Comprised of experts from both technical committees.**
- . Preparing a test procedure to determine suitability for a battery to be cycled in a photovoltaic system.**

WORKING GROUP 3 SYSTEMS

- . "Characteristics of Utility Interface"
Draft International Standard (DIS)
Out for vote.**
- . In the process of preparing a draft
document on:
"Safety guidelines for grid-connected PV
systems mounted on buildings"**

WORKING GROUP 2 MODULES

- **"Requirements for reference solar modules"**
Ready for circulation as a Draft International Standard (DIS) for voting.
- **In the process of preparing a draft document on:**
"Design Qualification and type approval of terrestrial thin-film photovoltaic modules"

IEC/TC82 DOCUMENTS PRINTED SINCE MAY, 1992

- . IEC Publication 1215,
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Photovoltaic
and the
National Electric Code

Presented by:
David Meakin
Solar Energy Industries Association

At the
National Renewable Energy Laboratory

Photovoltaic
Performance and Reliability
Workshop

September 8-10, 1993
Golden, Colorado

Introduction:

The Solar Energy Industries Association (SEIA) has been working closely with the National Renewable Energy Laboratory (NREL) to address a variety of standards and codes issues. I would like to talk today about these efforts with respect to the National Electric Code (NEC).

Under a contract from NREL, SEIA has been exploring ways to increase the Photovoltaic Industries participation in the code making process, in specific the NEC. I will explain in detail what SEIA is doing to realize this goal in a moment. First I would like to give a brief history of the NEC to put our efforts into context.

Historical Overview

The first edition of the National Electric Code (NEC) was published in 1897 as a result of the efforts of various electrical, architectural, insurance, and allied interests. Under the banner of the National Conference on Standard Electrical Rules, delegates from a variety of national associations drafted and published the first edition of the code. In 1911 the National Fire Protection Association (NFPA) took over the sponsorship of the NEC when the National Conference on Standard Electrical Rules was disbanded. Then in 1920 the NEC came under the auspices of the American National Standards Institute (ANSI), which at the time was known as the United States of America Standards Institute and subsequently became the American Standards Institute. While ANSI took over responsibility for the NEC, the NFPA continued in the role of Administrative Sponsor and has been publishing the Code in pamphlet form since 1951 as well as including it in the National Fire Codes.

The process of amending and publishing the NEC takes three years and is the responsibility of the National Electric Code Committee. This committee consists of 20 individual Code Making Panels (CMP's) coordinated under a central Correlating Committee. The membership of the Code Making Panels come from many different disciplines such as electrical manufacturing, safety testing, electrical inspection and engineering design. The broad base representation is necessary to since it is the responsibility of each CMP to review, comment on, and accept or reject proposed amendments. It is also necessary since each panel may be responsible for as few as three or as many as 15 code articles. For example, CMP-3 is responsible for Article 690 which addresses Photovoltaic systems as well as Articles 300 and 305 which are consider wiring methods and temporary wiring.

The actions of the individual panels are coordinated by the Correlating Committee. This committee is also responsible for publishing the comments and actions taken by each CMP for public comment. It is from this committee that the final version of the amended code is issued for final acceptance and publication.

The NEC

The NEC its self is intended to address issues concerning the safe installation and operation of nearly all electrical power systems. However, there are exceptions. Excluded from coverage by the NEC are, for instance, Utility-owned and operated power generating and distributing installations, automobiles, railway cars, and maritime vehicles i.e. ships, boats, etc. Ignoring for the moment the exception, it can be readily assumed that almost all devices that require connection to an external power supply are covered under one or more

articles of the NEC including Photovoltaic systems.

Until recently photovoltaic systems had not been explicitly mentioned in the NEC. Never the less, it was generally assumed by Electrical Inspectors, who are responsible for enforcing the code, Electrical contractors, and Electricians that the NEC had jurisdiction over photovoltaic power systems. It was not until 1984 with help from the Department of Energy that Article 690, which explicitly covers PV power systems, was incorporated into the NEC. Since then the article has been revised twice, once in 1987 and again in 1990.

However, due to rapid advancements in PV technology, it has become necessary to revise Article 690 again. Unlike previous changes which have been relatively minor it has become obvious that a comprehensive review of the code must be conducted in order to bring the code up to date with current PV technology and applications.

SEIA's involvement with the NEC.

The realization of the need for a compressive review of the code was made apparent during the 1993 code cycle which began in November of 1990. In January of 1991 CMP-3 considered a proposal to amend Article 690 that would have allowed for exception to requirements stated in Articles 220 and 230-42¹. This amendment would have added a new section to Article 690 that would have exempted stand-alone PV systems in residential dwellings from the service entrance requirements imposed on AC power distribution systems. This proposal, identified by the NFPA as proposal 33-137(log #1408)² was not rejected because of unsound engineering practices or because it was considered unsafe. It was rejected because it was considered outside the scope of Article 690.

As a result SEIA's representative to CMP-3³ drafted a letter to the Chairman of the NEC Correlating Committee explaining his dissenting opinion. He also asked that the Correlating Committee consider convening a Technical Subcommittee to review the scope of Article 690.

In response to this request, based on recommendations from the Correlating Committee, the Chairmen CMP-3 offered the PV Industry the opportunity to convene a panel of experts that would constitute the core of a Technical Review Committee (TRC) with the intent of reviewing Article 690.

As mentioned before, the process of amending the code is a cycle that begins once every three years. Therefor, to take full advantage of the opportunity SEIA began soliciting the PV Industry to nominate participants for the TRC. As a result we have approximately 20 representatives from the PV industry that have committed to the project. Including representatives from PV panel manufactures, Inverter manufacturers, Design houses, and the National Laboratories. We also hope to involve the Safety Testing and Electrical Inspector community. It is SEIA's opinion, as well as that of others, that the most diversified possible representation on the TRC will be beneficial to the entire review process.

The TRC is will meet for the first time on October 22, 1993 to begin the three years process at the end of which the committee will submitted its final recommendations to the NFPA for the 1999 code cycle. Keeping in mind that the 1999 code cycle begins in November of 1996, at best the results of the review will not become effective for another six years.

During the three review several objectives will be addressed. To begin, a cover to cover assessment of the current code with respect to Article 690 will need to be conducted. The committee will seek to identify Articles of the code

that need improvement in guidance with respect to PV, Articles that give conflicting directions to those stated in Article 690, and those that need to reference or be referenced by Article 690. Based on this review the committee will be able to recommend some of the necessary changes needed.

The committee must also decide, at the outset, what other issues it will address. This is necessary since these issues will have an effect on the entire review process. Some of the more prominent issues are rewriting the scope of Article 690, Categorization of PV systems, Ground methods, and the 600 volt limit.

Without a doubt the most prominent issue that will be addressed by the TRC is the scope of Article 690. It is obvious from the events that brought this review about that the current scope of Article 690 must be addressed. What remains to be seen is how.

Another possible candidate for consideration is the concept, put forward by several members of the PV Industry, of categorizing PV systems with respect to size. Unlike conventional AC systems, PV systems can be configured for a wide range of operating voltages and power ratings. In order to avoid undue technical and economic burdens on small systems, it has been proposed that different categories or classes of PV system be defined. There could then be specific requirements within the NEC that would be applicable to each class of system.

For example, it would make economic as well as design sense to differentiate between a 200 watt stand-alone water pumping system, a 2,000 watt residential power system, and a 6 Megawatt grid-connected power system.

Another argument for such a classification comes into play when large power generating systems are considered. A large grid tied power systems owned by electric utilities are subject to regulation by the National Electric Safety Code (NESC), an IEEE maintained document, not the NEC. However, as it currently stands an identical system operated by a non-utility cooperation or private company is subject to the NEC requirements which can differ from the NESC. It does not make economic or technical sense to have identical systems regulated by different codes. By creating a classification within the NEC for such systems it would be possible to either resolve the differences between the codes or exempt such systems from the domain of the NEC.

The issue of grounding has been an ongoing debate for some time. The impetus for using non grounded systems comes from the Europeans where ungrounded systems are common. However there are safety issues that are also driving the debate. To resolve the safety and technical issues the committee will need to work closely with other standards bodies such as IEEE SCC-21 to develop a technical basis for any recommendations made.

As a final example, the 600 volt limit. Currently the NEC treats systems over 600 volts, in some cases, very differently from systems under this limit. The question then arises, is this necessary for all PV systems over 600 volts and if not under what circumstances should exceptions be made?

These examples do not constitute a comprehensive list rather they are a starting point from which the TRC can proceed. The issues eventually addressed by the TRC can only be determined by the committee its self. And their decisions will, in large part, be based on input from the PV Industry. This is why it is incumbent to the PV Industry to involve its self in the process as much as possible.

Conclusion:

Because of the length of time required to effect changes in the code it is imperative that the PV Industry actively participate in the codes process so as not to miss opportunities to effect codes to its benefit.

It is through opportunities such as the offer from CMP-3 to review the NEC that SEIA will continue to assist the PV Industry in becoming more involved in the standards and codes process.

It is important that PV manufacturers and System Designers be aware of the requirements of the NEC. Without this awareness products will be developed that will not be acceptable for application in many of the markets that are now developing for the PV Industry.

Acknowledgments:

I would like to thank everyone who has made the realization of this Technical Review possible. Though I can not mention everyone I would like to give special thanks to Laxmi Mrig at NREL for his advice and guidance and to John Wiles at Southwest Technology Development Institute for his unselfish willingness to share his technical knowledge and expertise of the National Electric Code.

1. Article 220 defines branch circuit feeder calculations and Article 230-42 considers Services in particular residential service requirements.
2. Proposal was submitted by John Wiles, Southwest Technology Development Institute, Las Cruces, NM 88003.
3. Robert Nicholson, Solar Cells, Inc., 2650 Raymond Road, Toledo, Ohio 43615

PV Performance & Reliability Workshop

September 8 - 10, 1993

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September 8 - 10, 1993
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September 8 - 10, 1993

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September 8 - 10, 1993

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PV Performance & Reliability Workshop

September 8 - 10, 1993

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PV Performance & Reliability Workshop

September 8 - 10, 1993

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