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Photovoltaic Performance and Reliability Workshop

L. Mrig, Editor
September 7-8, 1995
Denver West Marriott
Golden, Colorado

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by the Midwest Research Institute
for the U.S. Department of Energy
Under Contract No. DE-AC36-83CH10093

Prepared under Task No. PV660103

November 1995

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Preface

This conference proceedings is the compilation of papers presented at the eighth PV Performance and Reliability Workshop held at the Denver West Marriott Hotel on September 7-8, 1995. Twenty two of the twenty six presentations which were submitted in a timely manner are included. This Workshop is one of the technology transfer mechanism employed by the PV Performance and Engineering Project in exchanging technical information in the field of PV component and system reliability.

At this time, 10 to 20 year warranty on many of the commercial modules are being provided by PV module manufacturers routinely. Several years of warranty is also being provided by inverter manufacturers. This is very encouraging but there are at present no general warranties on system performance or system reliability which is what I believe will be necessary in the future. As you will read in several of the presentations, many of the attributes that assist in defining PV performance and reliability are still evolving. And specifically, the data base on thin film PV technologies performance and reliability is still very much under development.

I believe a forum like this is an appropriate setting to exchange technical information in an open format. Towards that end, we were able to persuade many of the major players in the PV performance and reliability field to speak at this conference. These proceedings provide a good description of what these experts believe the major issues in this area are from their perspective.

I would like to acknowledge my colleagues (B. Kroposki, Vice Chair, T. Basso, J. Burdick, A. Czanderna, K. Emery, T. McMahon, D. Myers, C. Osterwald) on the workshop program committee who were instrumental in providing the program structure and the detailed program agenda. Based on the questionnaire results on the usefulness of the workshop to the attendees and the feedback that I received indicated that the Workshop program quality over the years has been steadily improving which I will attribute to the diligent efforts of the Workshop program committee responsible for the program agenda.

I sincerely hope you find these proceedings useful in your work.

Laxmi Mrig
Workshop Chairman

Photovoltaic Performance and Reliability Workshop
September 7-8, 1995
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OPENING SESSION

Chair: Laxmi Mrig
Co-Chair: Ben Kroposki

DOE National Photovoltaic Program

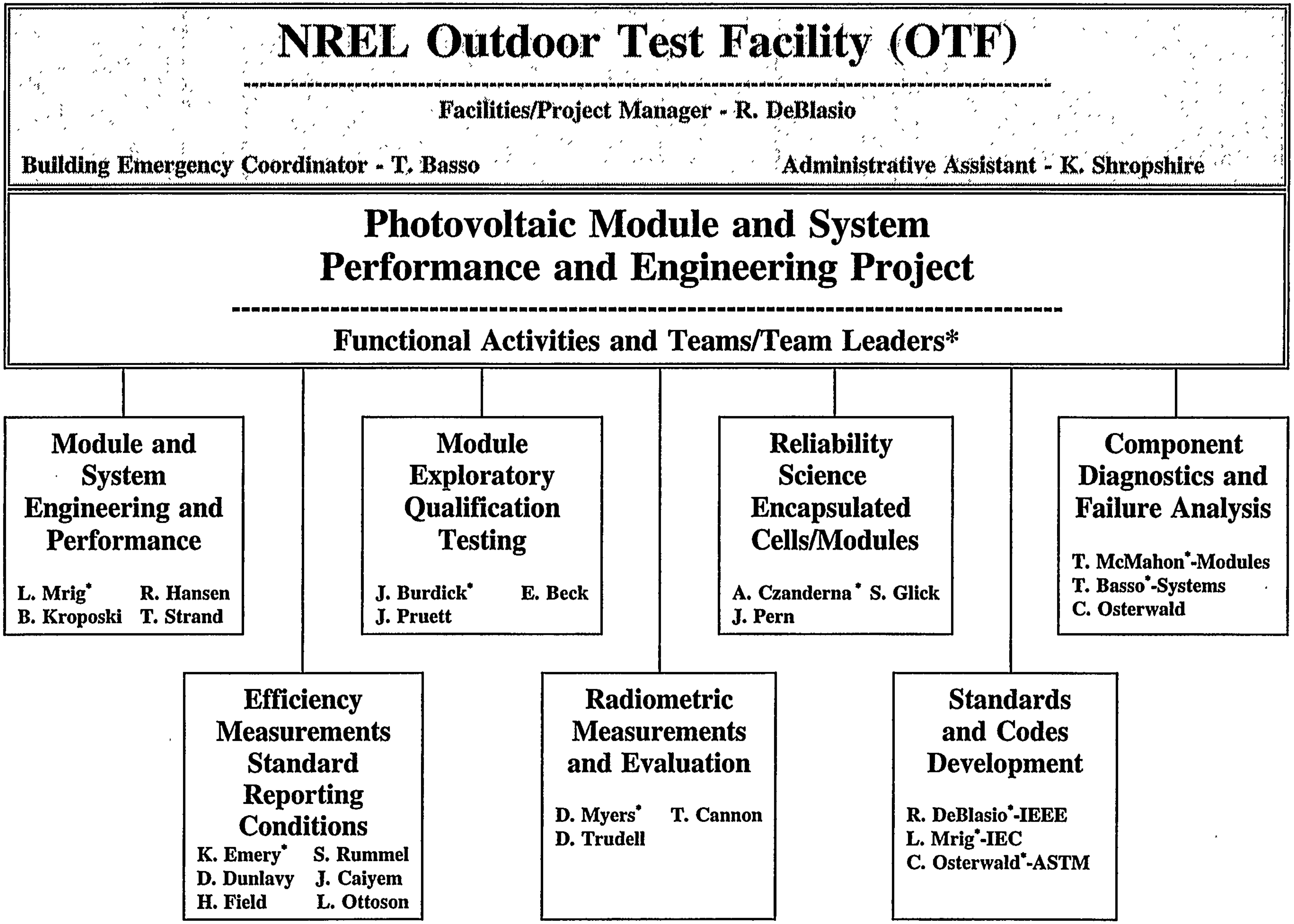
Outdoor Test Facility (OTF)

Location: **National Renewable Energy Laboratory**
Golden, Colorado

by

Dick DeBlasio

PV Performance and Reliability Workshop
September 7, 1995



NREL Outdoor Test Facility (OTF)

Facilities/Project Manager - R. DeBlasio

Building Emergency Coordinator - T. Basso

Administrative Assistant - K. Shropshire

Photovoltaic Module and System Performance and Engineering Project

Functional Activities and Teams/Team Leaders*

Module and System Engineering and Performance
L. Mrig* R. Hansen
B. Kroposki T. Strand

Efficiency Measurements Standard Reporting Conditions
K. Emery* S. Rummel
D. Dunlavy J. Caiyem
H. Field L. Ottoson

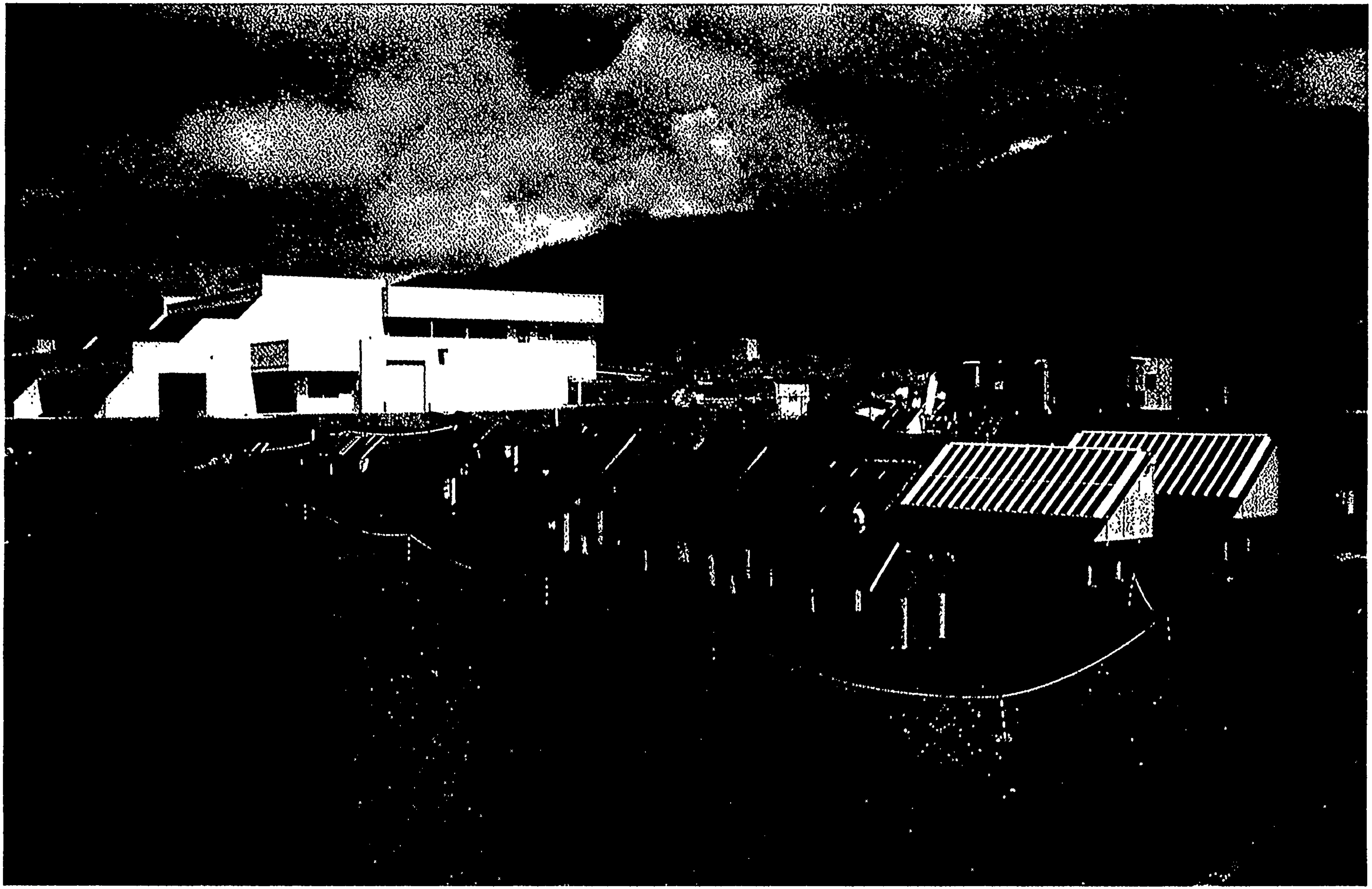
Module Exploratory Qualification Testing
J. Burdick* E. Beck
J. Pruett

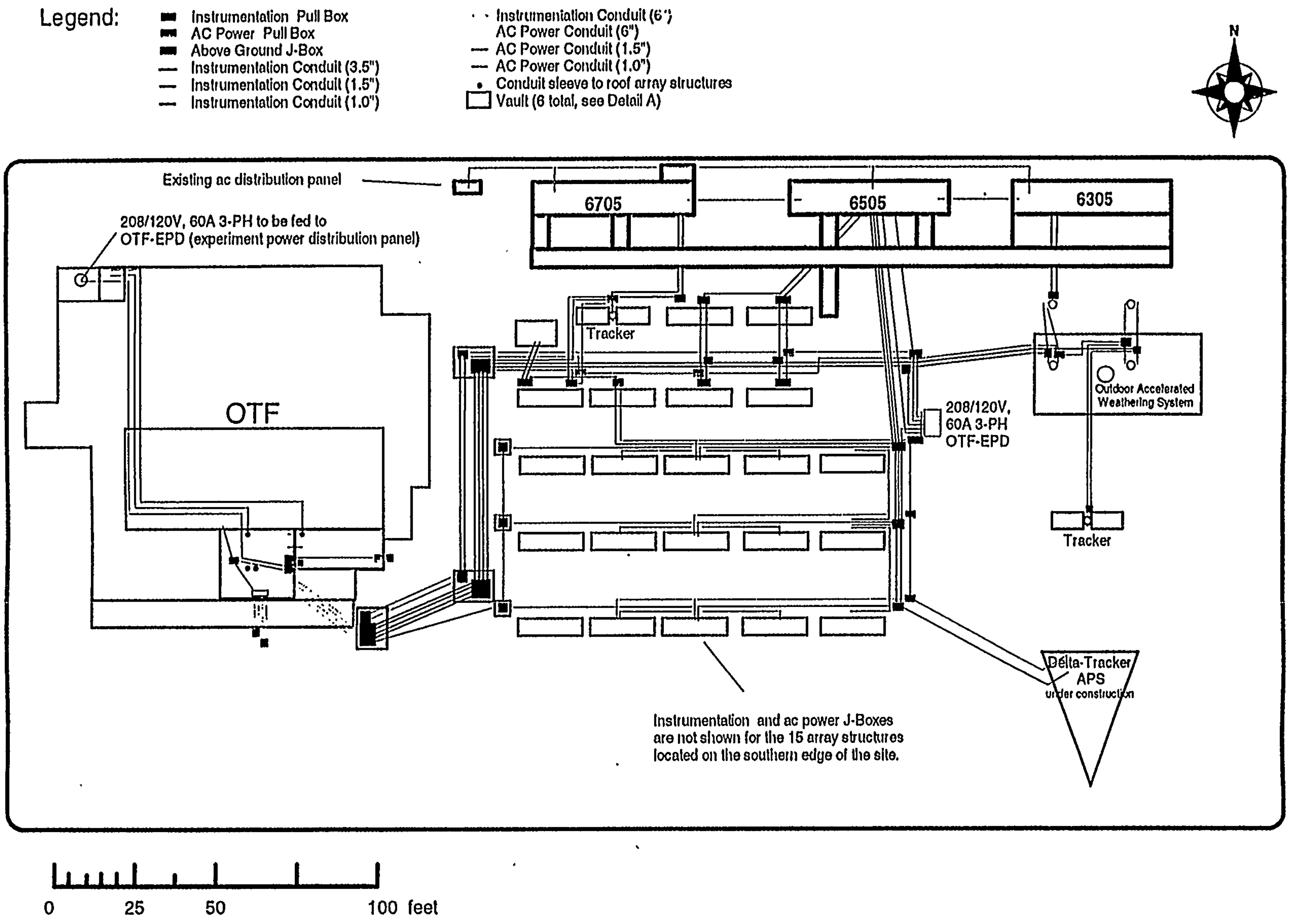
Radiometric Measurements and Evaluation
D. Myers* T. Cannon
D. Trudell

Reliability Science Encapsulated Cells/Modules
A. Czanderna* S. Glick
J. Pern

Standards and Codes Development
R. DeBlasio*-IEEE
L. Mrig*-IEC
C. Osterwald*-ASTM

Component Diagnostics and Failure Analysis
T. McMahon*-Modules
T. Basso*-Systems
C. Osterwald





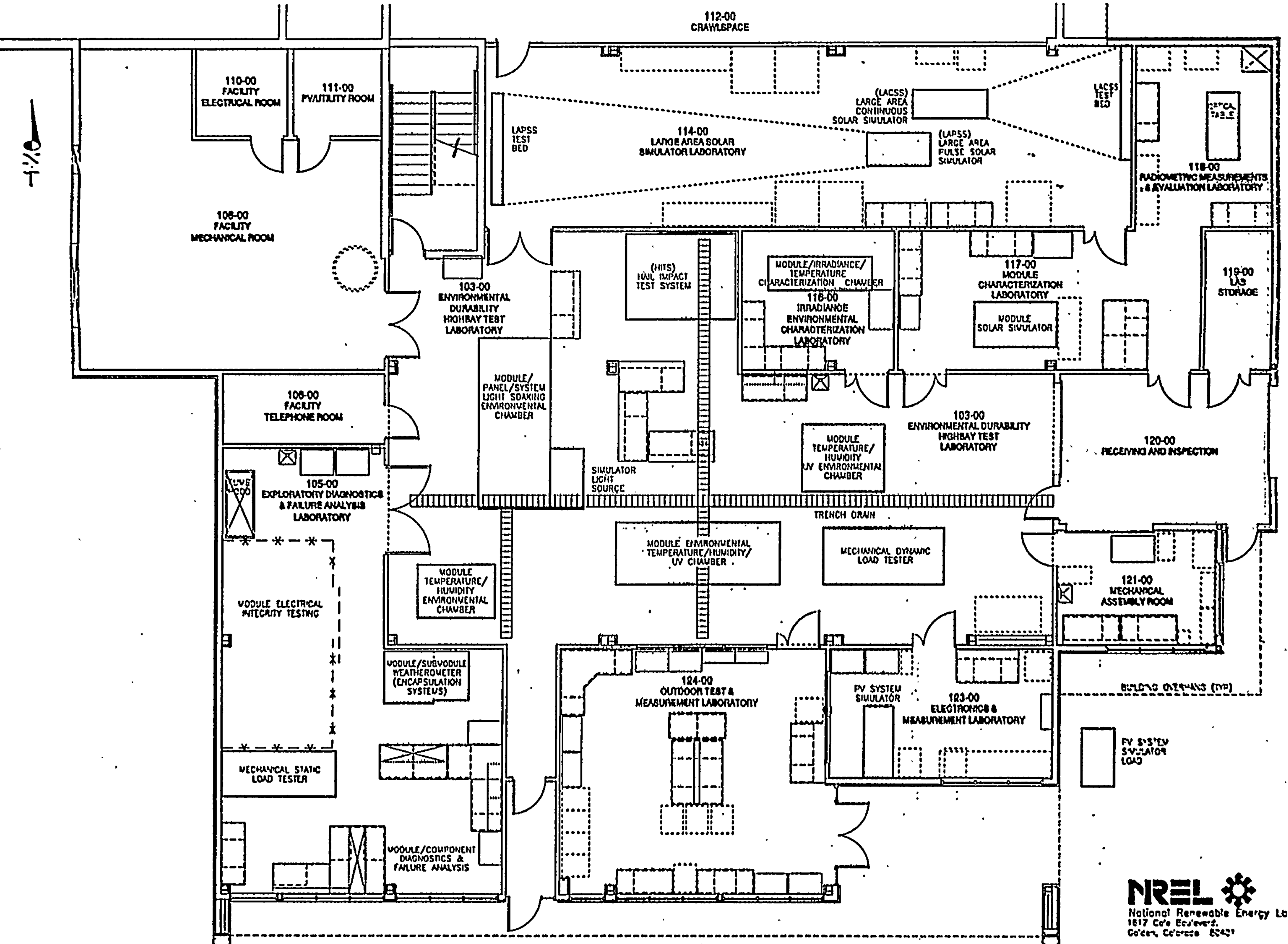
NREL National Renewable Energy Laboratory	DRAWN BY: BK & TS DATE: 4/21/95 REVIEWED BY: R. DEBLASIO DATE	SCALE: APPRX. REVISION 2 SHEET 1 OF 2	PROJECT: PV MODULE AND SYSTEM PERFORMANCE AND ENGINEERING	TITLE: OTF EXPERIMENT SITE CONDUIT SCHEDUAL

OTF Description

- **OTF building houses PV laboratories, control room, and work stations for outdoor testing, and exploratory tests and measurements.**
- **Two-story OTF floorplans total approximately 950 m^2 (10,200 ft^2); upper level (~ 3,100 ft^2) for offices and meeting space; and lower level (~ 7,100 ft^2) for labs, control room, and building facilities.**
- **Two roof levels have 40 m (130 ft) of array mounting structure for PV module/array/system outdoor testing and PV radiometric measurements.**
- **Adjacent field site module/array/system experiments are monitored for performance by data acquisition interties between the OTF monitoring and control room and each outdoor experiment.**

OTF Schedule

• 1992 August	Completed conceptual design
• 1992 November	Funding authorized by DOE Started Title I Design
• 1994 January	Started Title II Design
• 1994 April	Issued RFP for construction
• 1994 August	Began construction Currently on schedule and within budget
• 1995 May	Planned completion Initiate fitup and move-in
• 1995 Fall	Planned fitup completion



OUTDOOR TEST FACILITY (OTF)
LABORATORY/EQUIPMENT LOCATIONS

SCALE: [illegible]
(DRAFT 8/93)

NREL
National Renewable Energy Laboratory
1617 Cole Boulevard,
Golden, Colorado 80401

Operated for the
U.S. Department of Energy
By Midwest Research Institute

DOE National Photovoltaic Program

Outdoor Test Facility (OTF)

OTF OPEN HOUSE AND WORKSHOP RECEPTION

THURSDAY (5 - 7 p.m.)

SEPTEMBER 7, 1995

Location: NREL Outdoor Test Facility (OTF)
Golden, Colorado

Phone.kat 6/20/95

PV MODULE & SYSTEMS PERFORMANCE & ENGINEERING PROJECT

NAME	PHONE #	LOC.	BRANCH
Basso, Tom	384-6765	OTF-209-03	4110
Beck, Elvira	384-6766	OTF-209-06	4110
Burdick, Joe	384-6767	OTF-209-05	4110
Caiyem, Yehoshua	384-6181	FETA/6505	4110
Cannon, Ted	384-6763	OTF-205	4110
Czanderna, Al	384-6460	SERF E202	4120
DeBlasio, Dick.Proj. Mgr.	384-6760	OTF-203	4110
Dunlavy, Don	384-6690	SERF E200-5	4120
Emery, Keith	384-6632	SERF E120	4120
Lab	384-6458	SERF E219-21	
Field, Halden	384-6685	SERF E200-6	4120
Glick, Steven	384-6650	SERF E200-59	4120
Hansen, Bob	384-6364	FETA 6505	4110
Kroposki, Benjamin	384-6170	OTF-209-02	4110
Mrig, Laxmi	384-6764	OTF-206	4110
Myers, Daryl	384-6768	OTF-209-04	4110
McMahon, Tom	384-6762	OTF-204	4110
Lab	275-3874	16/269	
Osterwald, Carl	384-6630	SERF/E100-28	4120
Ottoson, Larry	384-6186	FETA/6505	4120
Pern, John	384-6615	SERF E100-41	4120
Lab	384-6712	SERF E216	
Pruett, Jim	275-6052	JSF	
Pruett, Jim	384-6164	FTLB/155	4110
Rummel, Steve	384-6287	OTF-217-01	4110
Shropshire, Kathy.Admin.	384-6761	OTF-202-01	4110
Strand, Troy	384-6104	OTF-209-01	4110
Trudell, David	275-3751	16/229	4110
*****			
Trudat Luu	384-6315	FETA/6505	4110
Ernest Van Dyk	384-6367	FETA/6505	4110

Additional Numbers:

Meeting Room Phone: 384-6792
Visitors Phone: 384-6793

Our FAX # : 384-6790

PERFORMANCE SESSION
Chair: Anthony Catalano

DEPENDENCE OF CdTe RESPONSE ON BIAS HISTORY*

J. R. Sites, R. A. Sasala, and I. L. Eisgruber**
Department of Physics, Colorado State University

Several time–dependent effects have been observed in CdTe cells and modules in recent years. Some appear to be related to degradation at the back contact, some to changes in temperature at the thin–film junction, and some to the bias history of the cell or module. Back–contact difficulties only occur in some cases, and the other two effects are reversible. Nevertheless, confusion in data interpretation can arise when these effects are not characterized. This confusion can be particularly acute when more than one time–dependent effect occurs during the same measurement cycle. The purpose of this presentation is to help categorize time–dependent effects in CdTe and other thin–film cells to elucidate those related to bias history, and to note differences between cell and module analysis.

Back–contact problems primarily increase series resistance, and hence decrease fill–factor, on a time scale of months. Increased junction temperature due to illumination decreases V_{OC} on a time scale of minutes, but forward bias increases V_{OC} over a time scale ranging from milliseconds to hours. The bias–history increase in V_{OC} appears to be due to long–lived traps which are below the Fermi level at low bias, but fall above it when the bias exceeds a critical value of approximately $V_{OC}/2$ for either CdTe or $CuIn(Ga)Se_2$–based cells. Results for externally–controlled bias history are similar to those for illumination controlled bias history. The magnitude of the time–dependent increase in V_{OC} for CdTe cells is about 35 mV and is not obviously correlated with overall cell efficiency. One practical result is that measurements with a pulse simulator will yield voltages about 5% lower than those with a steady–state solar simulation.

Control of time–dependent effects is somewhat more difficult for module measurements than for cells. In general, temperature control at the junction is less reliable with larger areas and with encapsulation of the active material. The magnitude of series resistance is larger in the typical thin–film module geometry, and because distributed resistance effects are greater, the series resistance and diode quality factor are not easily characterized as single parameters. Finally, since individual cells are not generally accessible, and cannot be assumed to have all parameters identical, module measurements can be skewed by one or two atypical cells.

---

*Work Supported by NREL.

**Current Address: Solar Cells, Inc., Toledo, Ohio.

DEPENDENCE OF CdTe RESPONSE ON BIAS HISTORY

Jim Sites, Rick Sasala,* and Ingrid Eisgruber
Colorado State University

*now at Solar Cells, Inc.
Work supported by NREL

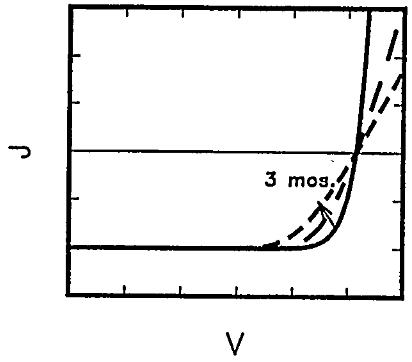
OBJECTIVES

1. Categorize changes in current-voltage response with time.

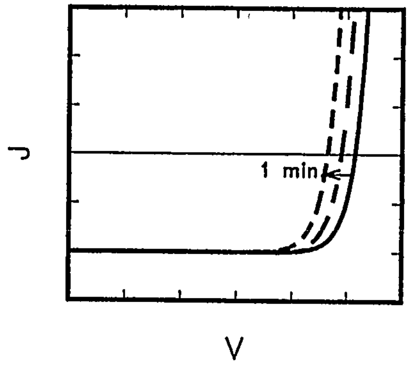
2. Explore time-dependent effects related to bias history.

3. Contrast analysis of cells and modules.

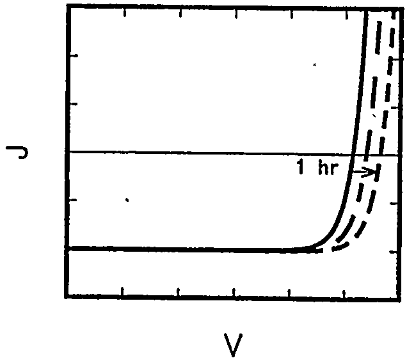
CATERORIZE CdTe J-V CHANGES WITH TIME



DEGRADATION
-Irreversible
-Primary parameter is series resistance (fill factor)
-Probable mechanism: decoupling of back contact



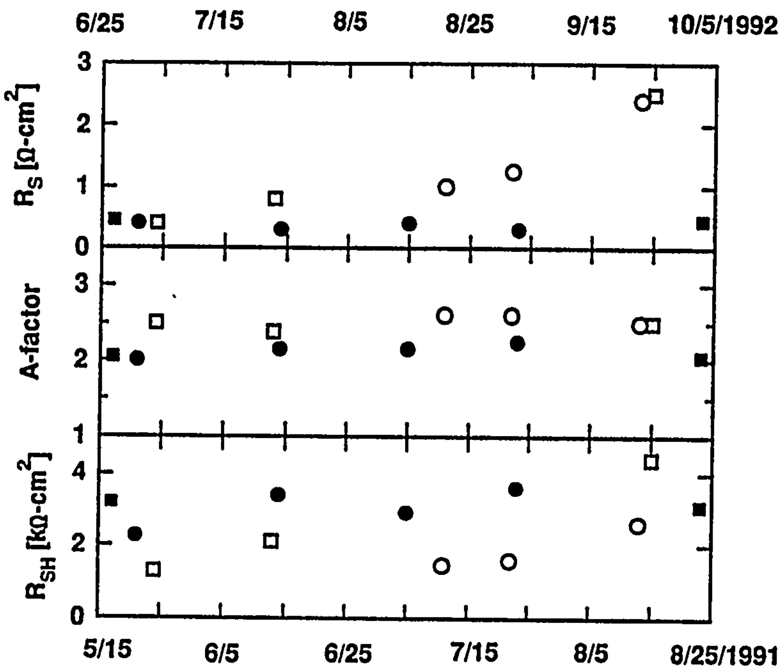
THERMAL
-Reversible
-Primary parameter is V_{OC}
-Hard to avoid with thin-film modules

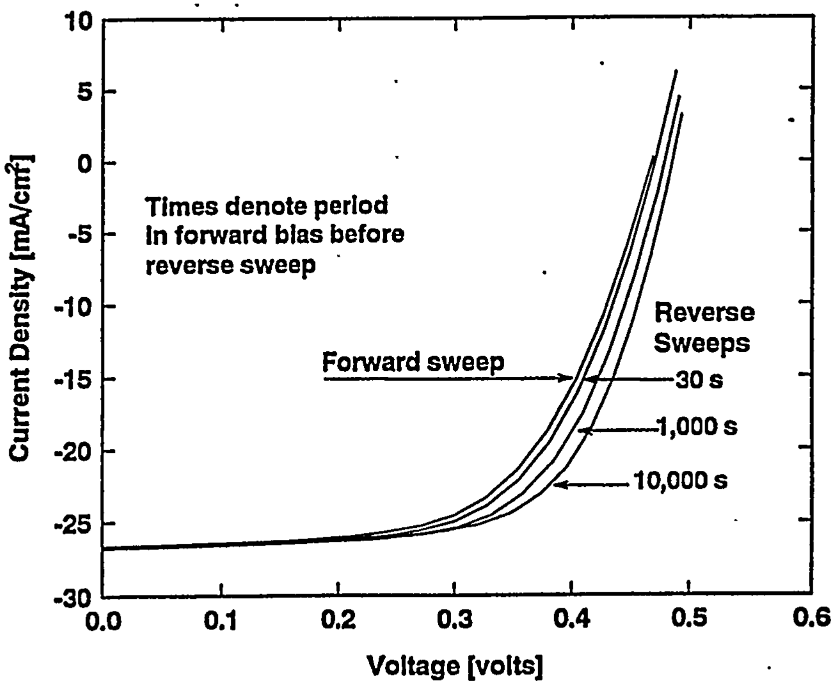


BIAS HISTORY
-Reversible
-Primary parameter is V_{OC}
-Positive direction for CdTe, CIS, CIGS

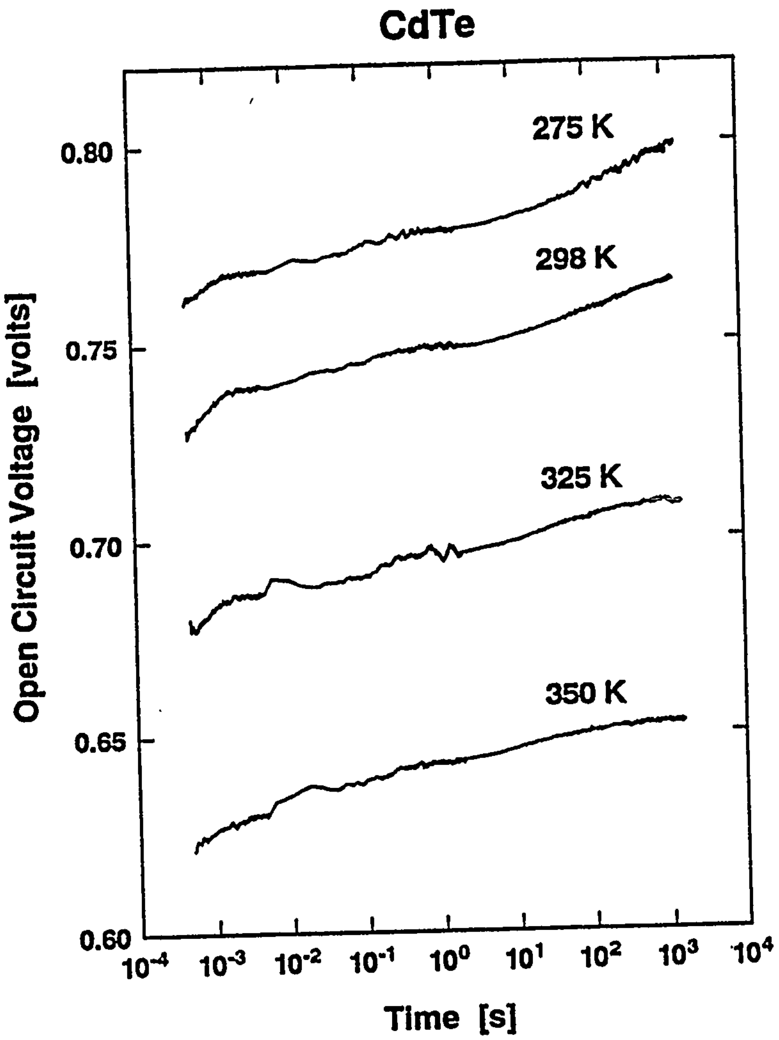
Univ. S. Florida CdTe Cell (100mW/cm^2, 25 °C)

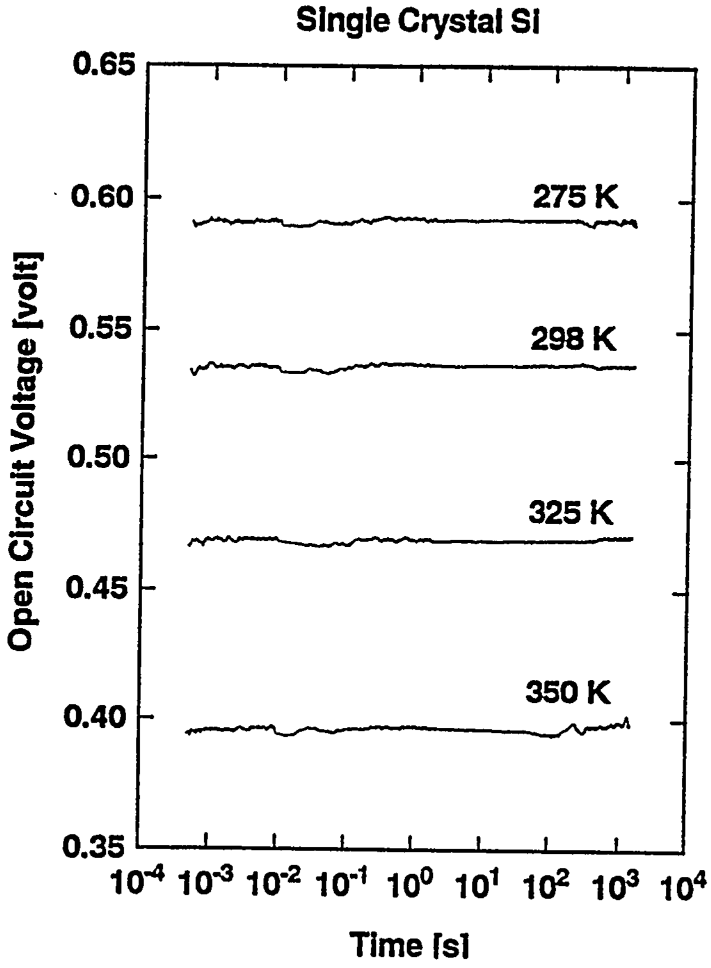
Year	1991	1992
Efficiency [%]	13.4-12.5	15
V_{OC} [mV]	840	860
J_{SC} [mA/cm^2]	22	23
fill factor	0.725-0.68	0.755
SERI/NREL	□	■
Colorado State	○	●

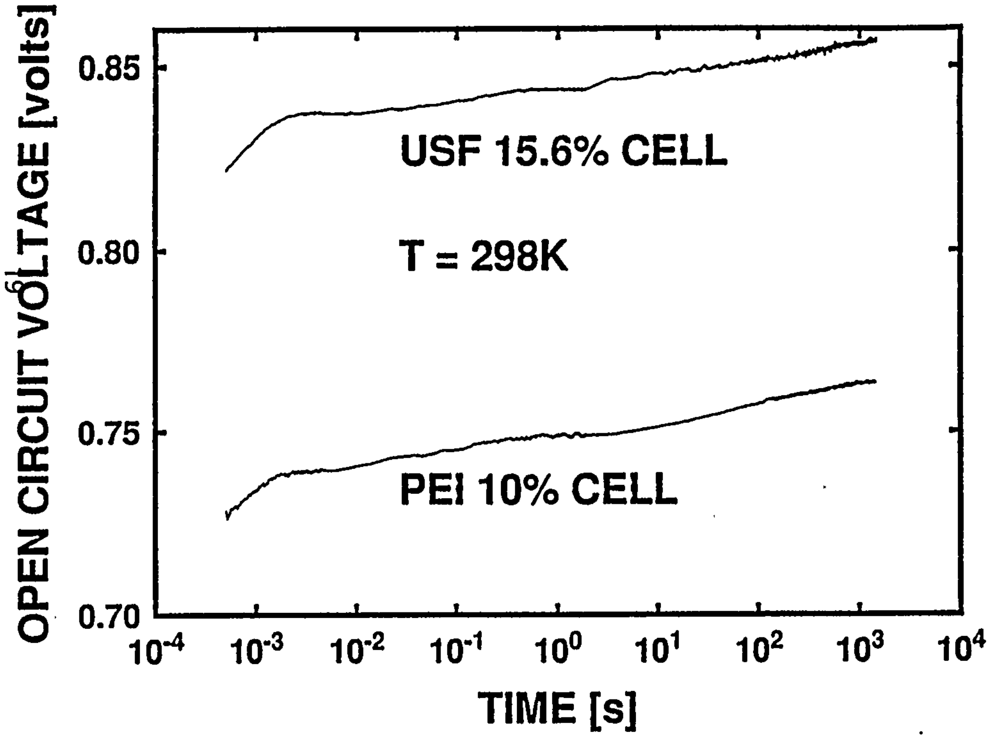


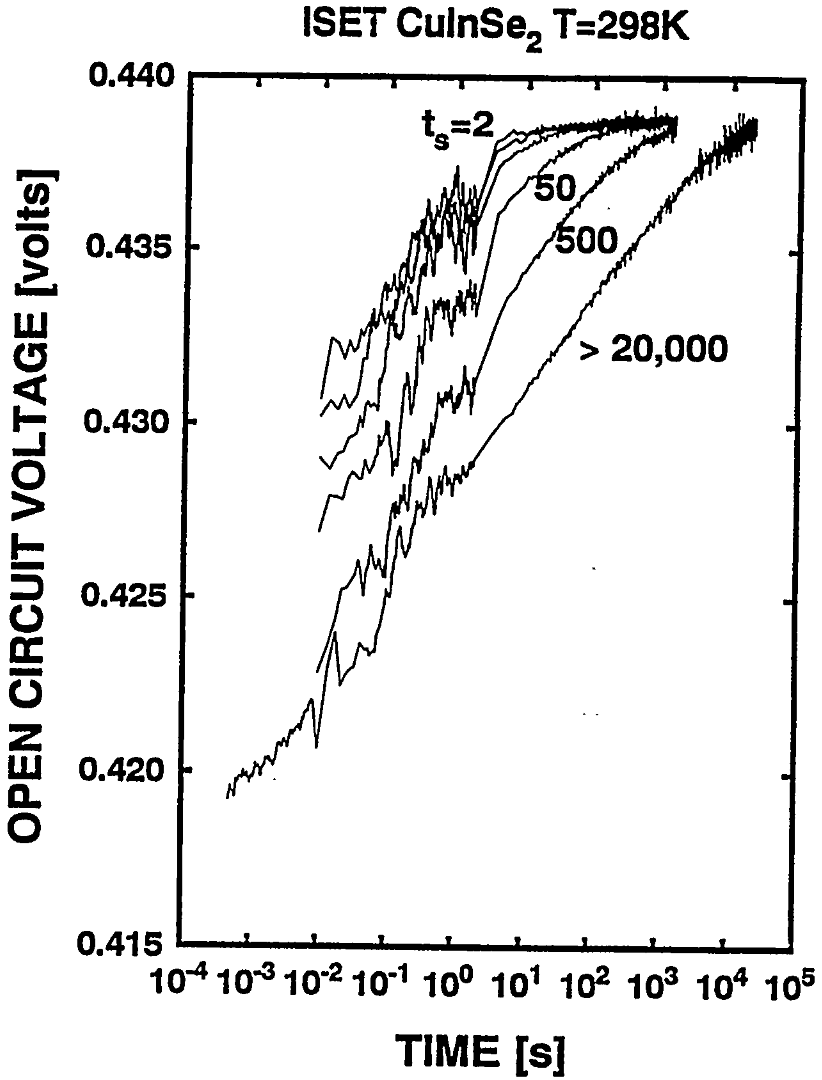


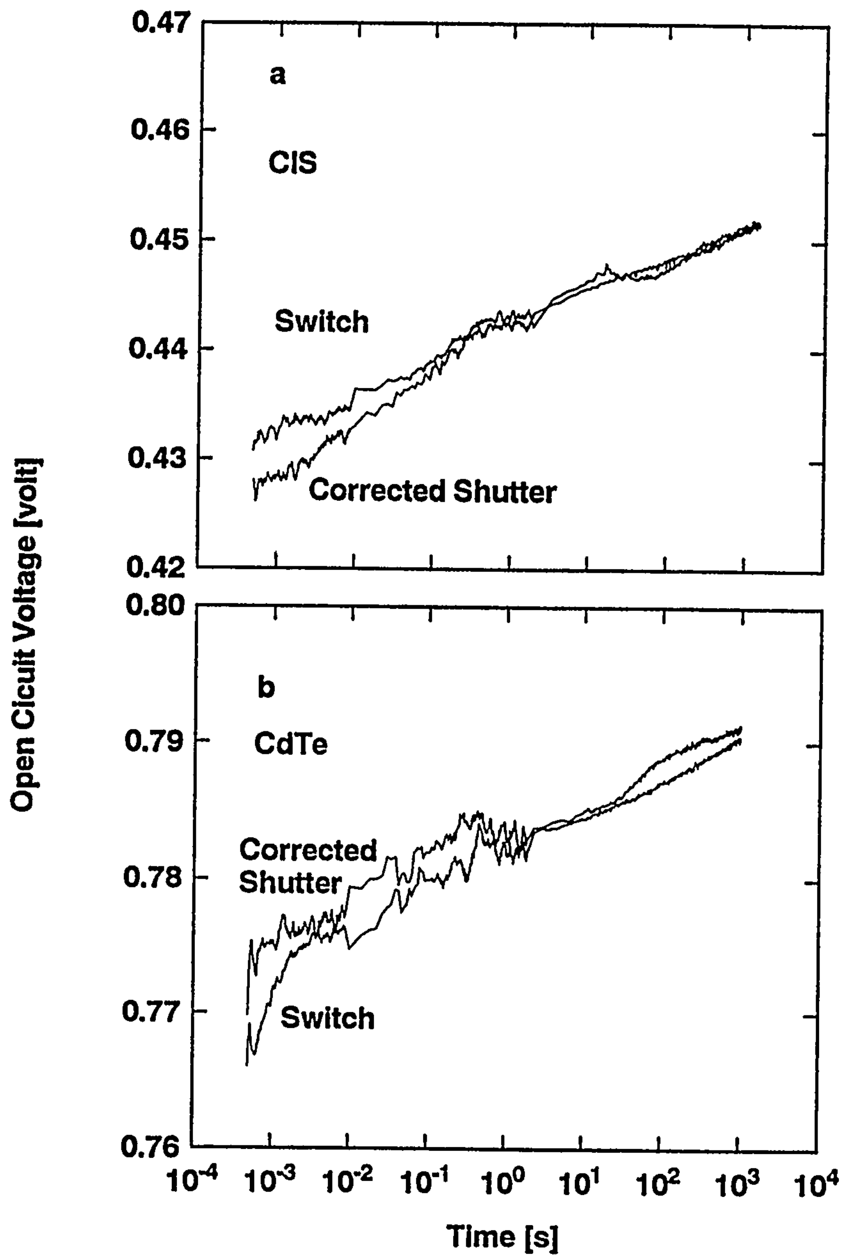
Variation in J-V curve with initial conditions.

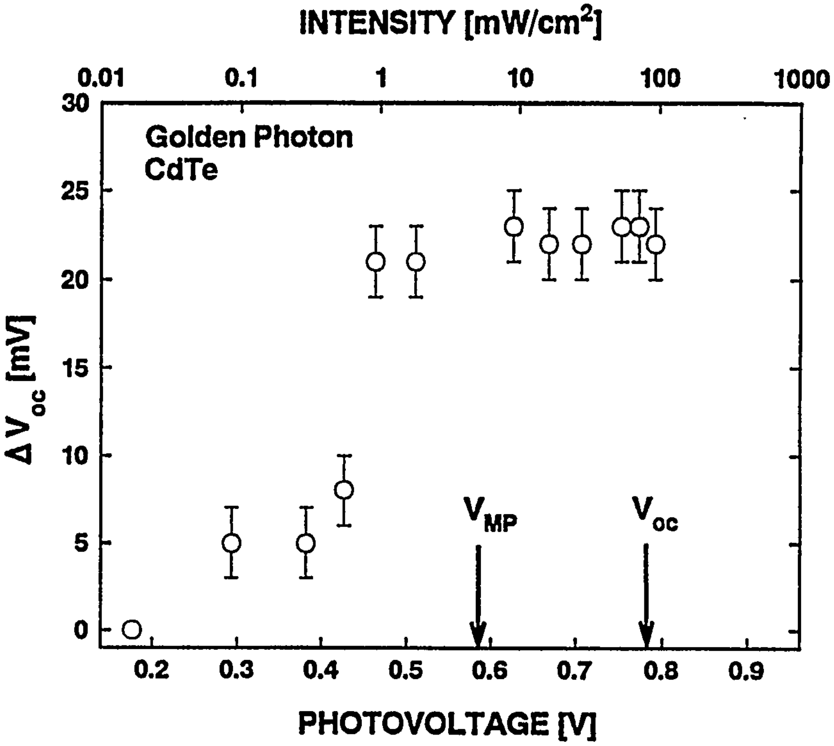

CdTe

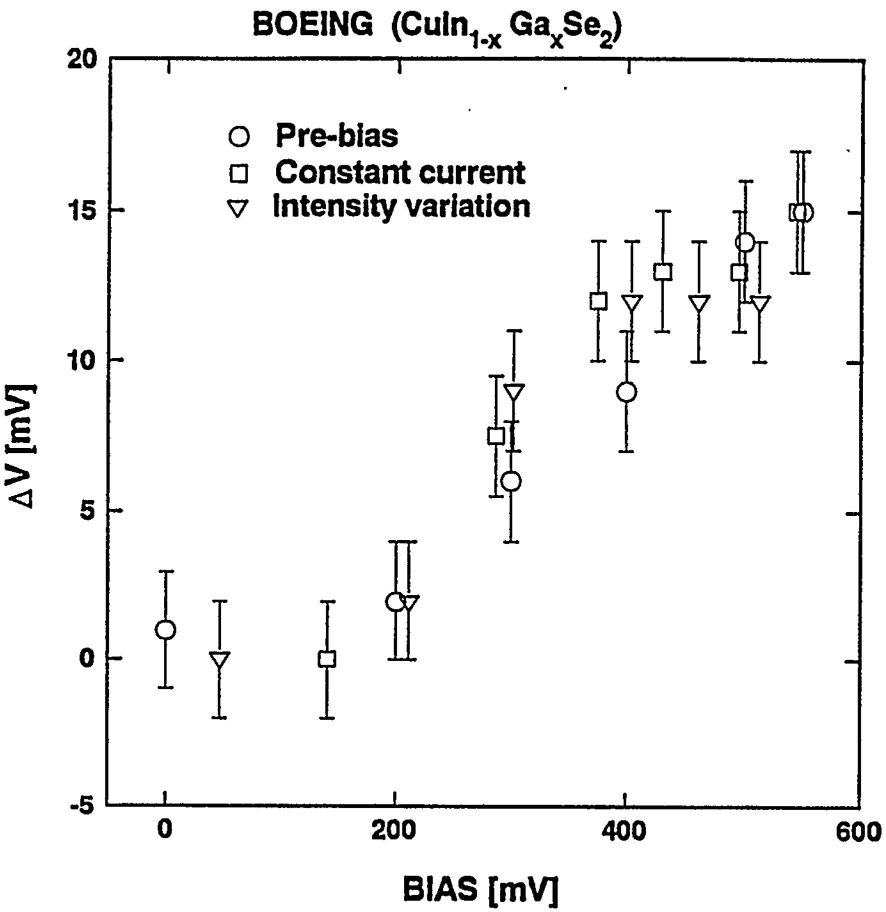

Single Crystal Si

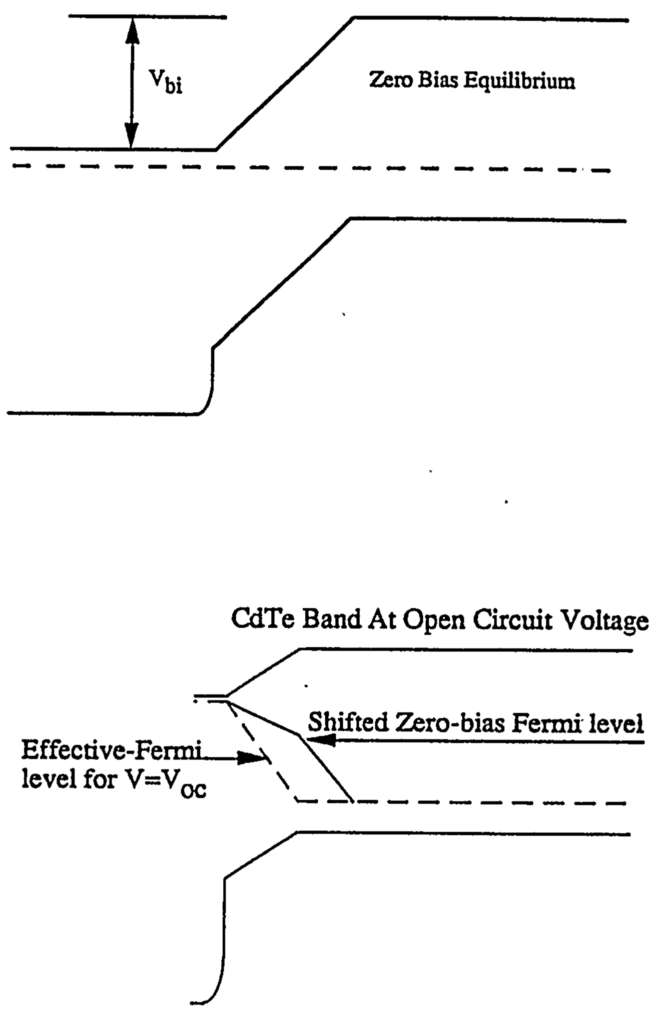

OPEN CIRCUIT VOLTAGE [volts]
0.85
0.80
0.75
0.70
USF 15.6% CELL
T = 298K
PEI 10% CELL
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
TIME [s]


ISET CuInSe$_2$ T=298K
OPEN CIRCUIT VOLTAGE [volts]
0.440
0.435
0.430
0.425
0.420
0.415
t_s=2
50
500
> 20,000
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
TIME [s]


a
CIS
Switch
Corrected Shutter
b
CdTe
Corrected Shutter
Switch
Open Cicuit Voltage [volt]
0.47
0.46
0.45
0.44
0.43
0.42
0.80
0.79
0.78
0.77
0.76
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
Time [s]

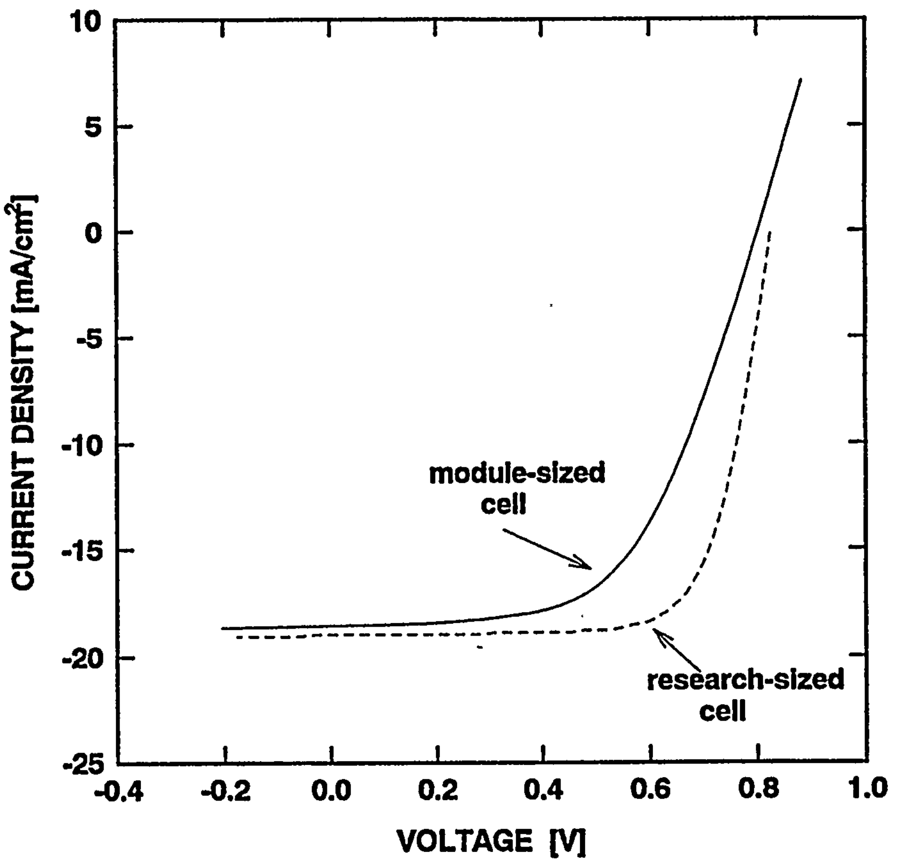

INTENSITY [mW/cm^2]
0.01 0.1 1 10 100 1000
Golden Photon
CdTe
ΔV_{oc} [mV]
30 25 20 15 10 5 0
V_{MP}
V_{oc}
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
PHOTOVOLTAGE [V]


BOEING $(CuIn_{1-x}Ga_xSe_2)$
○ Pre-bias
□ Constant current
▽ Intensity variation
20
15
10
5
0
-5
0
200
400
600
ΔV [mV]
BIAS [mV]

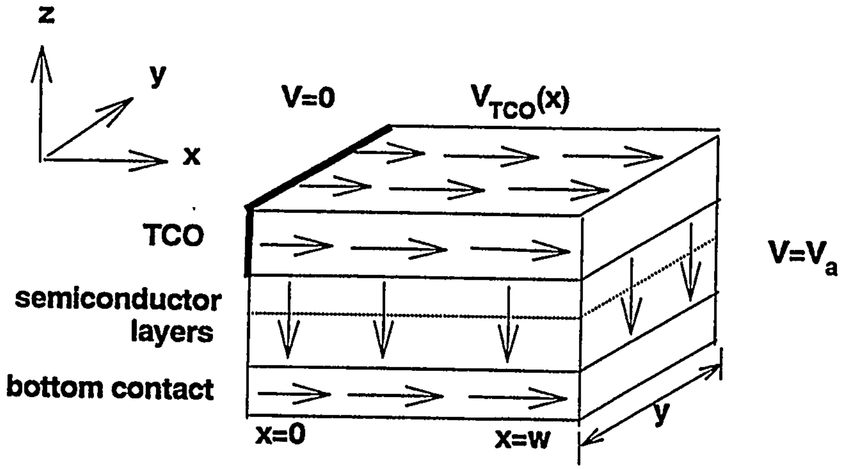

V_{bi}
Zero Bias Equilibrium
CdTe Band At Open Circuit Voltage
Shifted Zero-bias Fermi level
Effective-Fermi
level for $V=V_{OC}$

Primary features of the time-dependent voltage effect

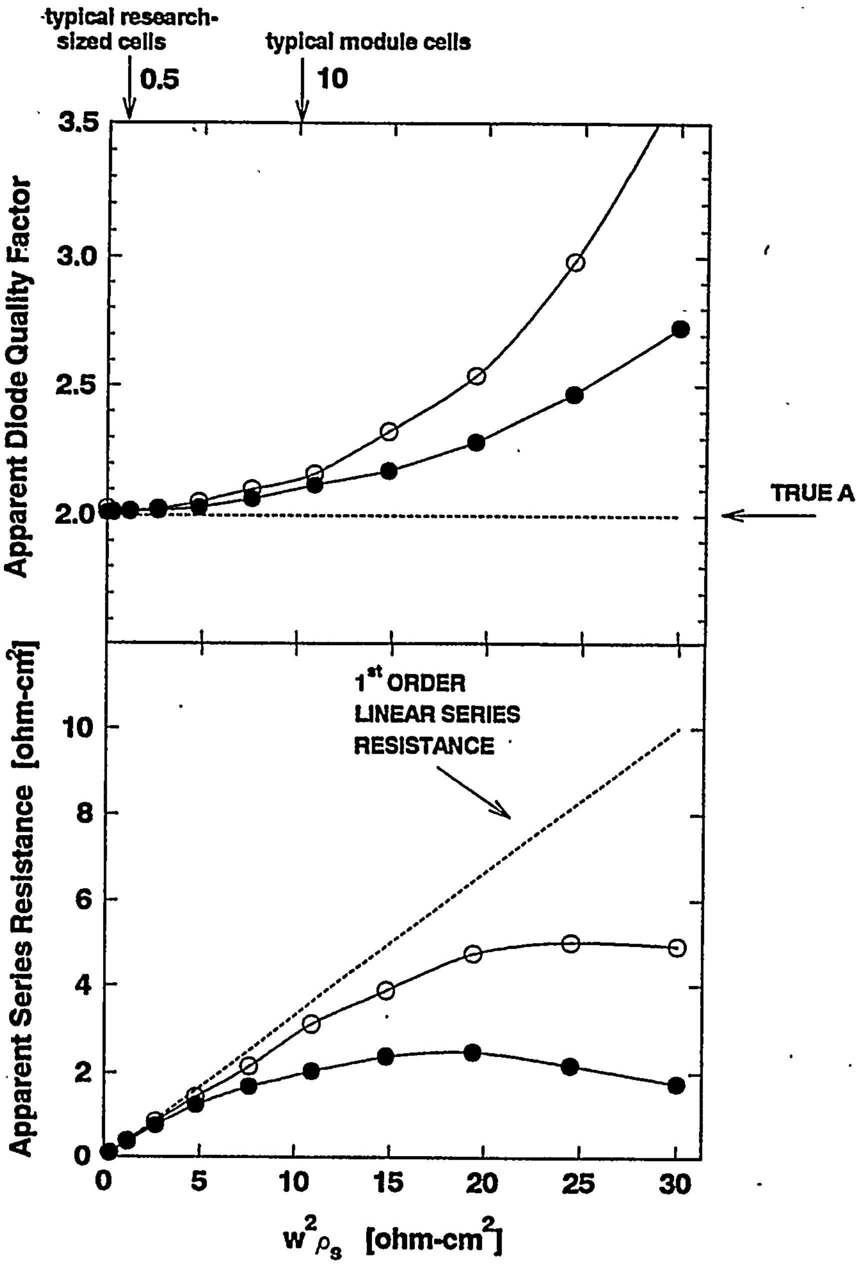
1. Voltage of most thin-film polycrystalline cells continues to increase after a shift to forward bias.
2. The increase is dependent on voltage history, not illumination history.
3. The likely explanation is depopulation of long-lived traps, which modifies the band shape in the depletion region.
4. The traps have time constants spanning at least the 1 ms to 10 ks range. Energies are just above mid-gap, and densities are comparable to absorber carrier densities.
5. Relaxation takes place with essentially the same range of time constants.



Current-voltage curves for research-geometry and module-geometry CdTe cells.



Module cell geometry. Thick line shows top contact.



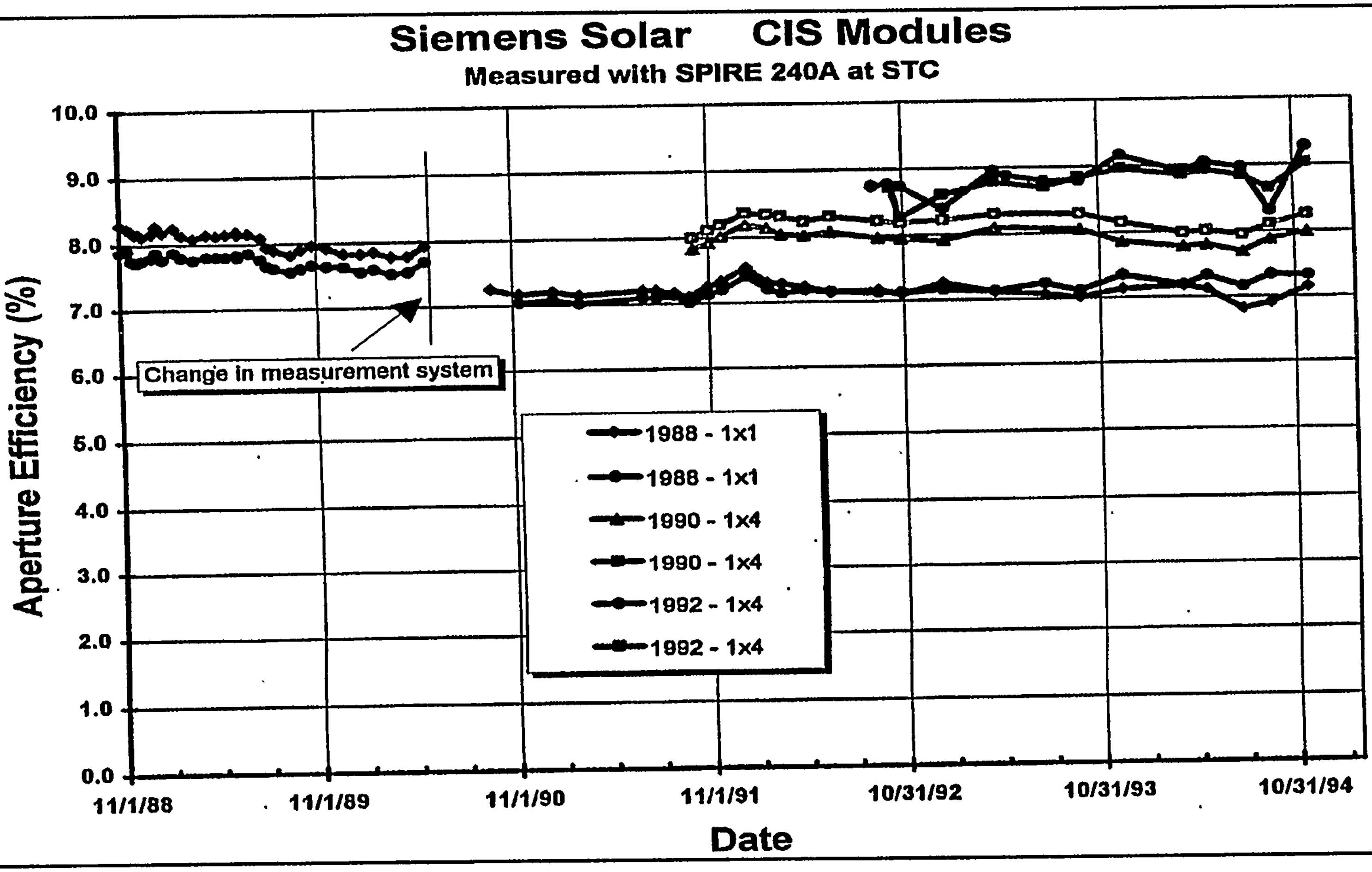
Effect of cell width and TCO sheet resistance on the apparent diode quality factor and series resistance for typical CdTe cells. Open circles are for standard illumination; filled circles for dark circles.

Environmental Testing Of CIS Based Modules

Dennis Willett

Siemens Solar Industries

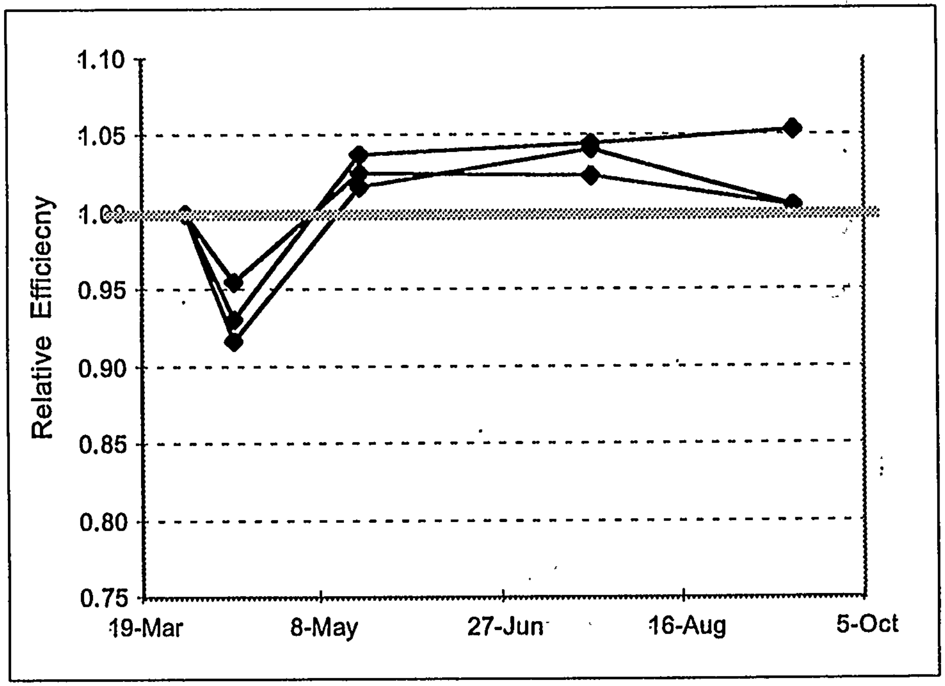
Siemens CIS modules NREL field data



Temporary power loss of laminated mini-modules

The typical temporary power loss due to lamination is -4 to -6%.

Modules recover fully in a few weeks of sun light.



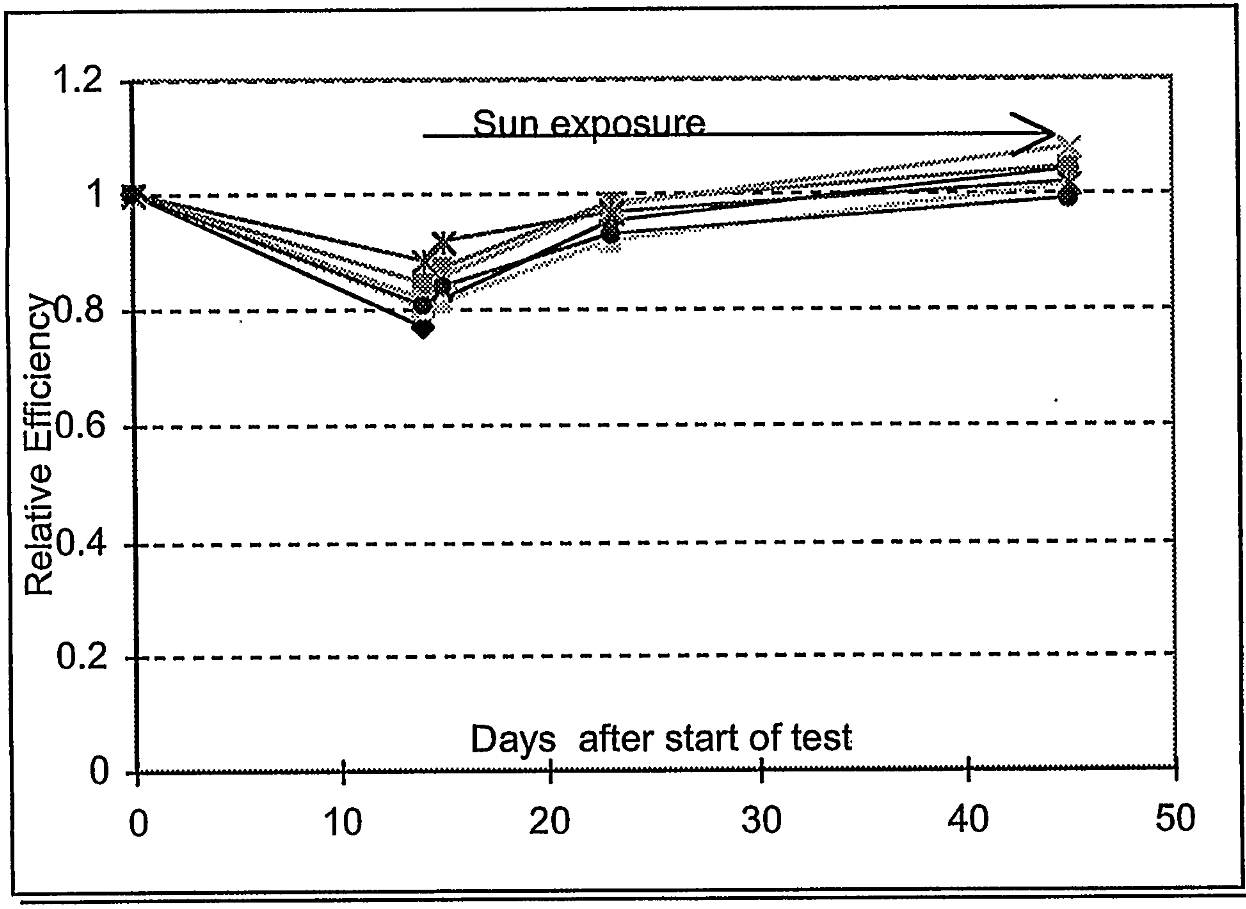
10 x 10 cm mini-modules have not yet passed IEC 1215 environmental tests

IEC 1215 Accelerated Environmental Testing

50 thermal cycles (-40°C / +85°C).
10 humidity freeze cycles (-40°C/ +85°C 85%RH)
1000 hours continuous damp heat (+85°C 85%RH)

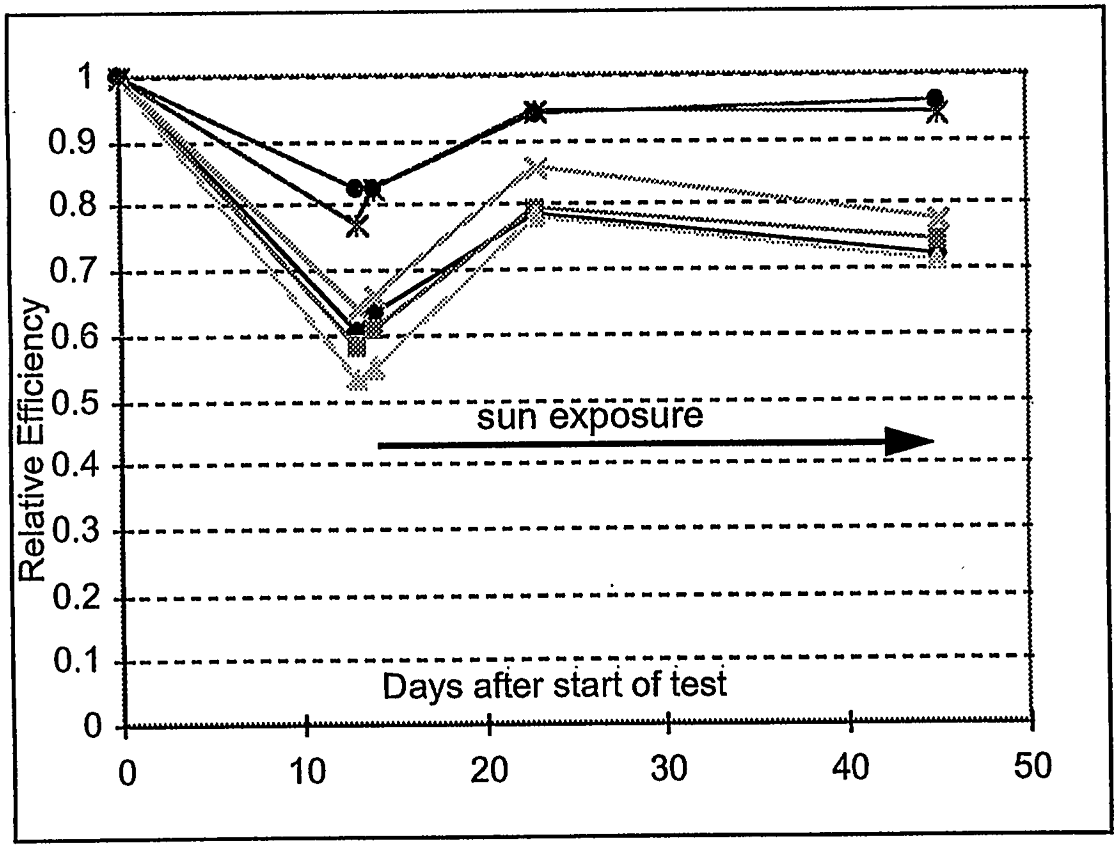
The samples tested are 10x10 cm glass/ EVA /glass laminates. The circuit aperture area is 49.8 sq.cm.

The 50 thermal cycle test



Mini modules lose efficiency but recover fully with sun exposure.

The 10 humidity freeze cycle test



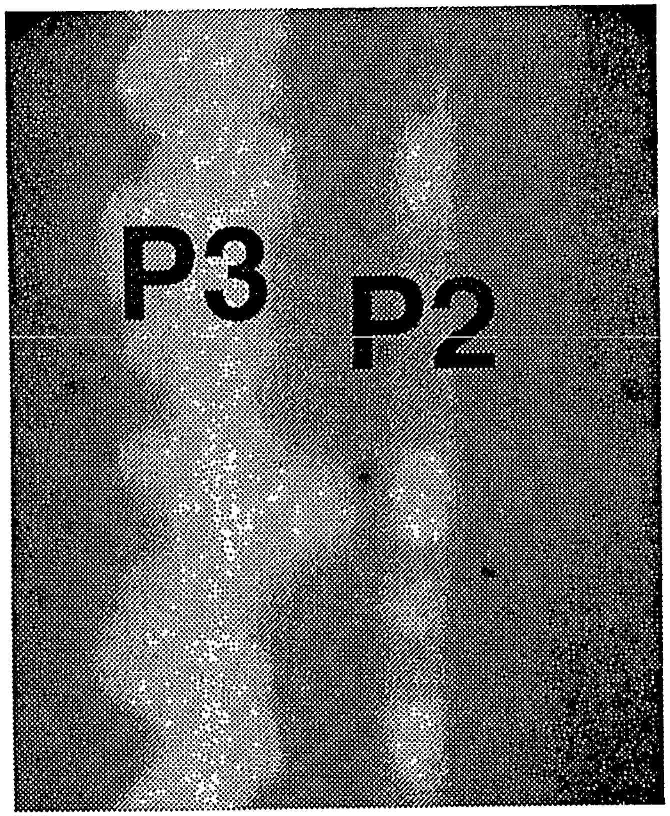
Losses are greater and recovery is more variable and incomplete.

The losses can be attributed to two components

1) A reversible loss due to heating in the dark qualitativly similar to losses seen after lamination

2) Irreversible loss due to moisture penetration of the package in damp heat.

Examination of the circuits after damp heat



The I-V tests indicated a large increase in series resistance.

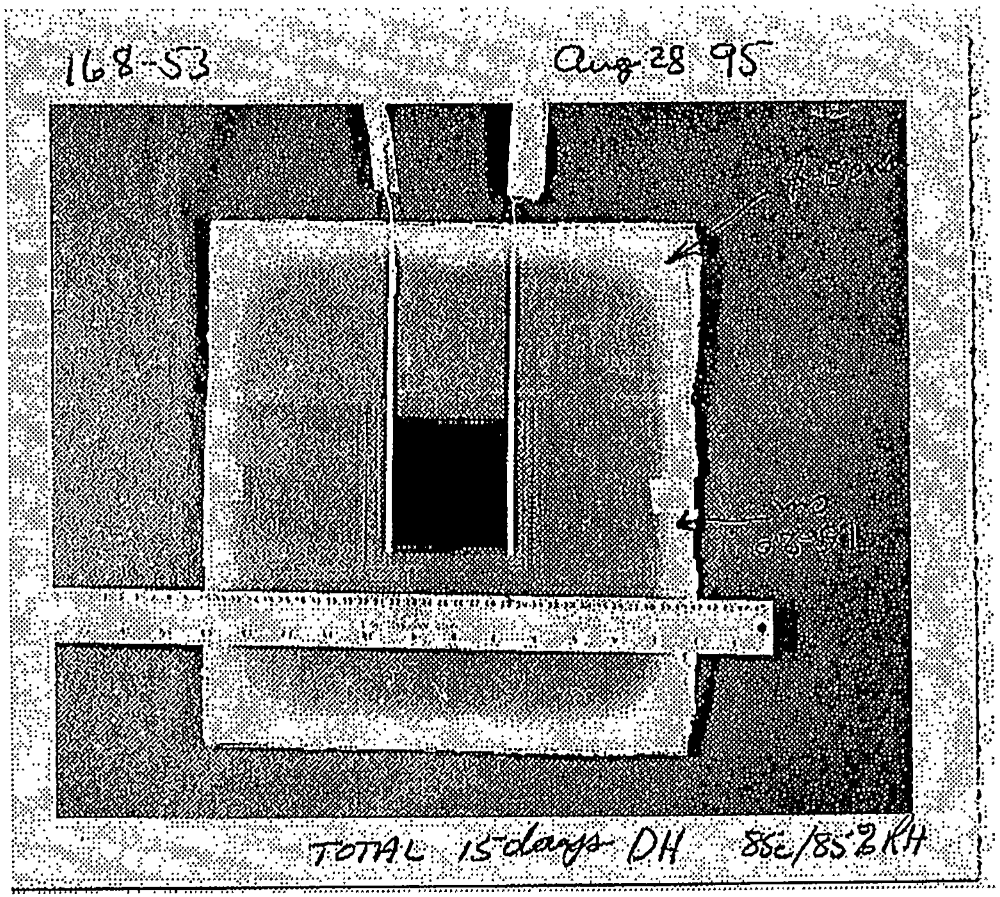
Microscopic examination showed many adhesion failures in the interconnects near the module edges.

Dissection showed the adhesion of the cover glass to EVA and base metal to EVA was poor.

Only the EVA to ZnO adhesion was good.

1000 hours of damp heat causes a large fogged edge.

Test coupons show moisture ingress into the package.



Interconnect test structures in damp heat testing

The sheet resistance increases strongly after the moisture reaches the ZnO.

The contact resistance increases earlier than the ZnO sheet resistance.

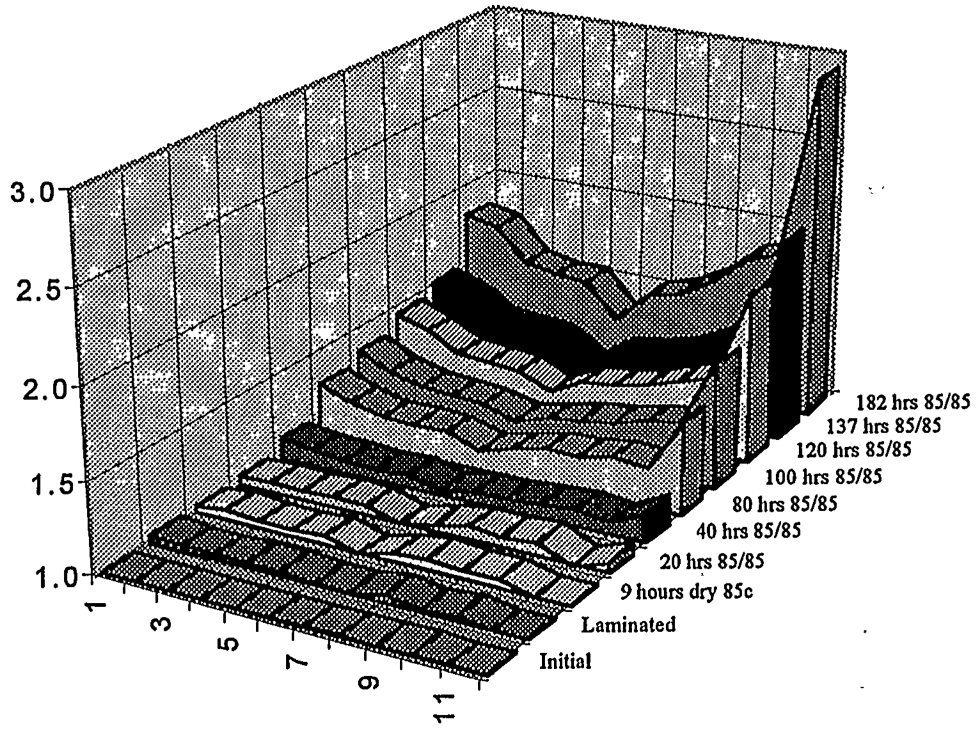
This earlier increase may be due to moisture wicking along the pattern lines.

Interconnect test structures can measure the ingress

The chart shows each line resistance normalized to the initial measurement.

The edges of the circuit are much more affected.

Pattern line #12 is closest to the edge.



Summary

Moisture ingress causes permanent increases in the series resistance of modules.

Improved packaging is need for better high humidity reliability.

Dry dark heat causes temporary power losses which recover in sun light.

The Reliability and Stability of Multijunction Amorphous Silicon PV Modules

David E. Carlson
Solarex
826 Newtown-Yardley Road
Newtown, PA 18940

Solarex is developing a manufacturing process for the commercial production of 8 ft^2 multijunction amorphous silicon (a-Si) PV modules starting in 1996. The device structure used in these multijunction modules is: glass/textured tin oxide/p-i-n/p-i^*-n/ZnO/Al/EVA/Tedlar where the back junction of the tandem structure contains an amorphous silicon germanium alloy (see Fig. 1). As an interim step, 4 ft^2 multijunction modules have been fabricated in a pilot production mode over the last several months. The distribution of initial conversion efficiencies for an engineering run of 67 modules (4 ft^2) is shown in Fig. 2. Measurements recently performed at NREL indicate that the actual efficiencies are about 5% higher than those shown in Fig. 2, and thus exhibit an average initial conversion efficiency of about 9.5%. The data in Fig. 2 indicate that the process is relatively robust since there were no modules with initial efficiencies less than 7.5%.

The modules are subjected to the qualification testing procedure shown in Fig. 3. The tests are all detailed in procedures established by the Commission of European Communities (CEC) or the NREL Interim Qualification Tests (IQT). The wet hi-pot test is performed at 4000 V since we are considering array voltages as high as 1500 V. Fig. 4 lists the qualification tests that are performed on Solarex PV modules and also references the CEC or IQT procedure.

The 4 ft^2 multijunction modules described above have been encapsulated using a single sheet of EVA/Tedlar and pass all the tests shown in Fig. 3. Long-term outdoor tests are continuing on 4 ft^2 modules, and 8 ft^2 multijunction modules will be available for testing in the next few months.

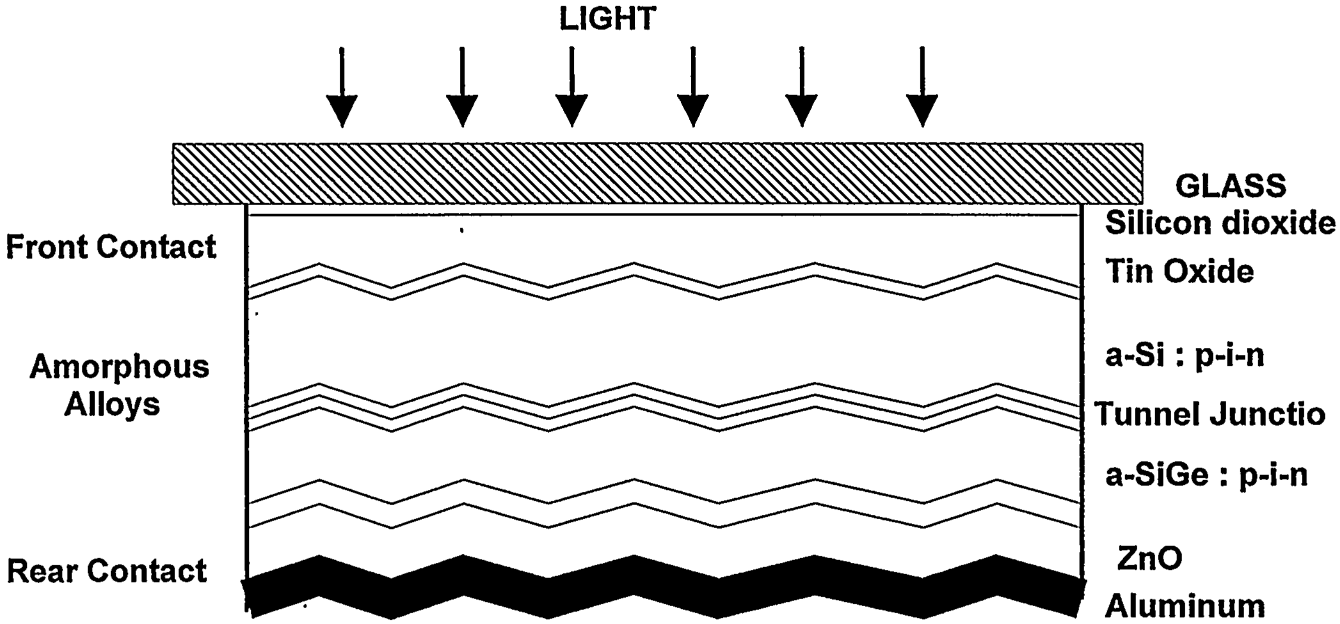
Solarex is commercializing multijunction modules with an a-Si/a-SiGe tandem structure since these modules exhibit higher stabilized conversion efficiencies than those exhibited by single-junction a-Si PV modules. As shown in Fig. 5, both single-junction and tandem junction a-Si PV modules exhibit light-induced degradation in the first few hundred hours of continuous light exposure. However, while single-junction modules typically stabilize at conversion efficiencies of about 4.5 to 5%, the present tandem-junction modules generally stabilize at efficiencies of about 8% to 8.5%.

Fig. 6 shows the degradation in normalized efficiency for 1 ft^2 tandem modules where 4 of the modules were exposed to continuous illumination indoors and 8 of the modules were mounted outdoors. Some of the modules were mounted outdoors in frames that enclosed the back while others had no back protection. There is no significant difference in the performance of the modules after more than 100 days of outdoor exposure (or 500 hours of equivalent indoor exposure). These modules were encapsulated using a spray-on polyurethane paint which passes all the tests shown in Fig. 3 except the wet hi-pot test.

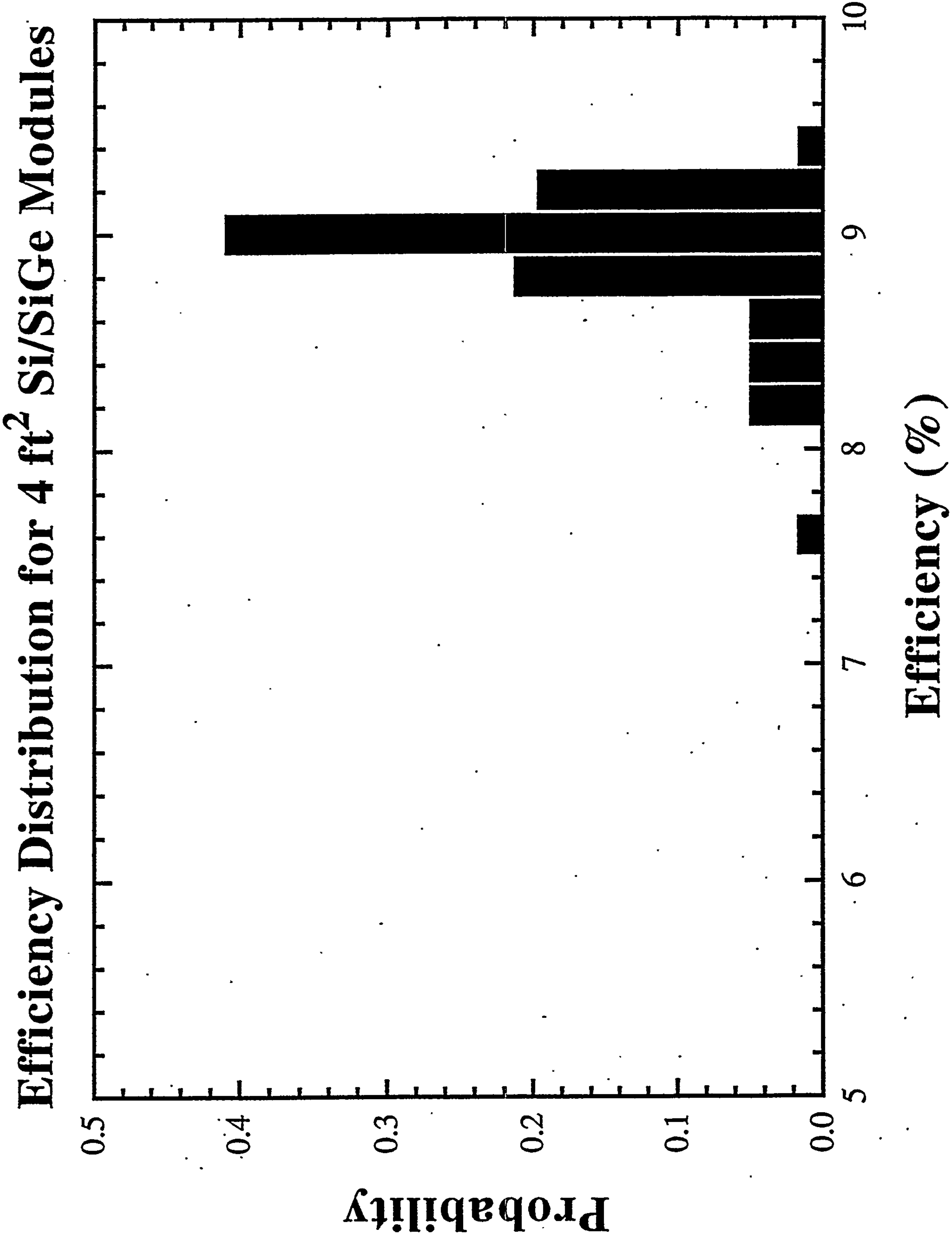
Figure 7 shows similar data for both 1 ft^2 and 4 ft^2 multijunction modules that were mounted outdoors. After about 200 days of outdoor exposure, the 4 ft^2 modules have degraded by about 14 - 18%. The average degradation observed on 1 ft^2 tandem modules is about 17% for 1000 hours of continuous illumination (~ 100 mw/cm^2).

The stability of the tandem junction structure has also been investigated at elevated temperatures both in the dark and under intense illumination. As shown by the top curve in Fig. 8, the normalized conversion efficiency starts to degrade after heat treating the structures for 1 hour at 200^0C, the degradation accelerates as the heat treatment temperature is increased. Both single-junction and tandem junction devices that are fabricated with tin oxide front contacts and zinc oxide/aluminum rear contacts exhibit similar behavior. This degradation appears to be due to the diffusion of hydrogen near the p/i interface. Fig. 9 shows that the degradation in the spectral response occurs mainly in the short-wavelength regime for a single-junction device heat treated at 220^0C. Exposing the devices to intense illumination (~ 50 suns) increases the rate of degradation significantly. This light-enhanced degradation at elevated temperatures is irreversible and occurs mainly at short wavelengths and can be attributed to the light-enhanced diffusion of hydrogen. This is in contrast to the reversible degradation observed at lower temperatures where the degradation in the spectral response occurs mainly at longer wavelengths (see Fig. 10).

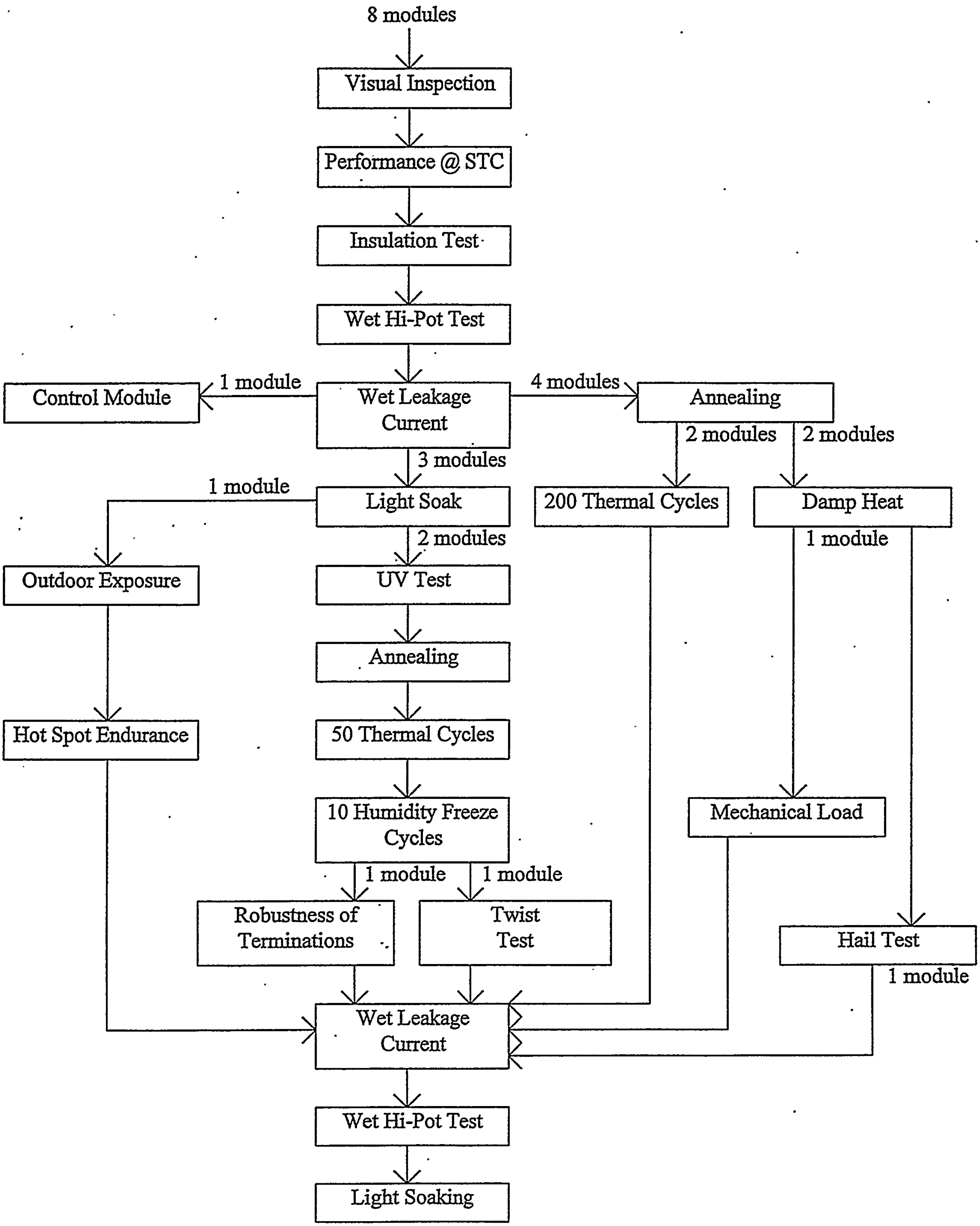
Degradation due to the diffusion of hydrogen will not be a factor under normal operating conditions since the activation energy is ~ 1.5 - 1.7 eV (see Fig. 11). However, since the activation energy for hydrogen diffusion decreases to ~ 1.0 eV under intense illumination, a tandem cell operating at 100^0C will degrade significantly after a few days at ~ 50 suns.



Multijunction Tandem Device Structure

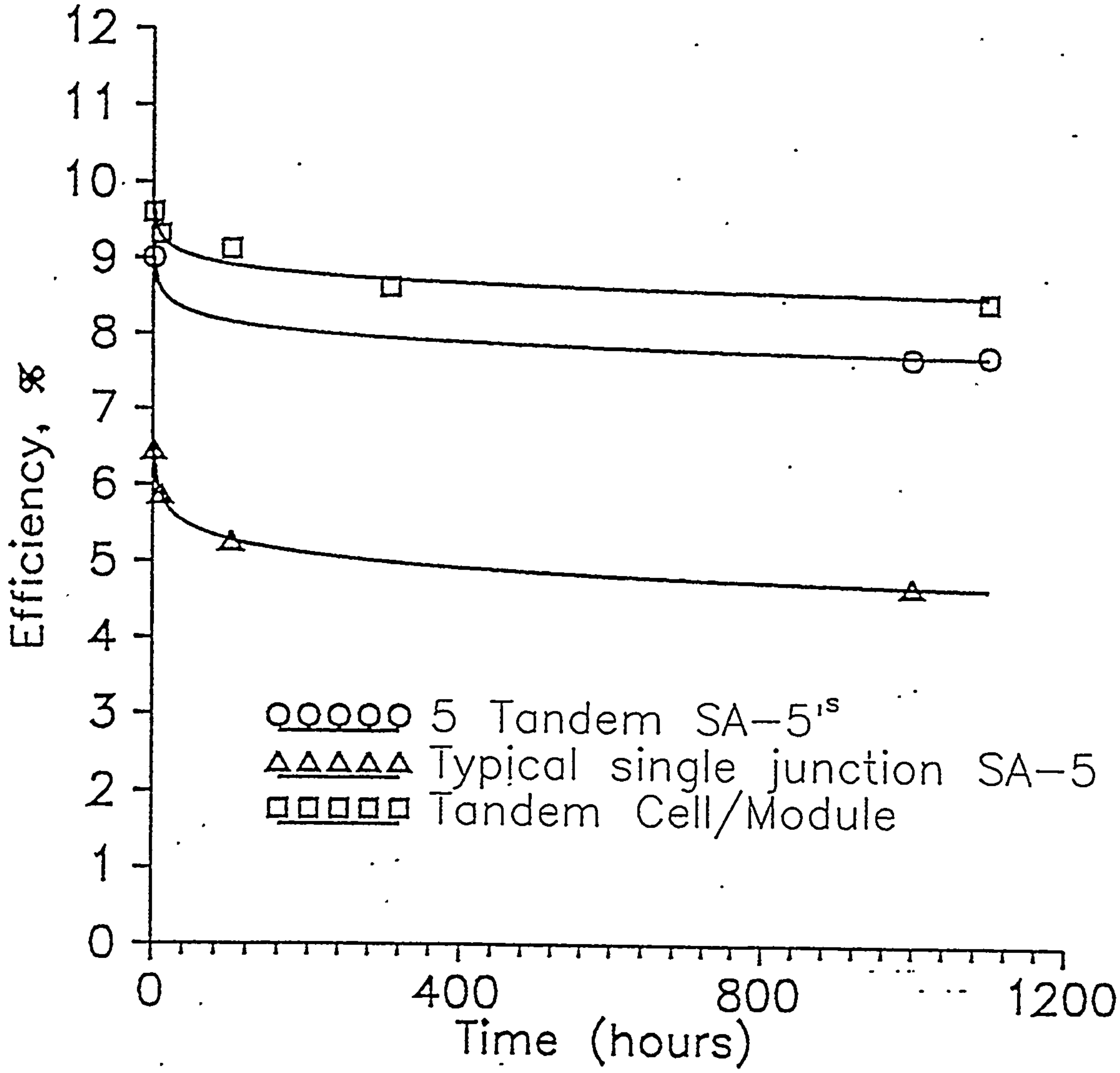


Efficiency Distribution for 4 ft^2 Si/SiGe Modules


8 modules
Visual Inspection
Performance @ STC
Insulation Test
Wet Hi-Pot Test
Control Module
1 module
Wet Leakage Current
4 modules
Annealing
2 modules
2 modules
3 modules
1 module
Light Soak
200 Thermal Cycles
Damp Heat
2 modules
1 module
Outdoor Exposure
UV Test
Annealing
Hot Spot Endurance
50 Thermal Cycles
10 Humidity Freeze Cycles
Mechanical Load
1 module
1 module
Robustness of Terminations
Twist Test
Hail Test
1 module
Wet Leakage Current
Wet Hi-Pot Test
Light Soaking

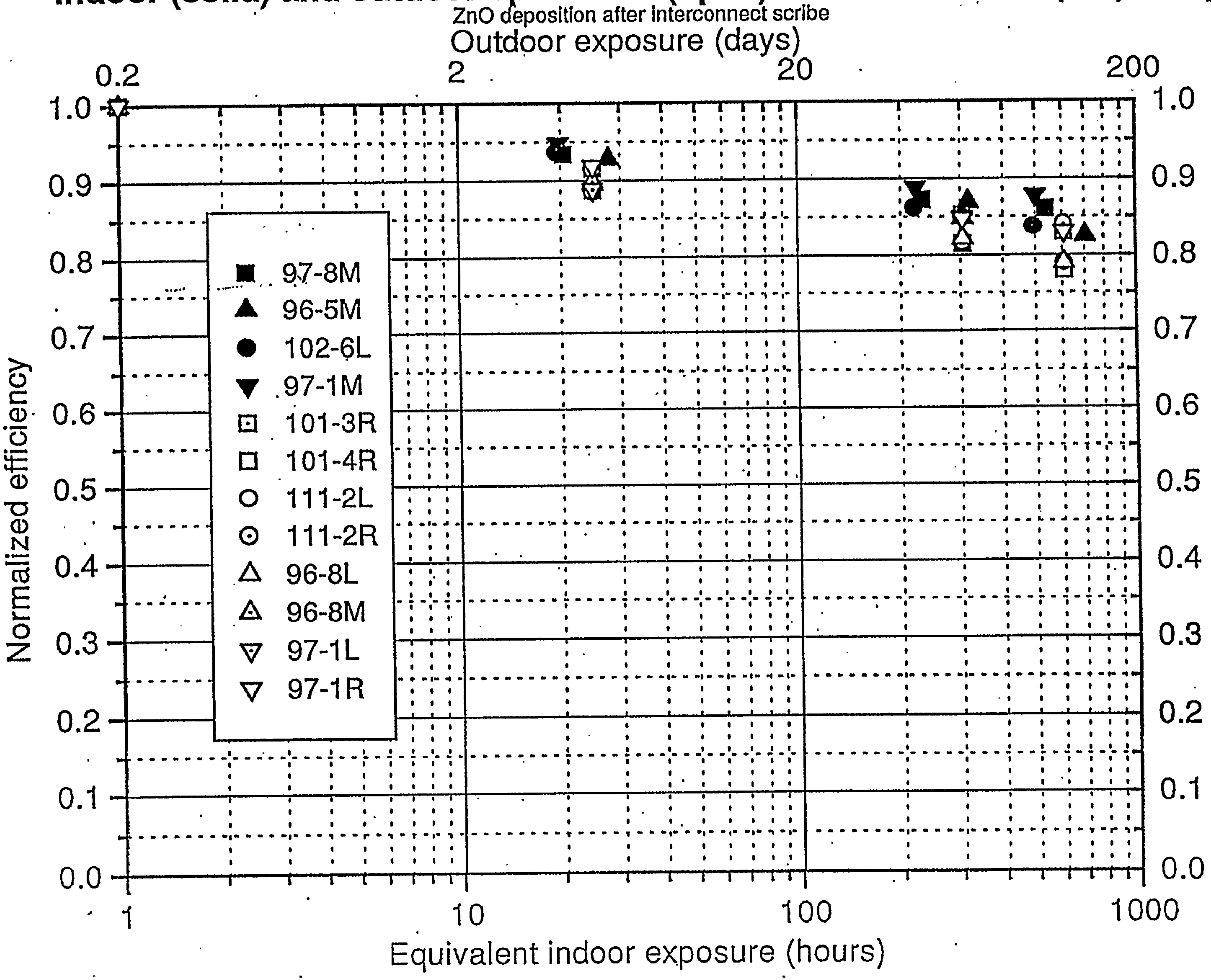
Solarex Qualification Tests

Test	Reference
Insulation	CEC B3
Measure Temperature Coefficient	CEC B4
Measure NOTC	CEC B5
Performance at NOTC	CEC B6
Performance at Low Irradiation	CEC B7
Outdoor Performance	CEC B8
Hot Spot Endurance	CEC B9
UV Exposure	CEC B10
Thermal Cycle	CEC B11
Humidity Freeze	CEC B12
Damp Heat	CEC B13
Robustness of Terminations	CEC B14
Twist	CEC B15
Mechanical Load	CEC B16
Hail Impact	CEC B17
Light Soaking	CEC B18
Annealing	CEC B19
Wet Leakage Current	CEC B20
Wet Hi-Pot	IQT 4.11
Dynamic Load	IQT 4.8



12
11
10
9
8
7
6
5
4
3
2
1
0
Efficiency, %
0
400
800
1200
Time (hours)
5 Tandem SA-5's
Typical single junction SA-5
Tandem Cell/Module

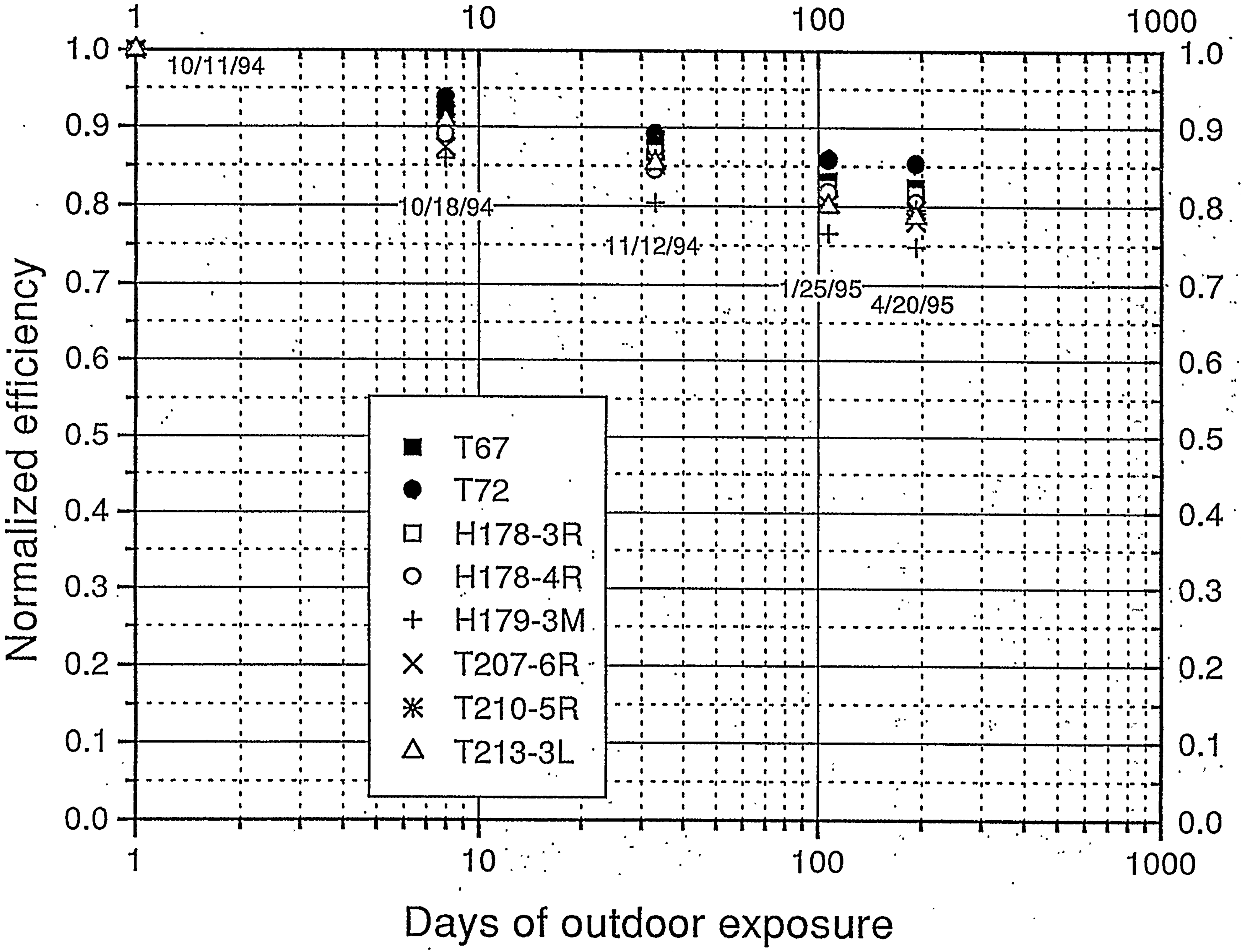
Indoor (solid) and outdoor open-back (open) and closed-back (dot) samples

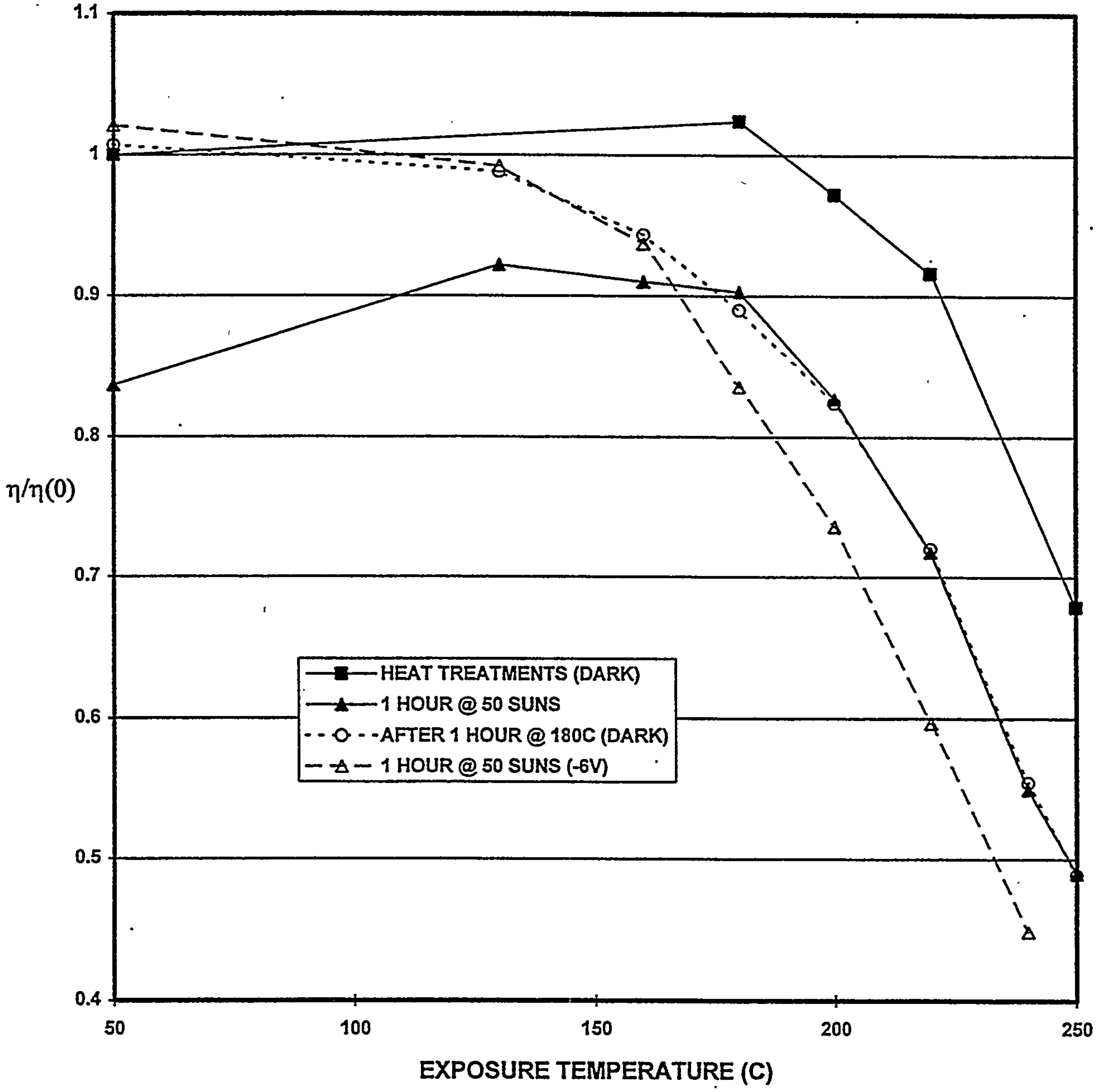


(Indoor: time adjusted for lamp intensity. Outdoor: 5 hrs/day)

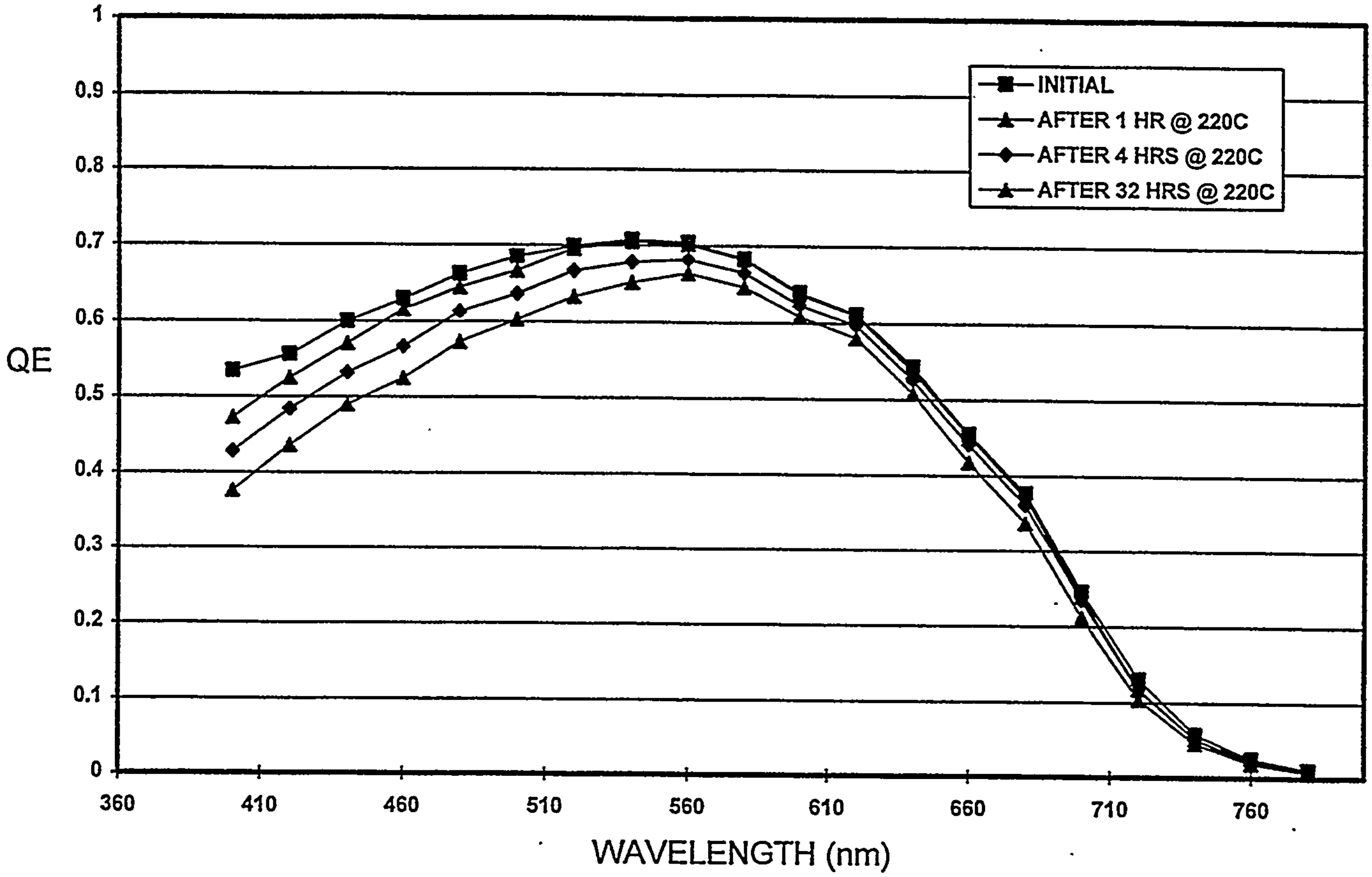
Results of 16x36 (solid), 12x13 Voc (open), and 12x13 Pm (symbol) samples degraded outdoors

No ZnO in interconnect scribes

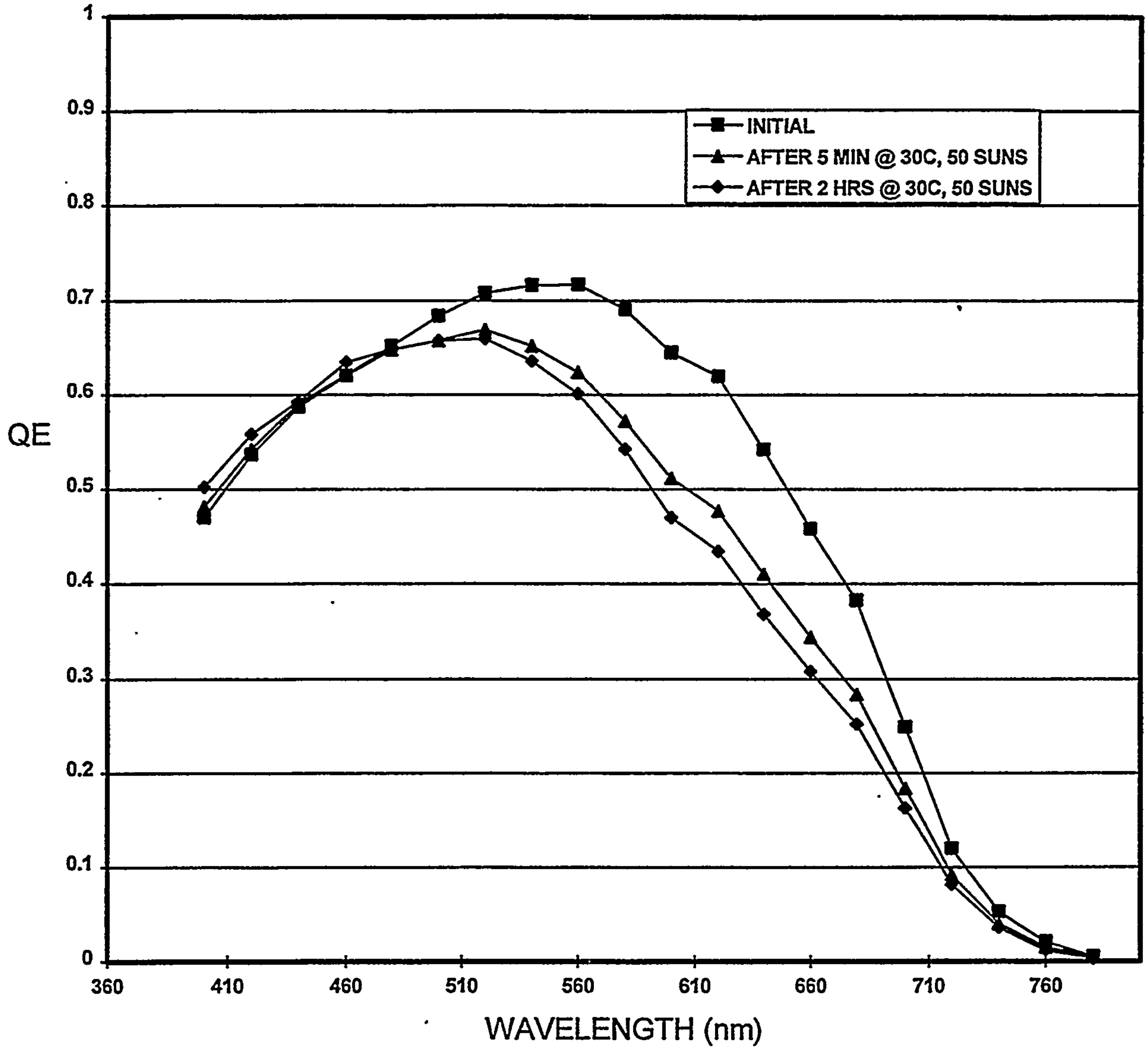




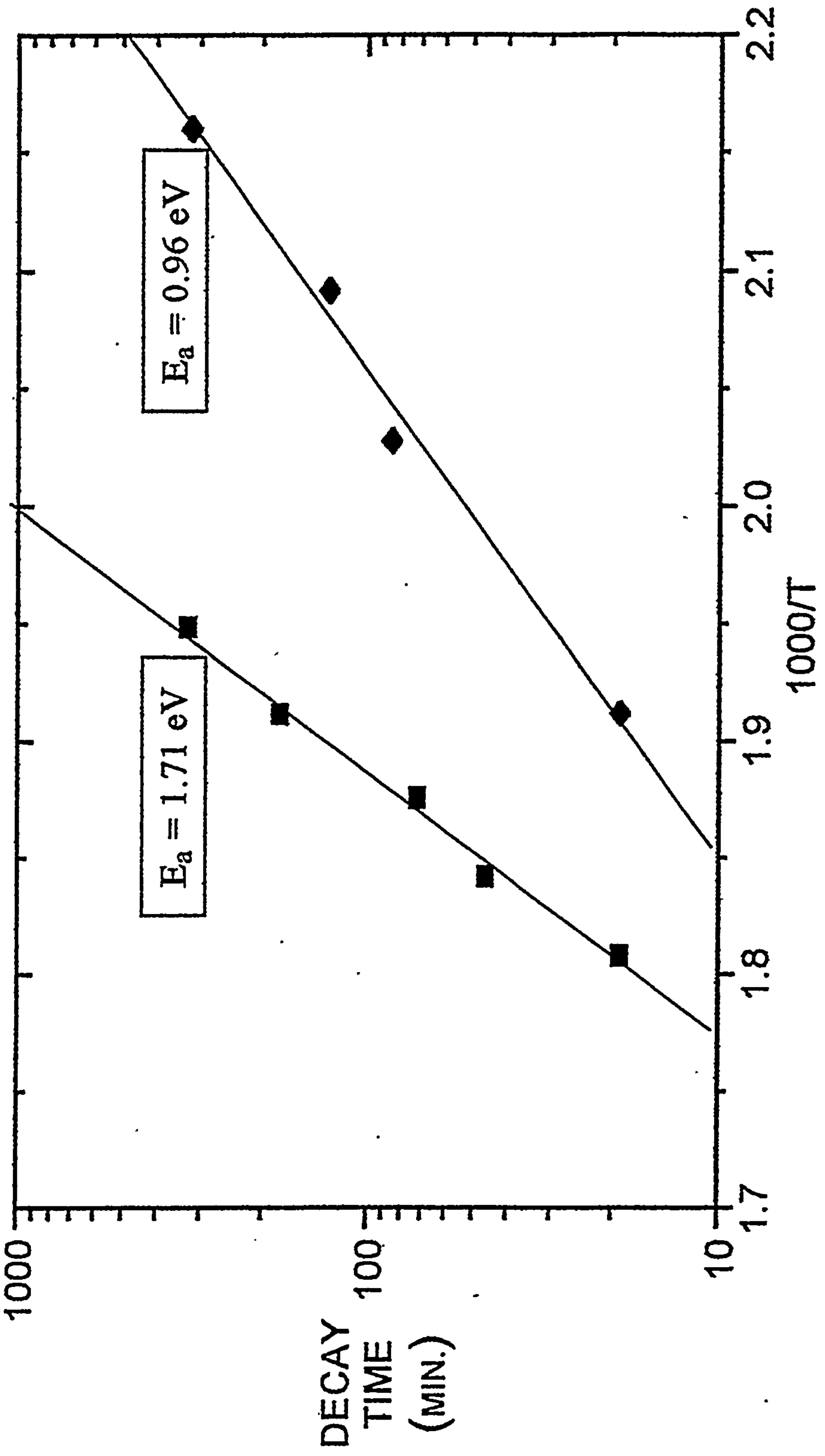
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
η/η(0)
50
100
150
200
250
EXPOSURE TEMPERATURE (C)
HEAT TREATMENTS (DARK)
1 HOUR @ 50 SUNS
AFTER 1 HOUR @ 180C (DARK)
1 HOUR @ 50 SUNS (-6V)



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
QE
360
410
460
510
560
610
660
710
760
WAVELENGTH (nm)
INITIAL
AFTER 1 HR @ 220C
AFTER 4 HRS @ 220C
AFTER 32 HRS @ 220C



INITIAL
AFTER 5 MIN @ 30C, 50 SUNS
AFTER 2 HRS @ 30C, 50 SUNS
QE
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
360
410
460
510
560
610
660
710
760
WAVELENGTH (nm)



DECAY TIME (MIN.)
1000
100
10
1.7
1.8
1.9
2.0
2.1
2.2
1000/T
$E_a = 1.71$ eV
$E_a = 0.96$ eV

A HOLISTIC VIEW OF CRYSTALLINE SILICON MODULE RELIABILITY

Jack I. Hanoka
Evergreen Solar, Inc.
Waltham, MA

Several aspects of module reliability are discussed, particularly with reference to the encapsulant and its interaction with the metallization and interconnection of a module. A need to look at the module as a whole single unit is stressed. Also, the issue of a slight light degradation effect in crystalline silicon cells is discussed. A model for this is mentioned and it may well be that polycrystalline cells with dislocations may have an advantage.

Polymers such as transparent encapsulants degrade when the polymer bonds are broken by UV light and when oxygen is present. Photooxidation is the main culprit in degradation of encapsulants. Thus, UV screening or improved UV stabilization within the polymer along with minimizing oxygen ingress are key to minimizing degradation.

The importance of good adhesion and bonds at interfaces is stressed. The unique qualities of silane coupling agents are described.

The goal of a reliable 30-year module has probably not yet been attained. Technical advances in polymers and possible advances in glasses used for superstrates could allow for this goal to be realized in about 5 years.

A HOLISTIC VIEW OF CRYSTALLINE SILICON MODULE RELIABILITY

Jack I. Hanoka
Evergreen Solar, Inc.
Waltham, MA

NREL Reliability Workshop
Golden, CO
September 7-8, 1995

Evergreen Solar

Outline

1. Approach taken
2. Key areas of concern
3. Focus on the encapsulant
4. Digression on polymers
5. Bonding and adhesion
6. Summary

Approach

Holistic : “Emphasizing the importance of the whole and the interdependence of its parts”

1. Solar cells
2. Metal contacts and leads
3. Encapsulant or pottant
4. Superstrate and substrate

Goal : A reliable 30-year module

Questions:

Are we there yet?

If not, what will it take?

Crystalline silicon solar cells

- Inherently stable device: basically a large-area diode
- No moving parts, nothing to wear out, should last >>30 years
- Can tolerate a surprisingly large number of crystalline defects and still make quite efficient solar cells
- But some things are bad even in very small quantities, i.e., transition metals
- Recently, a small degradation effect noticed where Jsc (mainly) drops 3–5% under light
    - Seen in single-crystal and polycrystalline cells
    - Effect is reduced in polycrystalline cells (1–3%)
    - Lesser effect in polycrystalline cells could be because of dislocations present

Evergreen Solar

Encapsulant

Ideal: Transparent, elastic, chemical bonds to all relevant surfaces, no degradation under heat and sunlight, cost-effective, melts at usual lamination temperatures

Reality: No such material exists yet but we are approaching this ideal

Bare transparent polymers which do or should last > 30 years under sunlight:

Silicone
Acrylic - PMMA
Tefzel - Teflon

Polymer degradation

Factors:
- UV
- Oxygen
- Heat
- Moisture

Chemical bonds in polymer can be broken by UV light in the 300–380 μm range

Polymers degrade by oxidation

<u>Photooxidation</u>

Degradation results in:

- Loss of mechanical properties
- Loss of bonding and adhesion
- Discoloration

Chemical additives can significantly retard degradation

- Anti-oxidants, UV absorbers, HALS
- These are being improved constantly--enormous market pull

Evergreen Solar

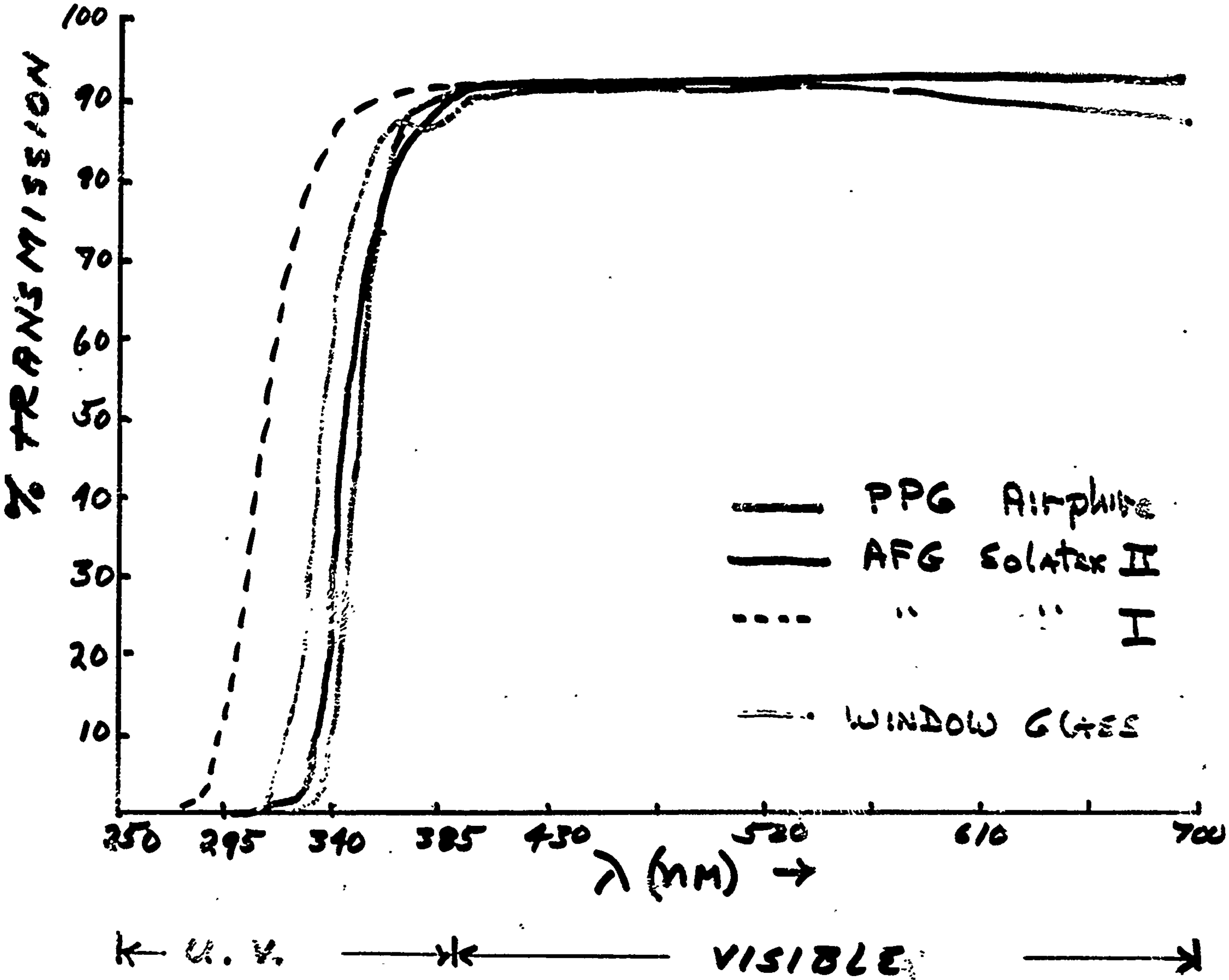
Superstrate glass as a UV screen

Newer glasses with cerium oxide

- Should see improvements in service lifetime of the encapsulant
- Springborn has found this to be true for EVA, along with other improvements in the EVA additives

However, the ideal glass does not exist as a commercial sheet product, i.e., total UV cutoff at $\lambda < 380\ \mu m$

If we had this, a good part of the battle would be won


% TRANSMISSION
100
90
80
70
60
50
40
30
20
10
250
295
340
385
430
520
610
700
λ (nm) →
PPG Airphire
AFG Solatex II
" " I
WINDOW GLASS
← U.V. →
← VISIBLE →

Oxygen

Ideal: Hermetic sealing

Practical: Very tight seals for edges, leads

Polymer backskin or substrate

Polymer backskin or substrate

Must have good barrier properties

(P) Permeability = Solubility x Diffusivity

Crystalline polymers much better than amorphous polymers. $P \propto$ thickness.

Other solutions for backskin: glass, Al foil

Interface bonding of encapsulant important

Bonding and adhesion

Good bonds -- moisture kept out

Hydrolytic stability -- useful criterion

Testing not too standardized -- there are over 27 ASTM tests for bonding and adhesion

3rd ingredient at interface to promote bonding

- Silane coupling agents
- Very effective for some polymer/glass interfaces

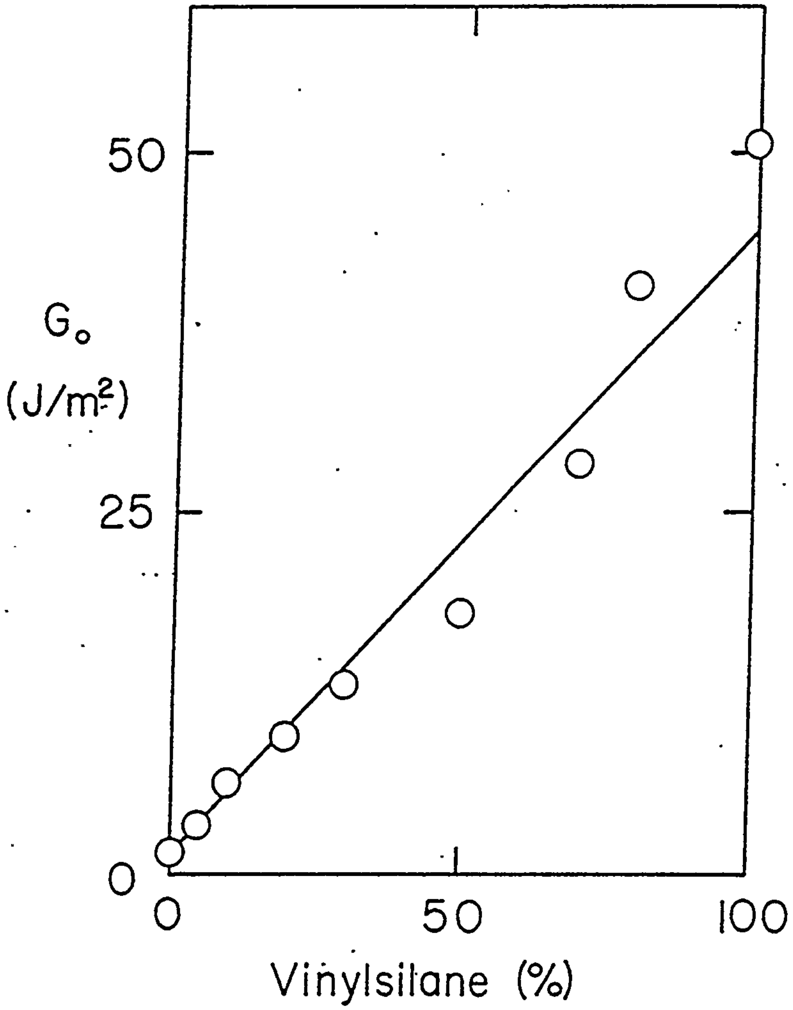


Fig. 30. Threshold strength of adhesion for a polybutadiene layer adhering to glass treated with varying proportions of triethoxyvinylsilane. (Taken from Ref. 161, published by John Wiley & Sons.)

Metallization -- interconnection

Corrosion can result from moisture ingress

Issue is quantitative not qualitative

All polymers have finite permeability to oxygen and water vapor

Adhesion and bonding to metal leads and connections -- more work could be done here, especially sealing around emerging leads

Summary

1. Module should be viewed as a whole -- components interact

2. Crystalline silicon is inherently stable -- small degradation effect in crystalline silicon probably due to Fe-B pairs -- polycrystalline may have an advantage

3. A 30-year module:
   Better UV screening or more UV resistant encapsulants
   Sealing out of oxygen and moisture
   Accelerated life testing more standardized

4. Prognosis:
   Not yet there but excellent chance of reaching it within 5 years

Photovoltaics Radiometric Issues and Needs

A Summary of the Results of the Photovoltaic Radiometric
Measurements Workshop, July 24-25 1995

Daryl R. Myers

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1617 Cole Blvd, Golden CO 80401

WORKSHOP OBJECTIVES

- *Identify* current and future needs and concerns for future DOE/NREL radiometric research and engineeringh related to PV
- *Report* progress on radiometric action items from previous workshops
- *Update* participants on current activities

PARTICIPATION

- 26 Attendees
    - 14 National Labs
    - 6 Industry
    - 4 Universities
    - 2 Utilities
- 13 issues/concerns discussed relating to PV engineering testing
- 6 issues concerns related to Solar Radiation Resource Data

RADIOMETRY FOR PV ENGINEERING APPLICATIONS

- *Traceability* to the World Radiometric Reference Working Standard Group of absolute cavity radiometers for broadband solar radiometric standards, and National Institute of Standards and Technology reference standards of spectral irradiance is critical to maintaining high standards of radiometric measurements.

- *Radiometric measurement guides for the PV community* are needed that can be easily understood and widely disseminated. Document broadband and spectral calibration, characterization, and measurement techniques

- *Well defined goals for PV radiometric measurements* must be described and documented. Define PV radiometric measurements needed; whether w. r. t. standard spectrum (SRC) or prevailing conditions (energy rating or performance)

- *Documented uncertainty analysis* must accompany broadband and spectral radiometric data to justify and/or limit the interpretation of PV calibration or PV performance data.

- *Periodic calibration checks and Statistical Process Control* need to be incorporated into radiometric measurements to meet quality assurance needs, and the requirements already set forth in accreditation standards, including interlaboratory collaborations.

- *Accreditation of PV testing, rating, and performance laboratories* will require addressing the points above to meet national and international accreditation and certification standards.

- *Current Broadband radiometric accuracy of ±3.0%* satisfactory for long term (more than 5 year) monitoring, but inadequate for efficient, accurate study of 1% per year degradation in PV performance or reference devices.

- *Increased participation in radiometric standards development* better disseminate procedures, methods; support national (ASTM, IEEE) and international (ANSI, ISO) consensus standards with U.S. interests and technical knowledge

- *Solar radiometric instrumentation* improved at the price of increased cost. Instrumentation characterization still very important (& labor intensive, costly). Better, less expensive instrumentation is still a need.

- *Indoor vs outdoor PV performance correlations* are relatively poor, within uncertainties of ±5%; study of diffuse (sky) radiation contributions and simulator collimated radiation distributions may resolve some of the discrepancies.

- *PV module and system ratings* are still needed representing the kiloWatthours produced as a function of kiloWatthours available for conversion

- *PV system and radiometric data correlations* can be studied for quality assurance of both system and radiometric instrumentation (near real time)

- *Accelerated weathering* and correlations with real exposure conditions require better measurements and understanding of enhanced, artificial radiation sources (Ultraviolet, Infrared, etc.) as well as various climate radiometric and meteorological data.

The overriding need is for enhanced communication of the existing NREL radiometric methods, procedures, practices, and expertise by the team to the PV community

PV SOLAR RADIOMETRIC RESOURCE DATA

- *Blanket coverage, including international coverage*: never measured (or meteorological) data for a specific site
- *Application guides* for correct use and interpretation of resource assessment data such as measured, statistically summarized, or "typical" data are needed
- *Encourage use of a single data base* would eliminate confusing comparison results based on different data bases

- *Interpolation and extrapolation* techniques for are needed, even for dense, gridded data sets, to obtain the 'blanket coverage' mentioned above.

- *Availability of data*, whether via hardcopy publications, magnetic media, or electronic transfer (Internet or e-mail) needs to be more effectively communicated.

- *Radiometric models and conversion algorithms* must be made available, validated and continually improved, and if possible made simpler to use, with less sophisticated input data requirements

RADIOMETRIC MEASUREMENTS & EVALUATION

Three immediate goals & near term objectives:

(1) **Disseminate NREL PV Radiometric expertise**: produce a technical manual, guide, or technical report describing NREL PV Module and System Performance and Engineering Project "best practice" for radiometric instrumentation, methods, and practices.

(2) **Maintain radiometric calibration traceability** to the World Radiometric Reference (WRR) through 8th International Pyrheliometric Comparisons to be conducted in Davos, Switzerland in October 1995. Continue liason and traceability to the National Institute of Standards and Technology Radiometric Physics Division for spectral radiometric calibrations, and improving radiometry for PV applications in general.

(3) **Increase participation in consensus standard development and validation** participating in consensus standards organizations, such as the American Society of Testing and Materials (ASTM), Institute of Electrical and Electronic Engineers (IEEE), and the Council for Optical Radiation Measurements (CORM), to aid in development and validation of radiometric standards related to PV performance and evaluation applications.

CONCLUSIONS

- Three main objectives to be incorporated into FY 1996 and future planning (Annual Operating Plans)

- "Stay the course" in terms of maintaining radiometric expertise, instrumentation, and capability for day-to-day operations

- Continued interaction with the PV engineering test community results in proper focus, direction.

Temperature and Irradiance Behavior of Photovoltaic Devices

Team Leader: Keith Emery (303) 384-6632

Cells:

Coordinator: Halden Field 384-6685
Donald Dunlavy

Modules:

Coordinator: Steve Rummel 384-6287
Jehoshua Caiyem
Laurence Ottoson

Procedures for Measuring Temperature Coefficients

With the irradiance fixed measure I-V as a function of temperature

- Assumes measured temperature is junction temperature.
- Assumes spectral mismatch error is temperature independent
- Different sign and values for multi-junction cells

Measure I-V outdoors at different irradiances and temperatures

- Assumes measured temperature is junction temperature.
- Assumes spectral mismatch error is temperature independent
- Different sign and values for multi-junction cells
- Typically neglects spectral variation with irradiance
- Temperature coefficient assumed independent of irradiance

Cell or Module Temperature

Temperature dependence is from the PV space-charge region temperature

Can measure front or back surface temperature

Under sunlight a temperature gradient will exist between the space-charge region and the point of temperature measurement

2-5°C for commercial Si modules
3->8°C for glass laminates
large for concentrators

Temperature Coefficient in ppm / °C

Perform a curve fit of a parameter, P as a function of temperature

$$T_{coef} = \frac{10^6}{P} * \left.\frac{\delta P}{\delta T}\right|_{T_n=25°C}$$

Correct P_{T_m} measured at temperature T_m to another temperature T

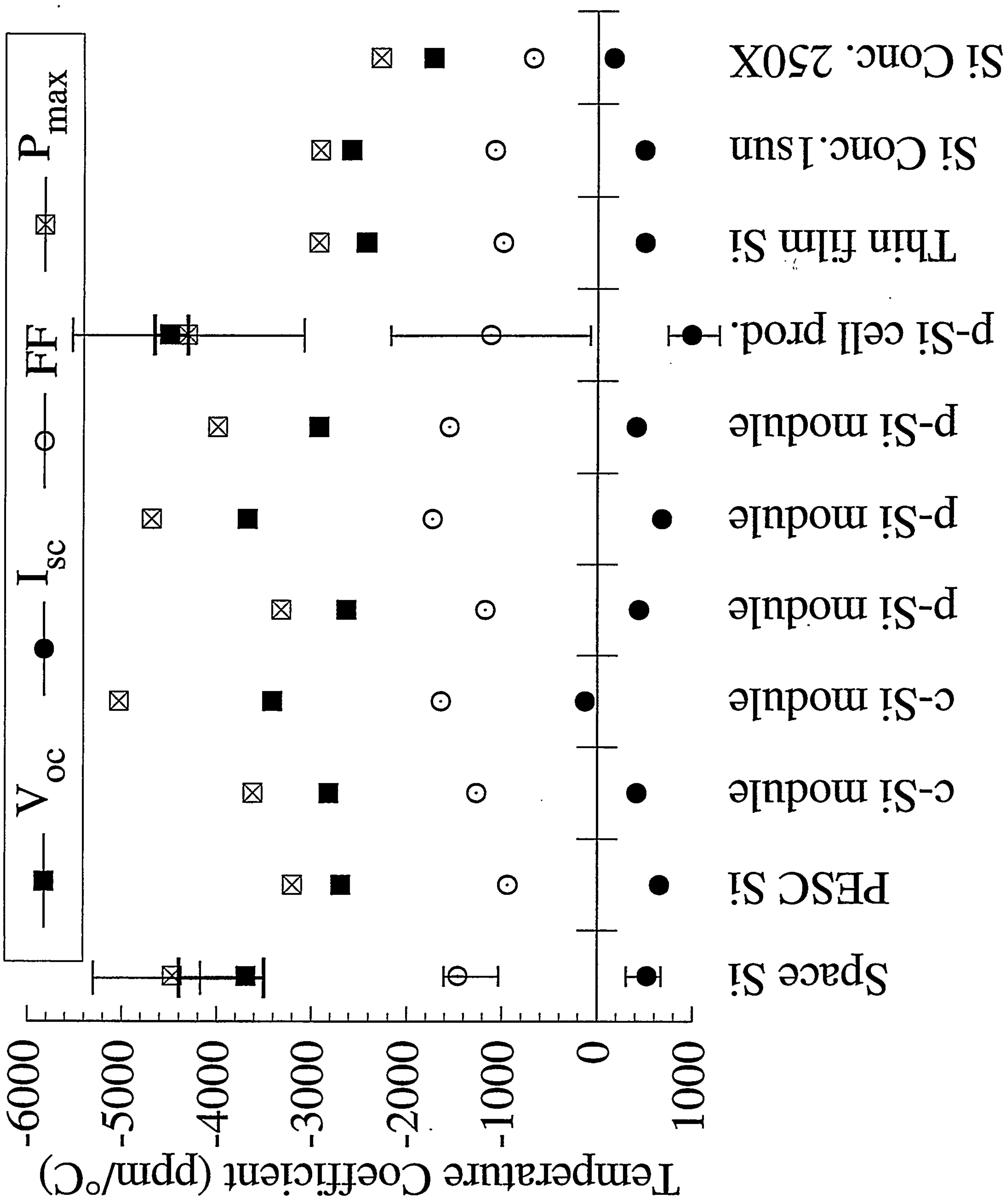
$$P_T = P_{T_m} + \frac{10^{-6} * T_{coef} * P_{T_m} * (T - T_m)}{1 - T_{coef} * 10^{-6} * (25°C - T_m)}$$

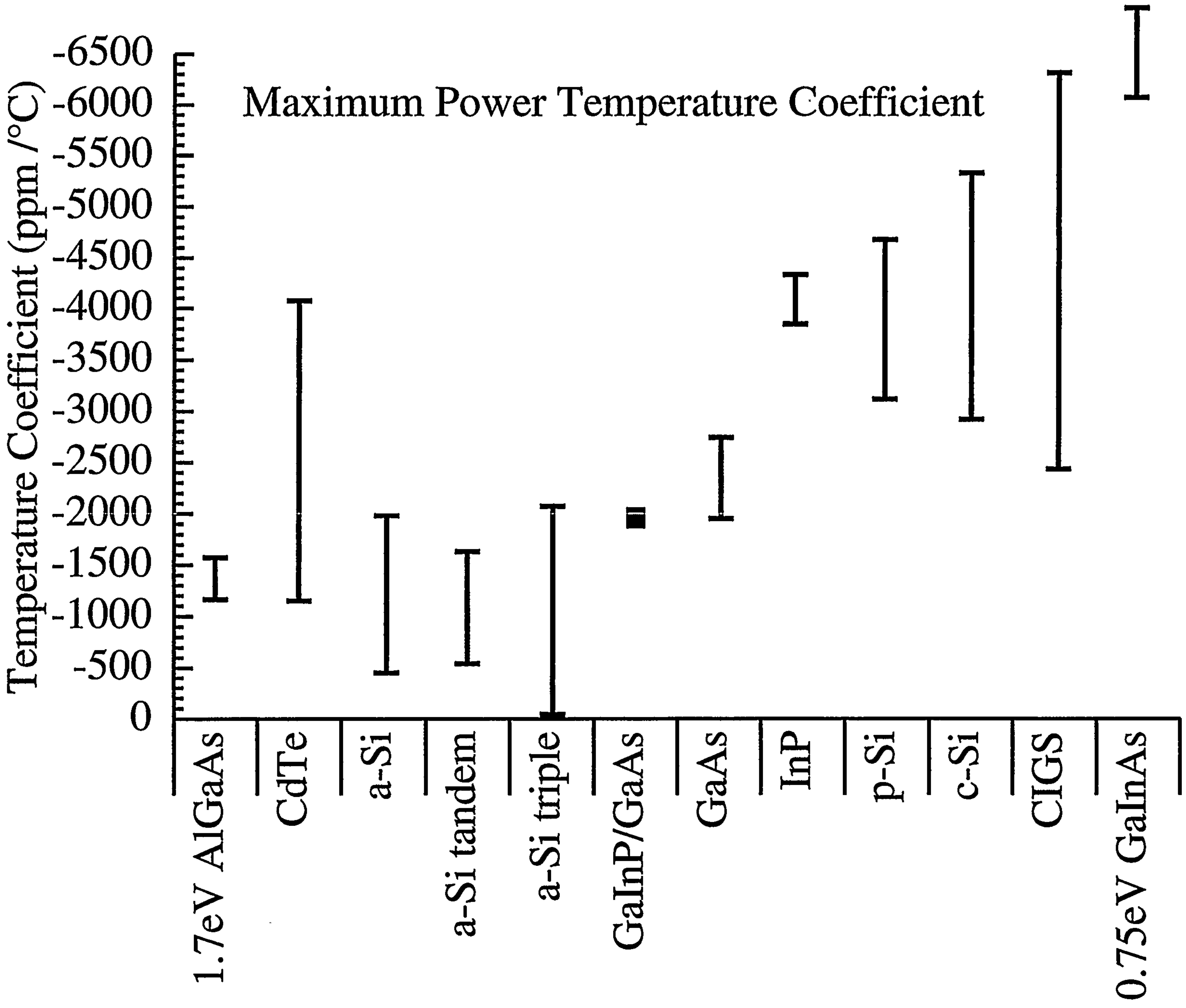
Single and Multi-Crystal Silicon Temperature Coefficients

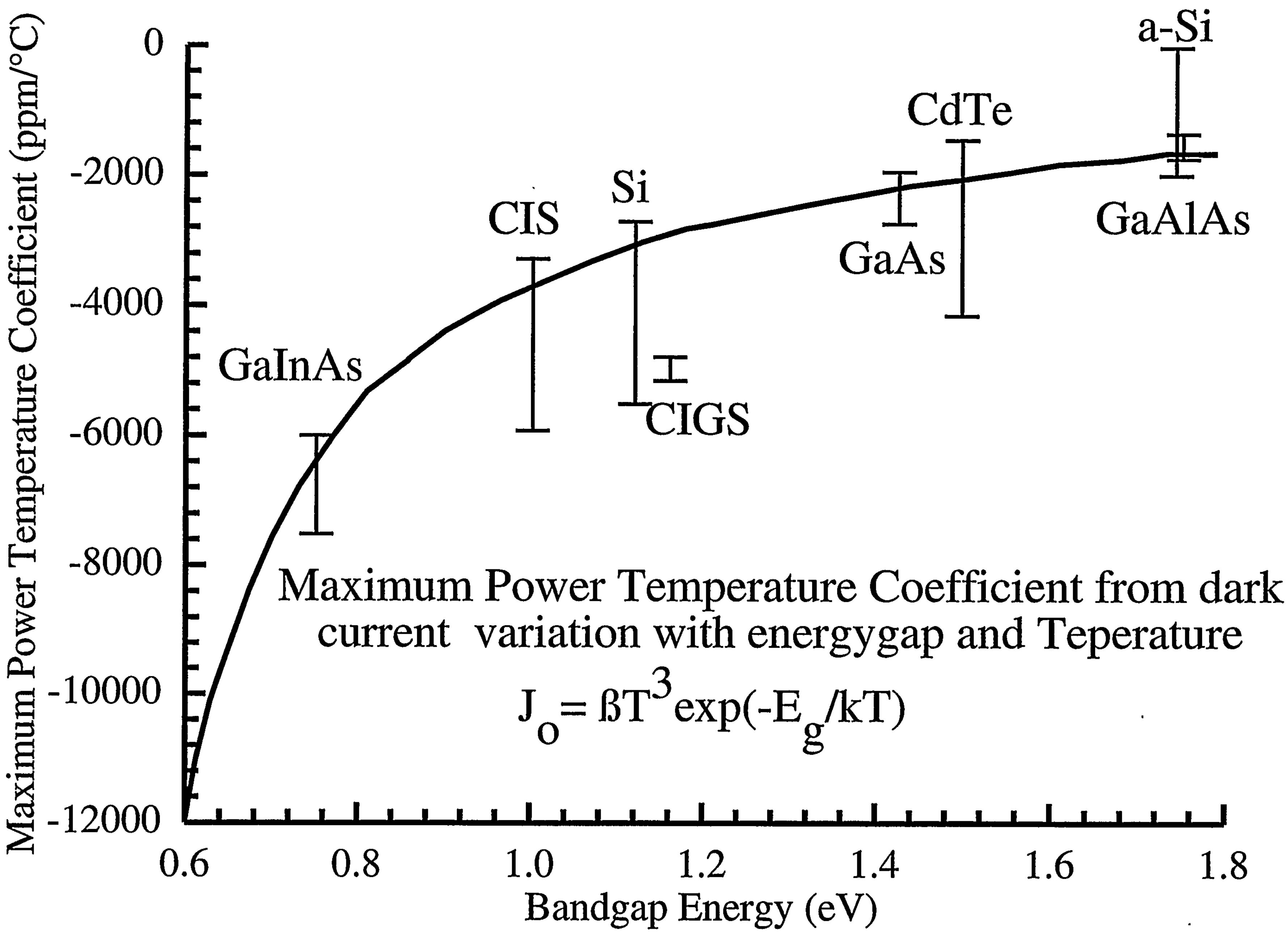
Type	V_{oc}	I_{sc}	FF	P_{max}
	-ppm/°C	ppm/°C	-ppm/°C	-ppm/°C
Space Si	3490-4510	380-710	1000-1600	4070-1600
PESC Si	2690	650	940	3200
c-Si module	2817	411	1265	3619
c-Si module	3413	-130	1642	5035
p-Si module	2632	435	1172	3318
p-Si module	3675	675	1732	4690
p-Si module	2925	407	1556	3996
p-Si cell prod.	4330-4679	738-1230	84-2159	3067-5569
Thin film Si	2429	493	993	2929
Si Conc.1/ 250 suns	2584/ 1724	488/ 168	1079/ 680	2916/ 2282

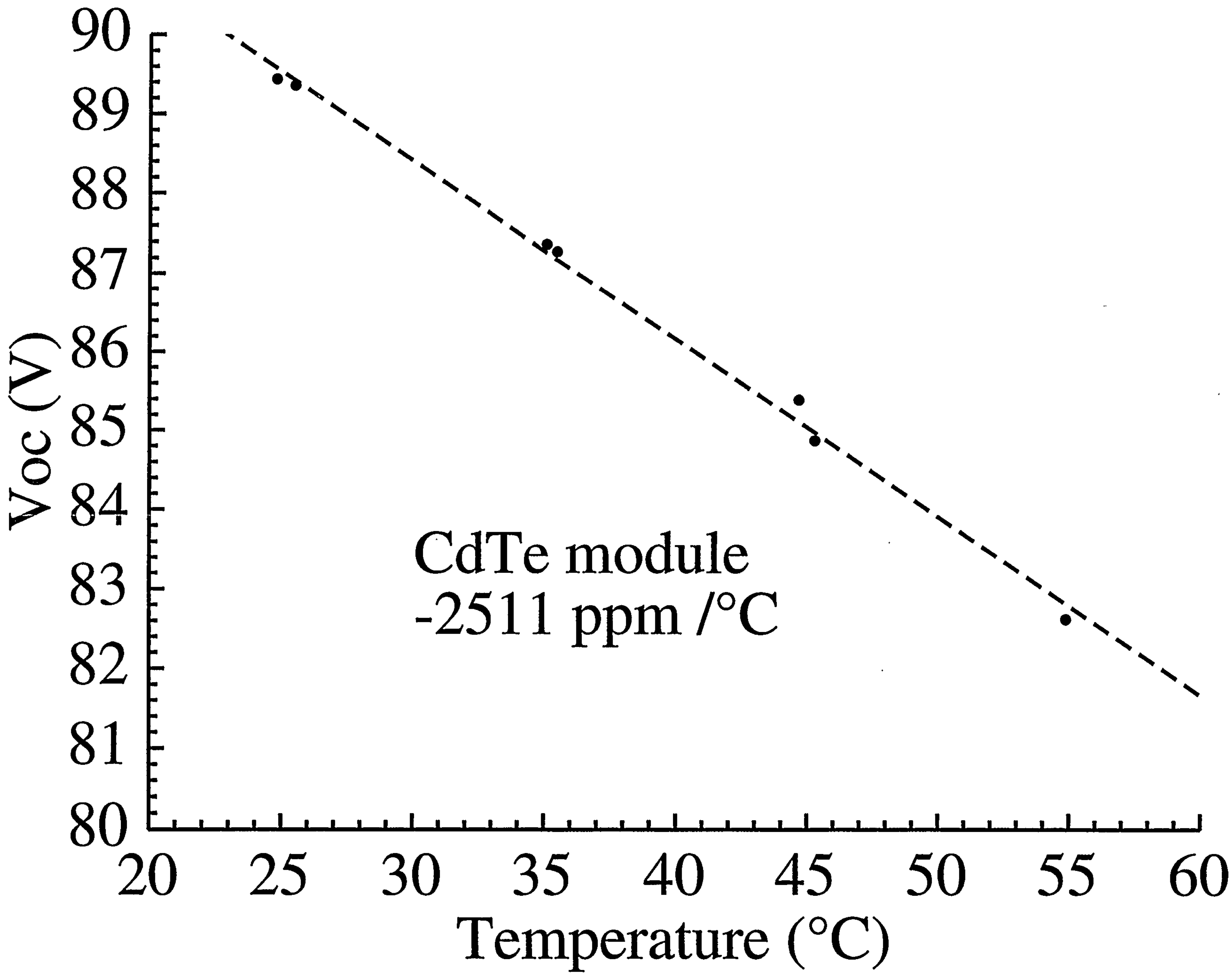
Intercomparison of Isc Temperature Coefficients (PEP 87' intercomparison)

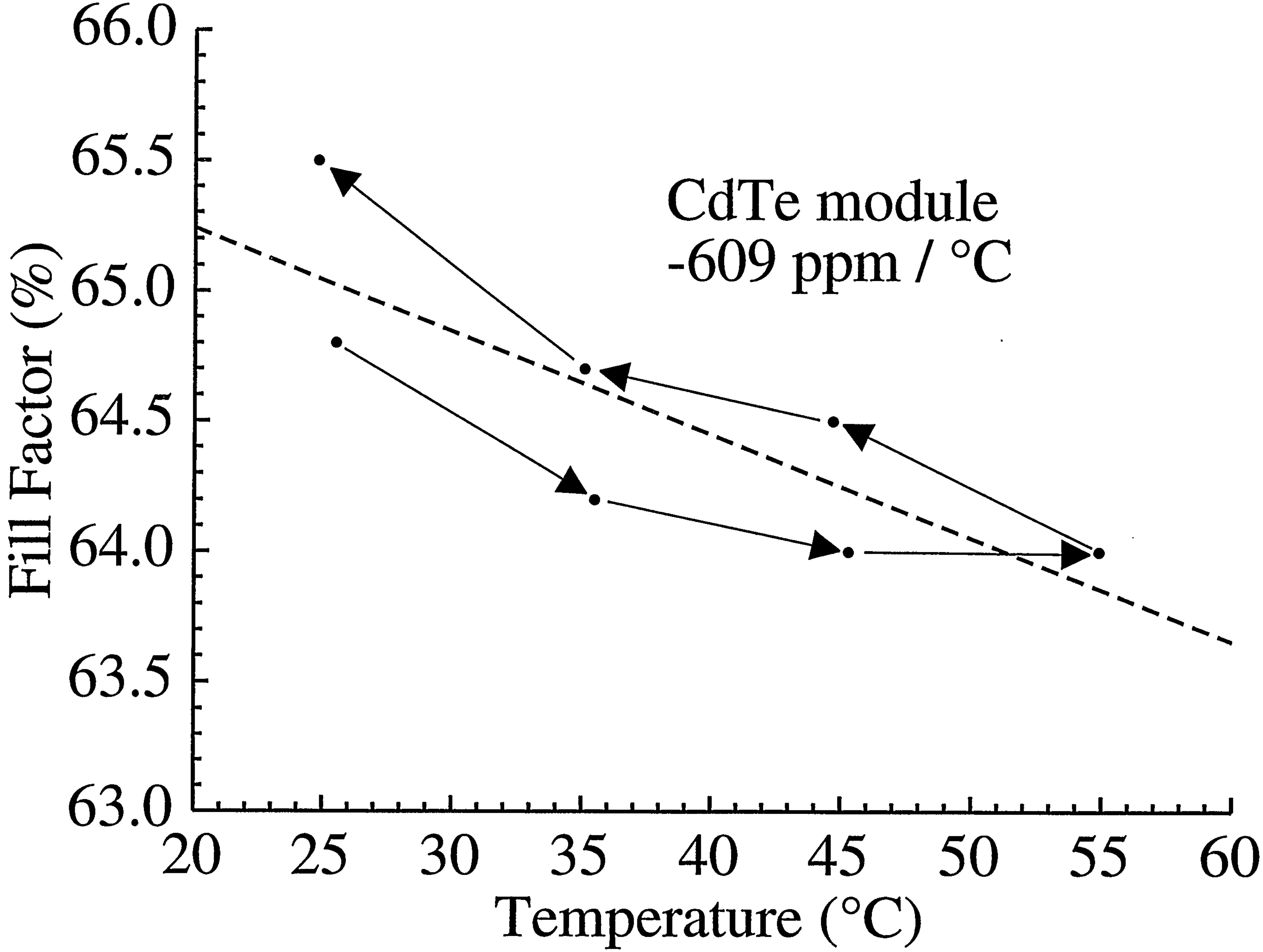
Group	Cell	Cell in module	Module
amorphous Si			
NREL	950	1580	1590
ENEA	-	890	-
PTB	1590	-	-
mono-Si			
NREL	580	680	380
ENEA	-	590	-
PTB	460	-	-

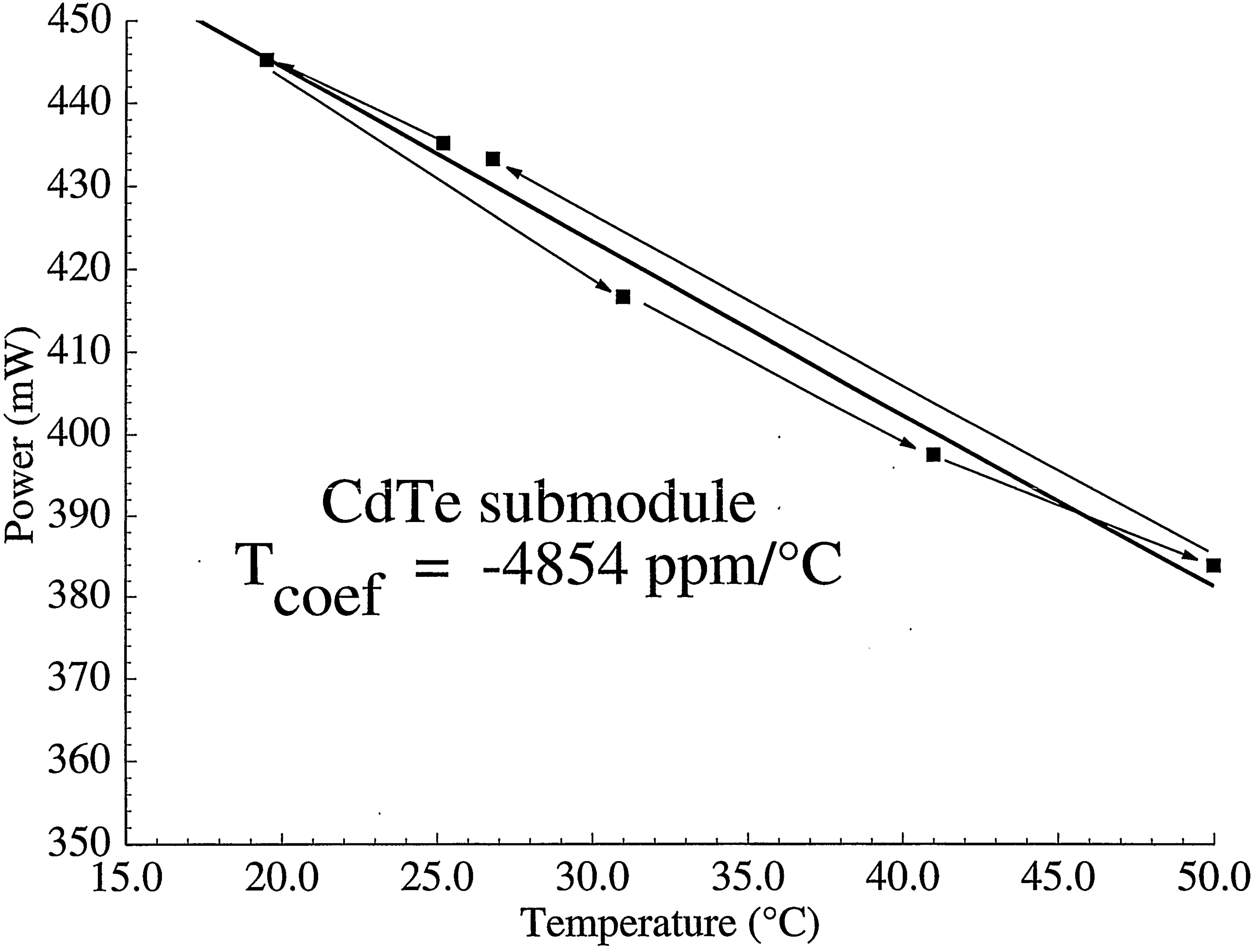

Temperature Coefficient (ppm/°C)
-6000
-5000
-4000
-3000
-2000
-1000
0
1000
Space Si
PESC Si
c-Si module
c-Si module
p-Si module
p-Si module
p-Si module
p-Si cell prod.
Thin film Si
Si Conc. 1sun
Si Conc. 250X
V_{oc}
I_{sc}
FF
P_{max}

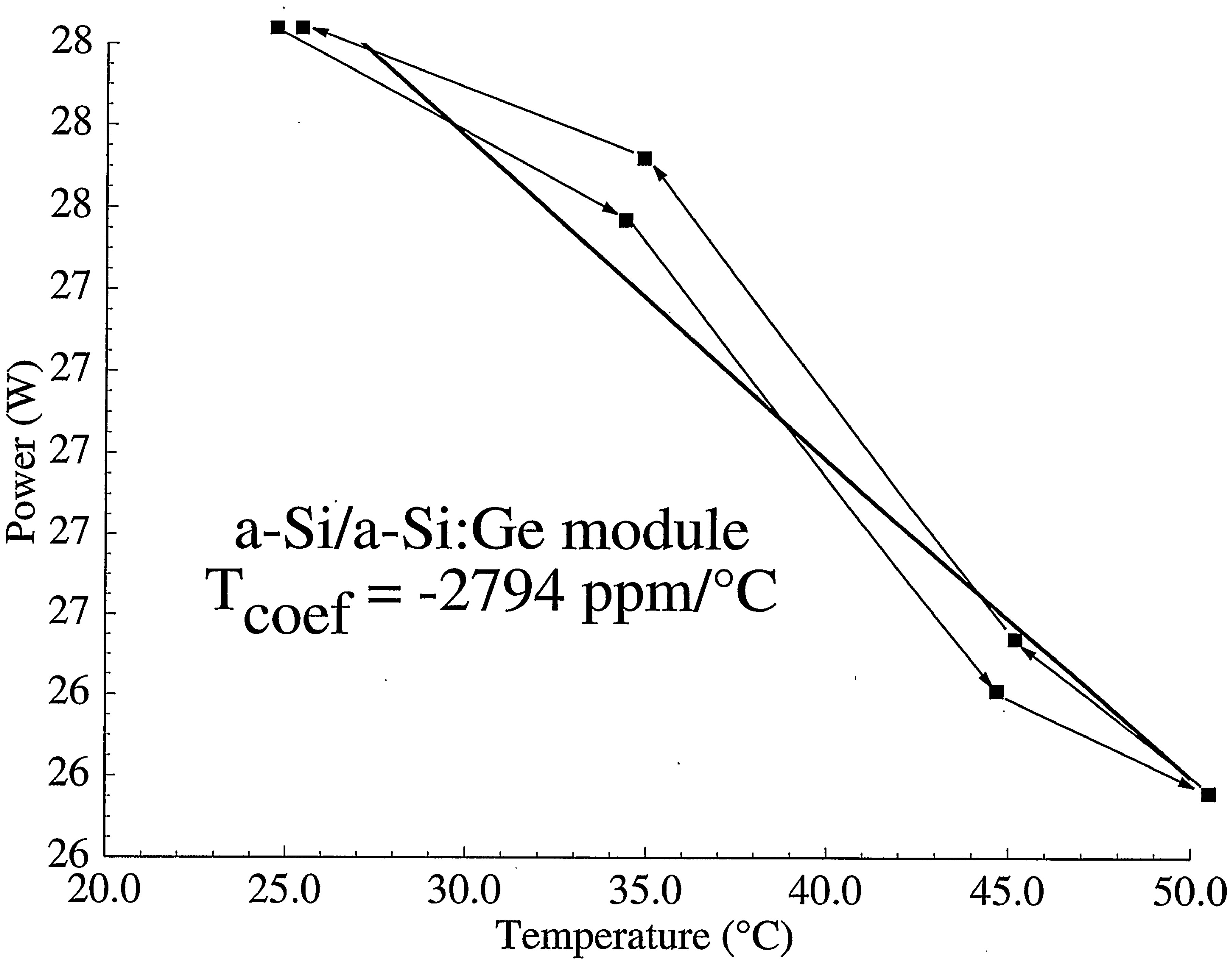

Maximum Power Temperature Coefficient
Temperature Coefficient (ppm /°C)
-6500
-6000
-5500
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
1.7eV AlGaAs
CdTe
a-Si
a-Si tandem
a-Si triple
GaInP/GaAs
GaAs
InP
p-Si
c-Si
CIGS
0.75eV GaInAs


Maximum Power Temperature Coefficient from dark current variation with energygap and Teperature
$J_o = \beta T^3 \exp(-E_g/kT)$
Maximum Power Temperature Coefficient (ppm/°C)
0
-2000
-4000
-6000
-8000
-10000
-12000
Bandgap Energy (eV)
0.6
0.8
1.0
1.2
1.4
1.6
1.8
GaInAs
CIS
Si
CIGS
GaAs
CdTe
a-Si
GaAlAs


90
89
88
87
86
85
84
83
82
81
80
Voc (V)
20
25
30
35
40
45
50
55
60
Temperature (°C)
CdTe module
-2511 ppm /°C


CdTe module
-609 ppm / °C
Fill Factor (%)
66.0
65.5
65.0
64.5
64.0
63.5
63.0
20
25
30
35
40
45
50
55
60
Temperature (°C)

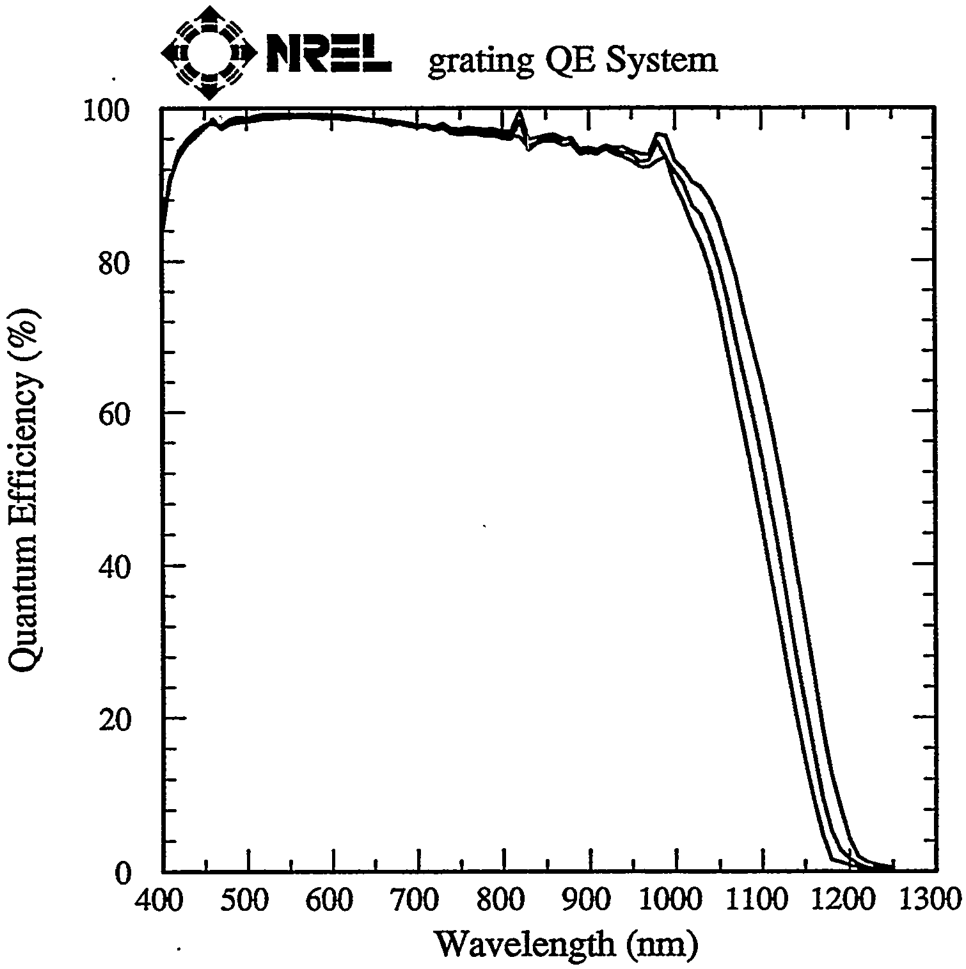

CdTe submodule
T_{coef} = -4854 ppm/°C
Power (mW)
450
440
430
420
410
400
390
380
370
360
350
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Temperature (°C)


a-Si/a-Si:Ge module
T_{coef} = -2794 ppm/°C
Power (W)
28
28
28
27
27
27
27
27
26
26
26
Temperature (°C)
20.0
25.0
30.0
35.0
40.0
45.0
50.0

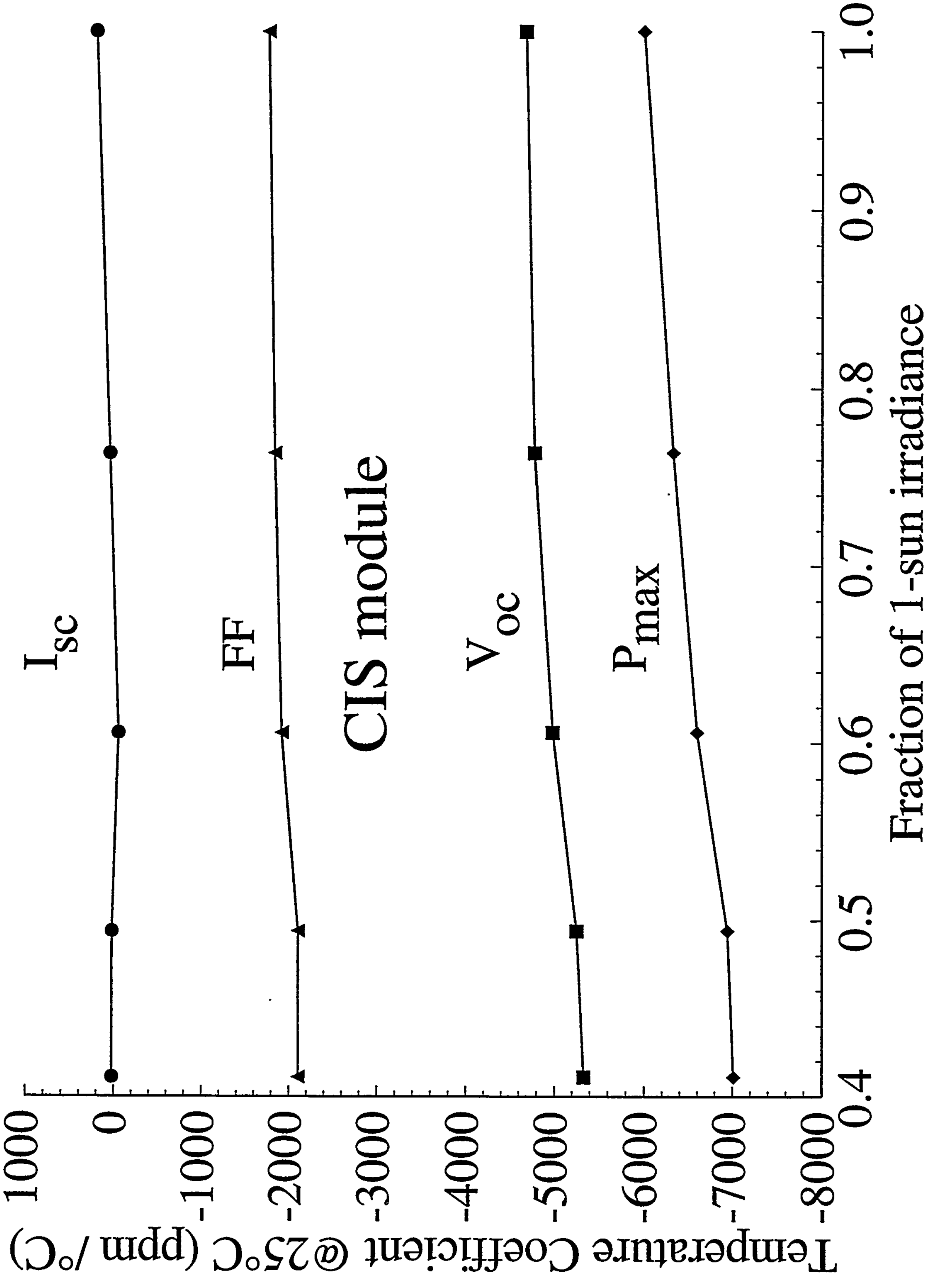
NREL High QE mono-Si

Sample: 2
Aug 31, 1995 12:40 PM

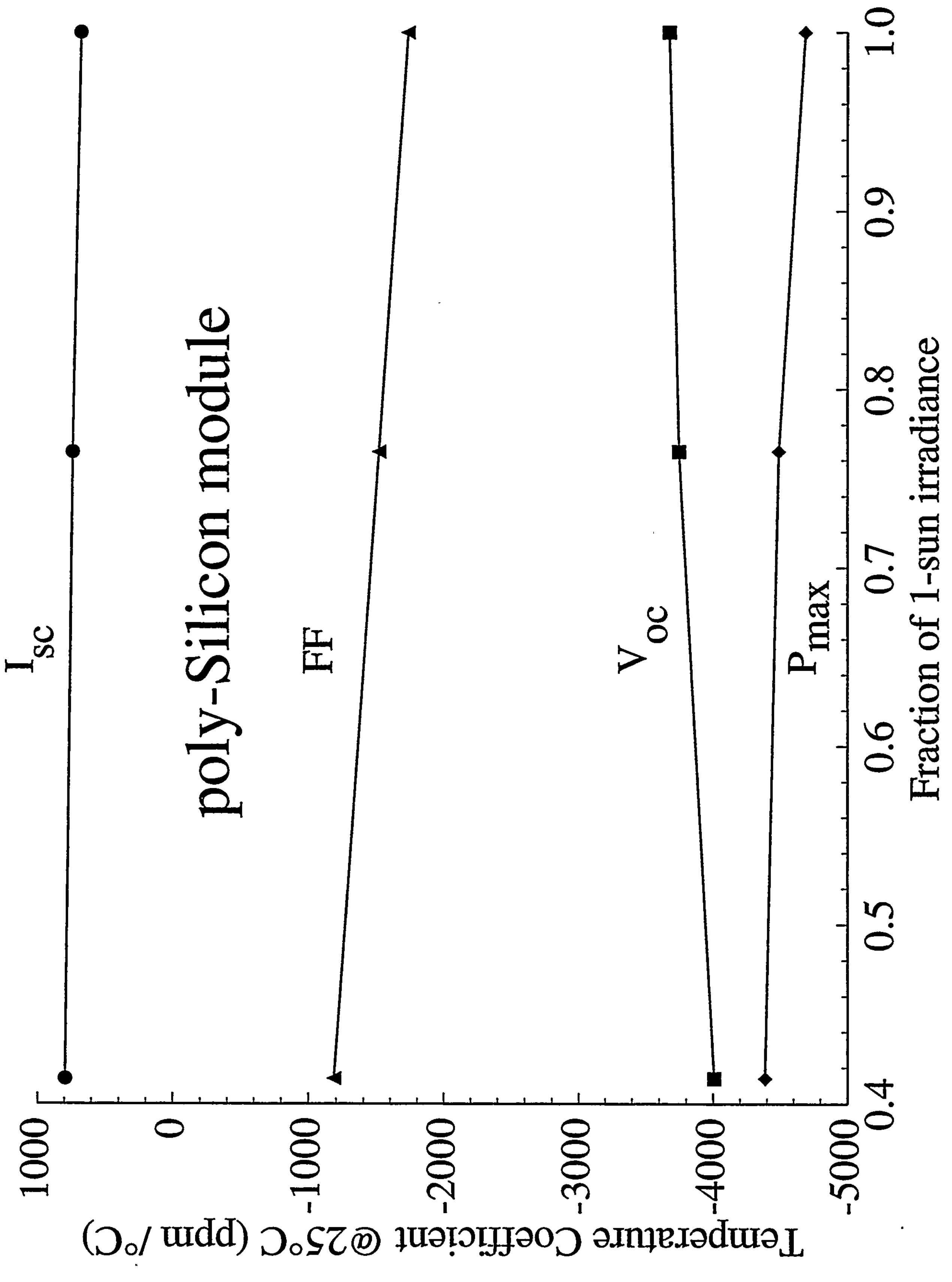
Temperature = 25.0,50.0, 82.5°C
Device Area = 0.3113 cm^2



zero voltage bias
no light bias



CIS module
I_{sc}
FF
V_{oc}
P_{max}
Temperature Coefficient @25°C (ppm /°C)
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
-8000
Fraction of 1-sun irradiance
0.4
0.5
0.6
0.7
0.8
0.9
1.0


poly-Silicon module
I_sc
FF
V_oc
P_max
Temperature Coefficient @25°C (ppm /°C)
1000
0
-1000
-2000
-3000
-4000
-5000
Fraction of 1-sun irradiance
0.4
0.5
0.6
0.7
0.8
0.9
1.0

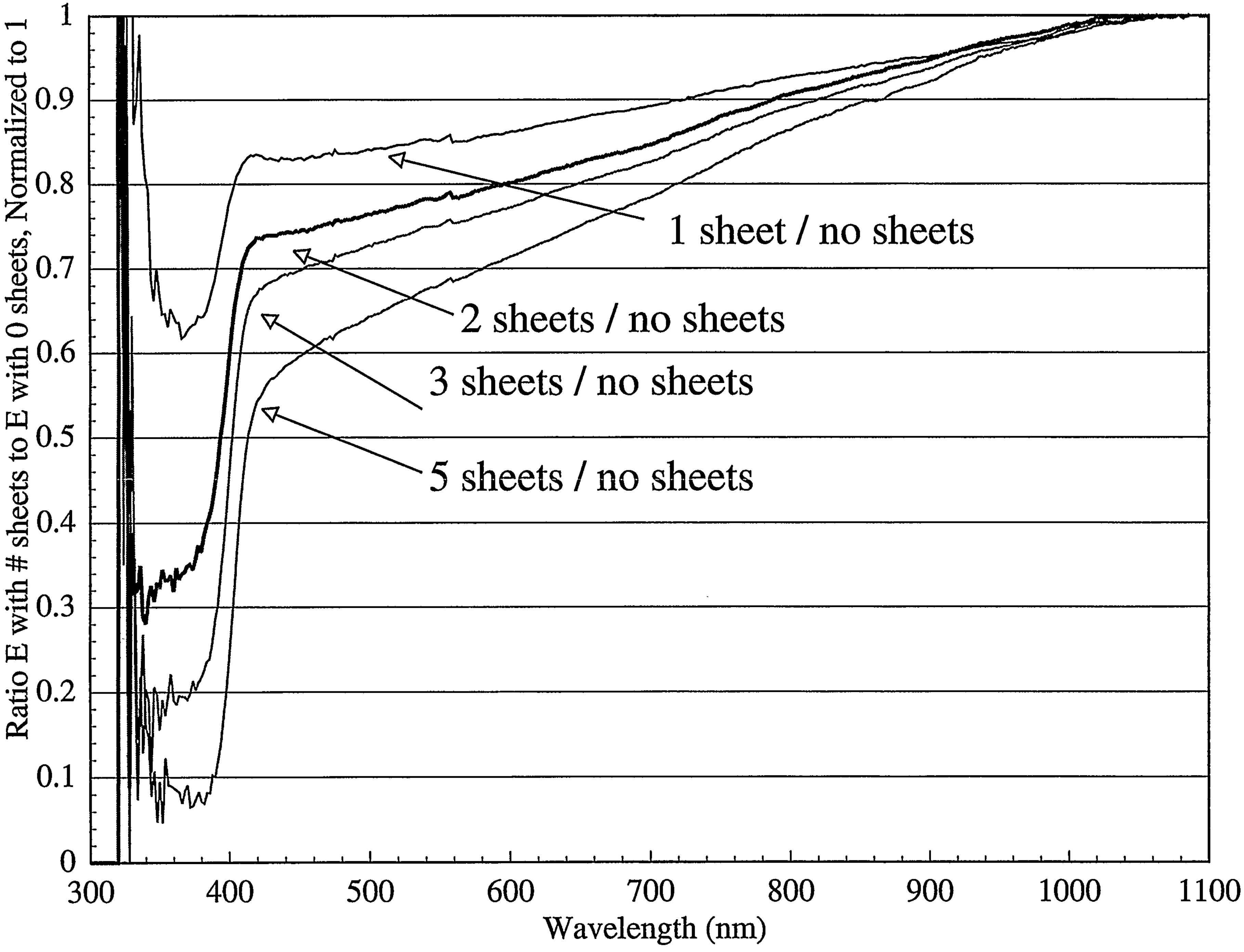
Procedures for Measuring Irradiance Coefficients

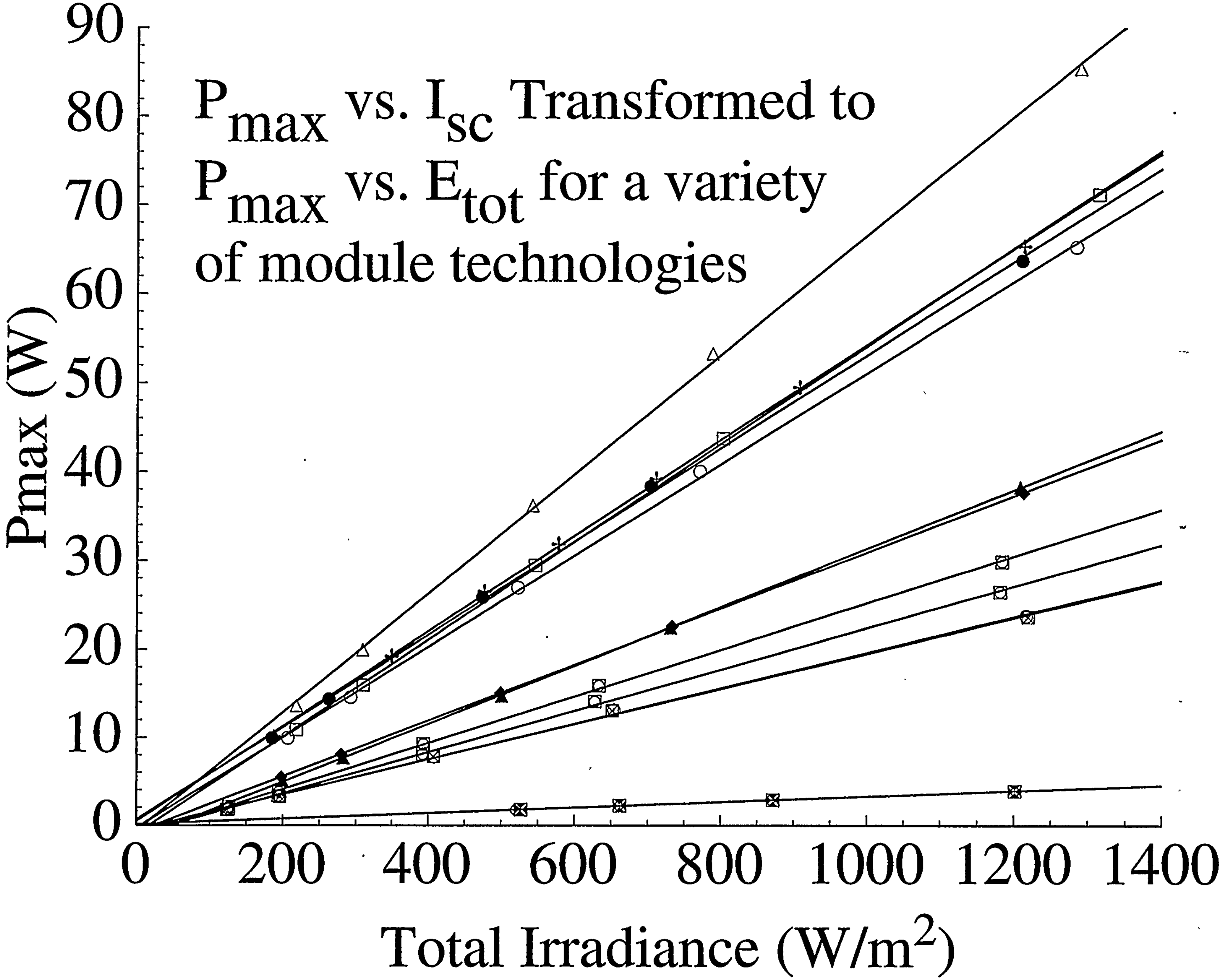
With Temperature fixed vary Irradiance

- Use screen or diffusing material to vary irradiance
- Temperature gradient between sensor and junction varys with irradinace fore a continuous light source
- Spectral error varys with irradiance for diffusing material

Measure I-V outdoors at different irradiances and temperatures

- Typically neglects spectral variation with irradiance
- Temperature coefficient assumed independent of irradiance


1 sheet / no sheets
2 sheets / no sheets
3 sheets / no sheets
5 sheets / no sheets
Ratio E with # sheets to E with 0 sheets, Normalized to 1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
300
400
500
600
700
800
900
1000
1100
Wavelength (nm)


Pmax vs. Isc Transformed to
Pmax vs. Etot for a variety
of module technologies
Pmax (W)
0
10
20
30
40
50
60
70
80
90
Total Irradiance (W/m2)
0
200
400
600
800
1000
1200
1400

Summary

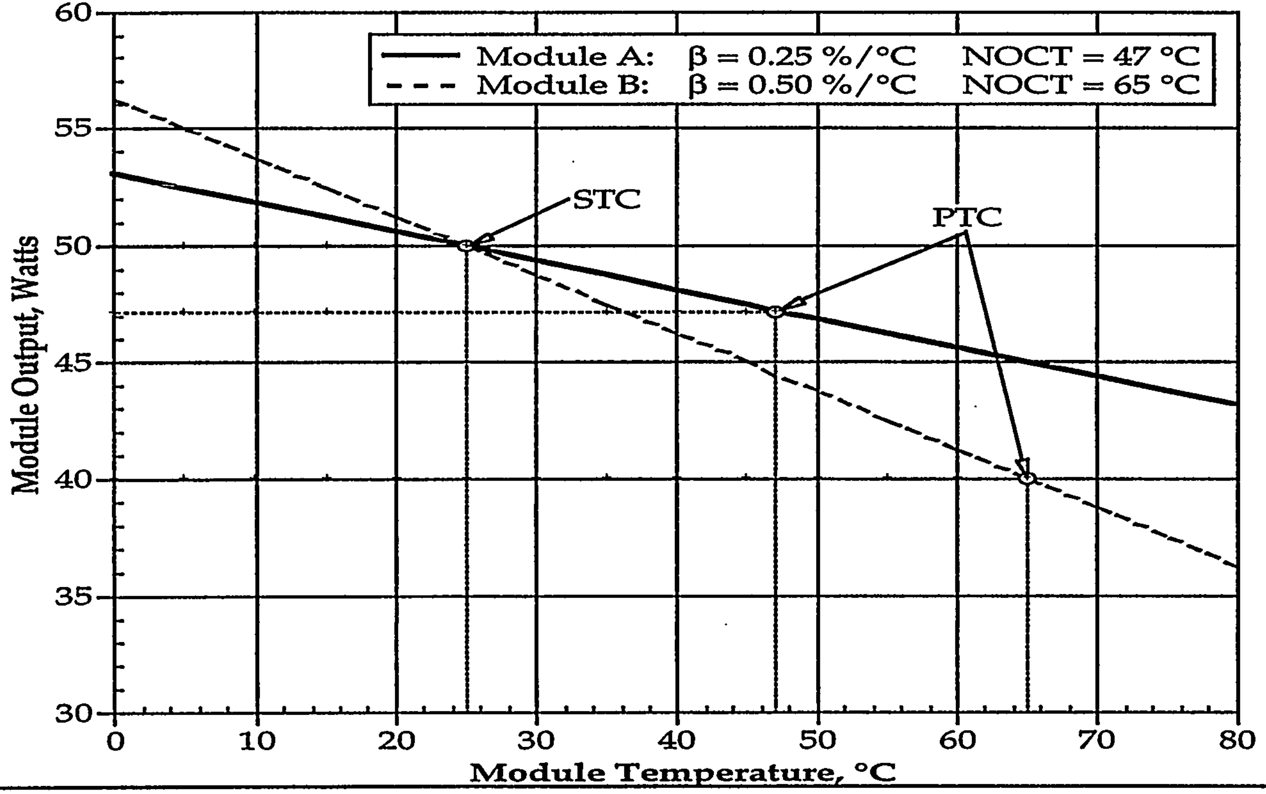
- Temperature coefficients vary widely for a given PV technology
- Cell Temperature coefficients are usually less than a modules
- Temperature coefficients for Multi-junctions are nonlinear and spectrally dependent
- Different methods give different temperature coefficients on the same sample. Uncertainty in T_{coef} is large
- Translation equations can be linearized

NREL
Module Energy Rating Methodology

C. Whitaker, J. Newmiller
Endecon Engineering
B. Kroposki, D. Myers, K. Emery, L. Mrig
National Renewable Energy Laboratory

Single-Point Rating Limitations

The brutal fact is that the peak-watt rating and its improvement, the NOCT *rating, so effective in communicating within and among government programs, technology developers, manufacturers, and demonstration operators, are virtually useless to the practical user* — C. Gay, 1982



50 Watt Modules Are Not All the Same

Project Goals

- Develop A Tool For
  - comparing different modules at the user's design conditions
  - evaluating one module in different climates
  - providing a Q&D method for estimating periodic energy production
- Provide An Achievable Module Rating
- Provide Incentive For Manufacturers To Optimize Modules To Non-STC Conditions
- Consensus Based — TRC
- NREL-Sponsored Activity

Project Team

- Endecon Engineering
  - Chuck Whitaker (PI)
  - Jeff Newmiller
  - Tim Townsend
- Pacific Energy Group
  - Howard Wenger
- NREL
  - Laxmi Mrig (TRC Chairman)
  - Ben Kroposki
  - Keith Emery
  - Daryl Myers
  - Joe Burdick
- Sunset Technology
  - Jerry Anderson

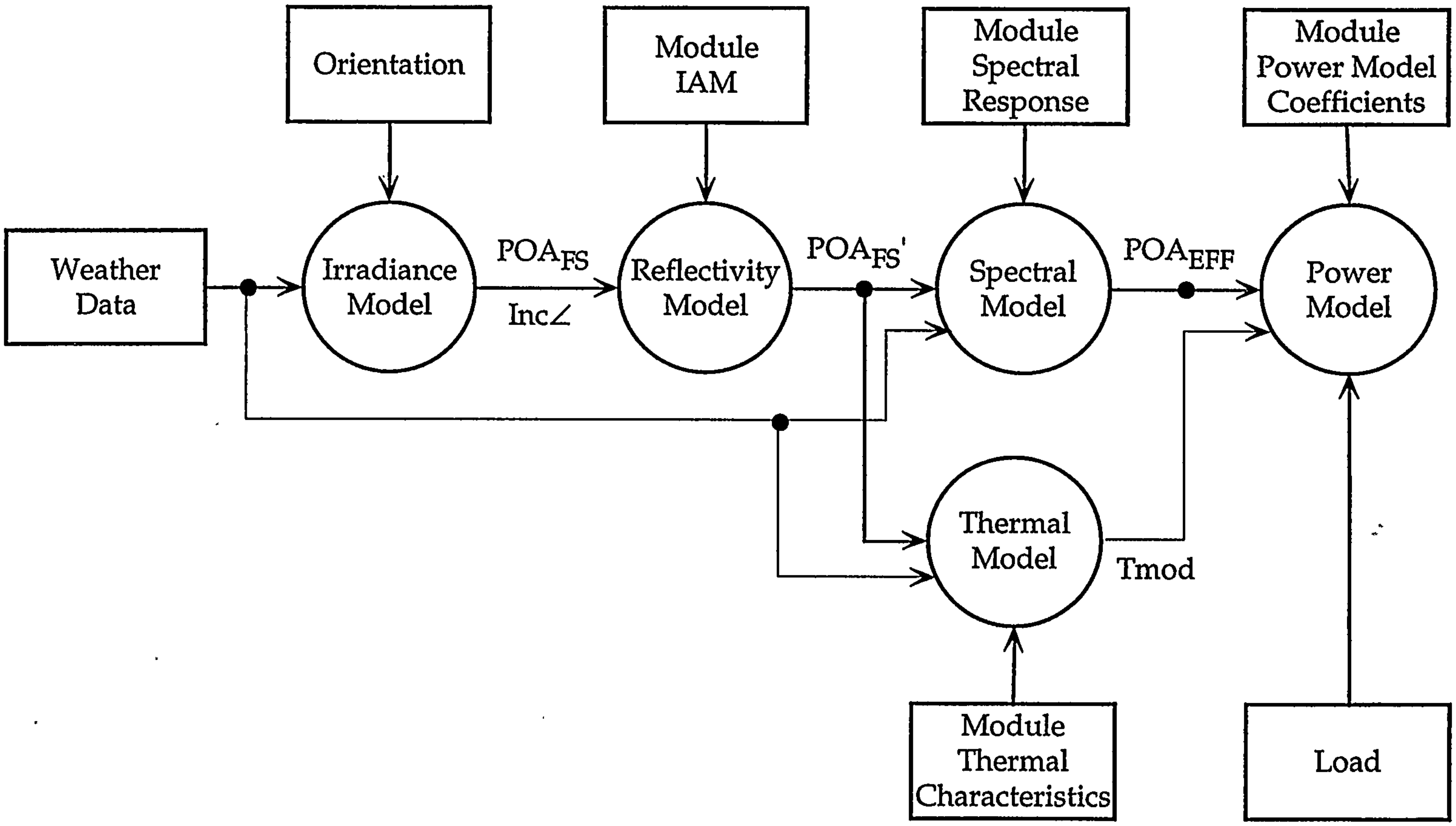
MER Approach

- Simulated module energy for five reference days
  - Cold/Sunny, Hot/Sunny, Cold/Cloudy, Hot/Cloudy, Normal Irradiance/Cool Environment
- Both peak power tracked (grid-tied) KW and fixed voltage (battery charging) Ah modes will be simulated
- Modules fixed, south facing, latitude tilt unless tracking is required
- Modules are assumed to be clean and stable

MER Activities

- MER Approach
  - Energy (PPT and fixed voltage) for 5 reference days representing a range of conditions
  - Performance model with appropriate module parameters and weather data
- Performance Models
  - Regression equations (PVUSA, etc.)
  - IV curve translations ("MIT", Sunset Technologies, ESTI)
  - Explicit V and I or P equations
  - Spectral, thermal, and incidence angle affects
- Weather Data
  - Provide weather data consistent with above from NSRDB
- Testing
  - Indoor and outdoor – 5 modules · technology
- Software

Model Flow Diagram



Weather Data

Orientation

Irradiance Model

POA_{FS}

Inc∠

Module IAM

Reflectivity Model

POA_{FS}'

Module Spectral Response

Spectral Model

POA_{EFF}

Module Power Model Coefficients

Power Model

Thermal Model

Tmod

Module Thermal Characteristics

Load

Anderson Translation

- Proposed by Jerry Anderson in response to problems with equations for IEEE standards
- Includes standard current and voltage temperature coefficients plus a new irradiance coefficient
- Coefficients obtained from a series of IV curves under different conditions (indoor or outdoor)

Module Energy Rating

Anderson Model

$$I_{2i} = I_{1i}\frac{I_{sc2}}{I_{sc1}} \qquad V_{2i} = V_{1i}\frac{V_{oc2}}{V_{oc1}}$$

$$\frac{I_{sc2}}{I_{sc1}} = \frac{H_2/H_1}{1+\alpha\left(T_1 - T_2\right)} \qquad \frac{V_{oc2}}{V_{oc1}} = \frac{1}{\left[1+\beta\left(T_1 - T_2\right)\right]\times\left[1+\delta\ \ln\left(H_1/H_2\right)\right]}$$

where

I = current, A
H = irradiance, W/m^2
V = voltage, V
T = module temperature, °C
α = temperature coefficient for current, °C^{-1}
β = temperature coefficient for voltage, °C^{-1}
δ = irradiance coefficient for voltage, m^2/W

and where subscripts

sc = short circuit
oc = open circuit
1,2 = at conditions 1 or 2
i = i$^{\text{th}}$ point on the IV curve

Blaesser Translation

- Developed by Gerd Blaesser of ESTI
- Similar to Anderson
- Requires outdoor measurements (IV curves)
- Integrated thermal model

Module Energy Rating

Blaesser Model

$$I_r = I\left(H_{I,r} / H_I\right) \qquad V_r = V + DV$$

$$i_r = I_r / I_{sc,r}\,, \qquad i = I / I_{sc}\,,$$

$$v_r = V_r / V_{oc,r}\,, \qquad v = V / V_{oc}\,, \qquad Dv = DV / V_{oc,r}$$

$$V = V_r - Dv \cdot V_{oc,r} \qquad v = \left(v_r - Dv\right) / (1 - Dv)$$

$$\boxed{Dv = a \cdot \ln\left(H_{I,r} / H_I\right) + b\left(T_{amb} - T_I\right) + c \cdot H_I}$$

$$FF = FF_r \frac{v_m}{v_{m,r}} = \frac{FF_r}{v_{m,r}} \frac{\left(v_{m,r} - Dv\right)}{(1 - Dv)}$$

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} = \frac{P_m}{V_{oc} I_{sc}}; \quad P_m = \frac{FF}{V_{oc} I_{sc}}$$

where	I = current, A i = normalized current H = irradiance, W/m^2 V = voltage, V v = normalized voltage a, b, c = coefficients T = temp (ambient or cell), C FF = fill factor P = power, W	and where subscripts	I = in-plane (for irradiance) r = at reference conditions amb = ambient (temperature) m = at maximum power point

Linear Irradiance-Only Model

- Proposed by D. Myers of NREL in response to his own observation that the inherent measurement errors may be larger than the magnitude of the contributions of any parameters other than irradiance

$$P = a \cdot H + b$$

- *a* and *b* calculated based on outdoor data
- For fixed voltage develop a series of coefficients for different voltages
- Doesn't require a reference IV curve
- Implied module temperature model

Interpolation Model

- Matrix of powers (or currents at a given voltage) for a range of irradiances and module temperatures
- Modeling errors reduced by interpolating between measured data points.
- Extrapolation may have to be "modeled"
- Module temperature, incidence angle, and spectral effects can be handled similarly
- May require more testing (more IV curves) than other methods

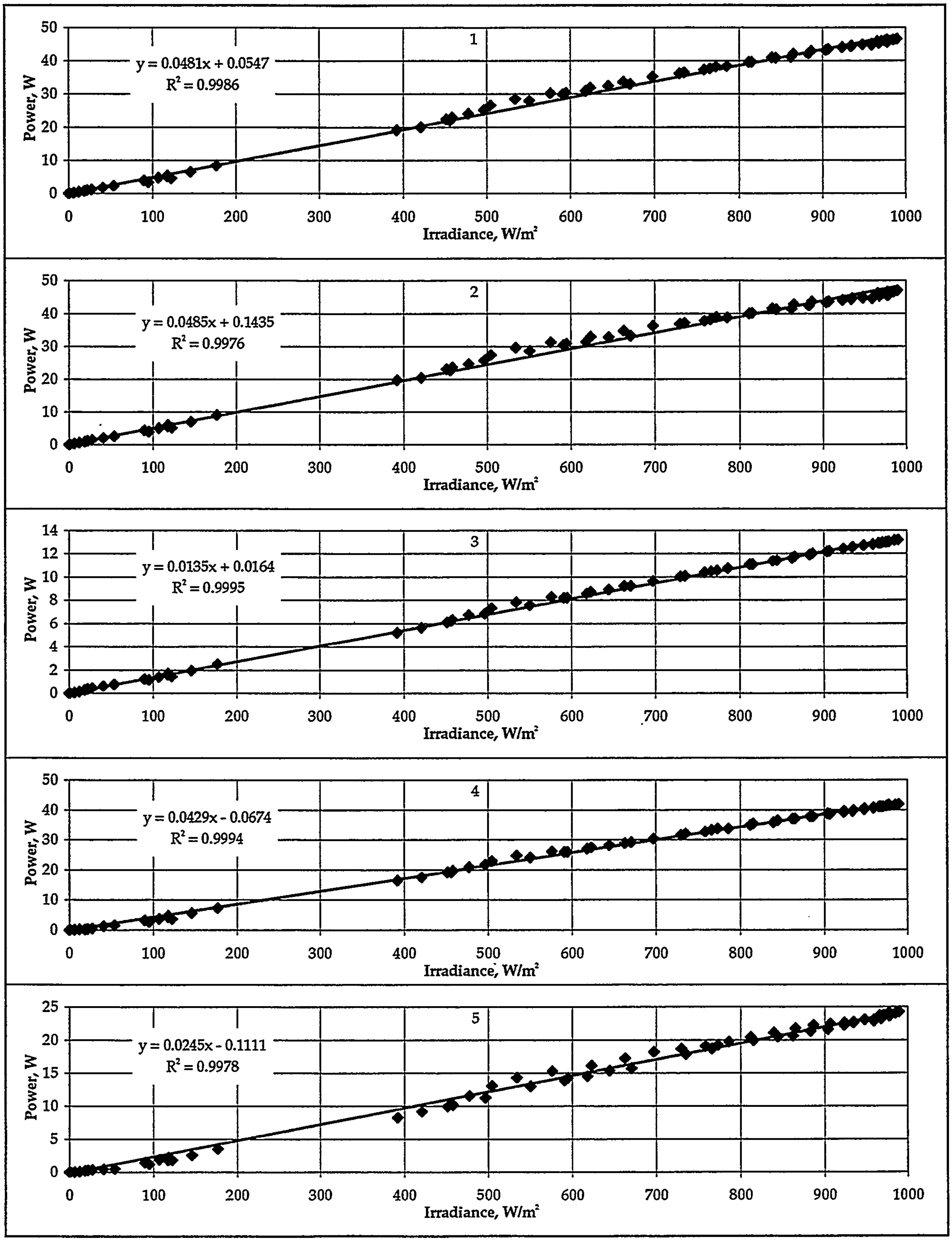
Other Models

- Module Temperature: Fuentes (PVFORM)
- Spectral: Spectra generated with SEDES II, used with measured module quantum efficiencies to calculate spectral correction factors
- Incidence angle: polynomial fit of module response as a function of incidence angle

Conclusions

- Refinement and validation of models and module characterization procedures is nearly complete
- Fairly good consensus among TRC members on major issues/great deal of debate on some of the details
- Selected reference days are representative of real extreme weather conditions but may not as extreme as expected
- Reference day module energy appears to be an effective comparison tool

Myers Model:
P = A+B*POA

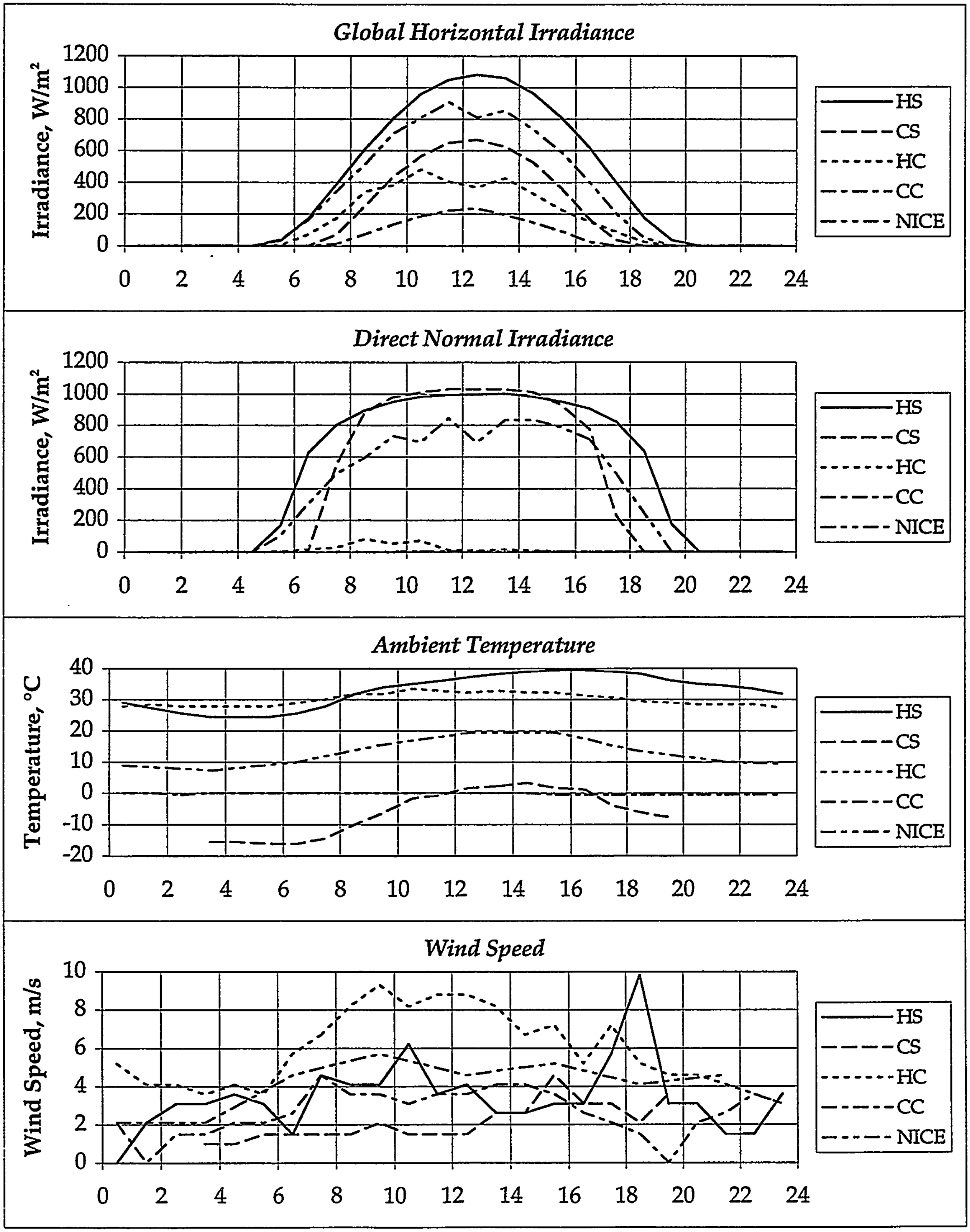


Module Energy Rating Project

First Crack Reference Days

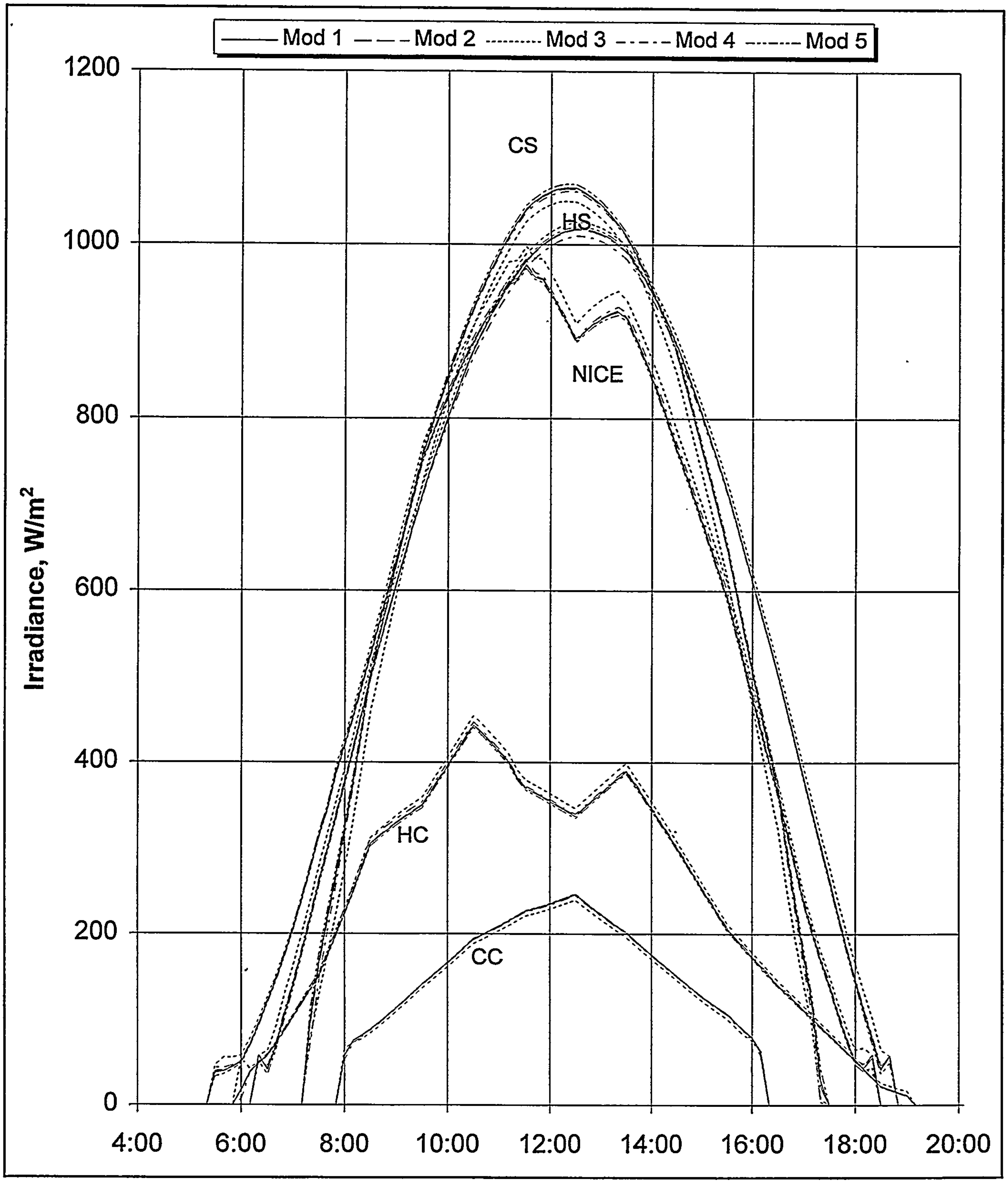
				GHI		DNI		Tamb		Wind Speed		Rel Hum
Day	Location	Month	Day Hrs	Peak (W/m²)	Total (kWh)	Peak (W/m²)	Total (kWh)	Peak (°C)	Wtd (°C)	Peak (m/s)	Wtd (m/s)	Wtd (%)
Hot Sunny	Phoenix, AZ	Jun	15	1080	9.14	1003	11.9	39.4	36.3	9.8	3.9	6.3
Cold Sunny	Alamosa, CO	Feb	11	671	4.34	1032	9.4	3.3	-0.6	4.6	2.2	50.9
Hot Cloudy	Brownsville, TX	Jul	15	480	3.47	81	0.3	33.3	32.1	9.3	7.9	59.8
Cold Cloudy	Buffalo, NY	Dec	10	237	1.32	2	0.0	0.0	-0.1	4.6	3.7	93.4
NICE	Sacramento, CA	May	14	905	7.12	846	8.3	19.4	17.3	5.7	5.0	65.4

Module Energy Rating
Reference Days



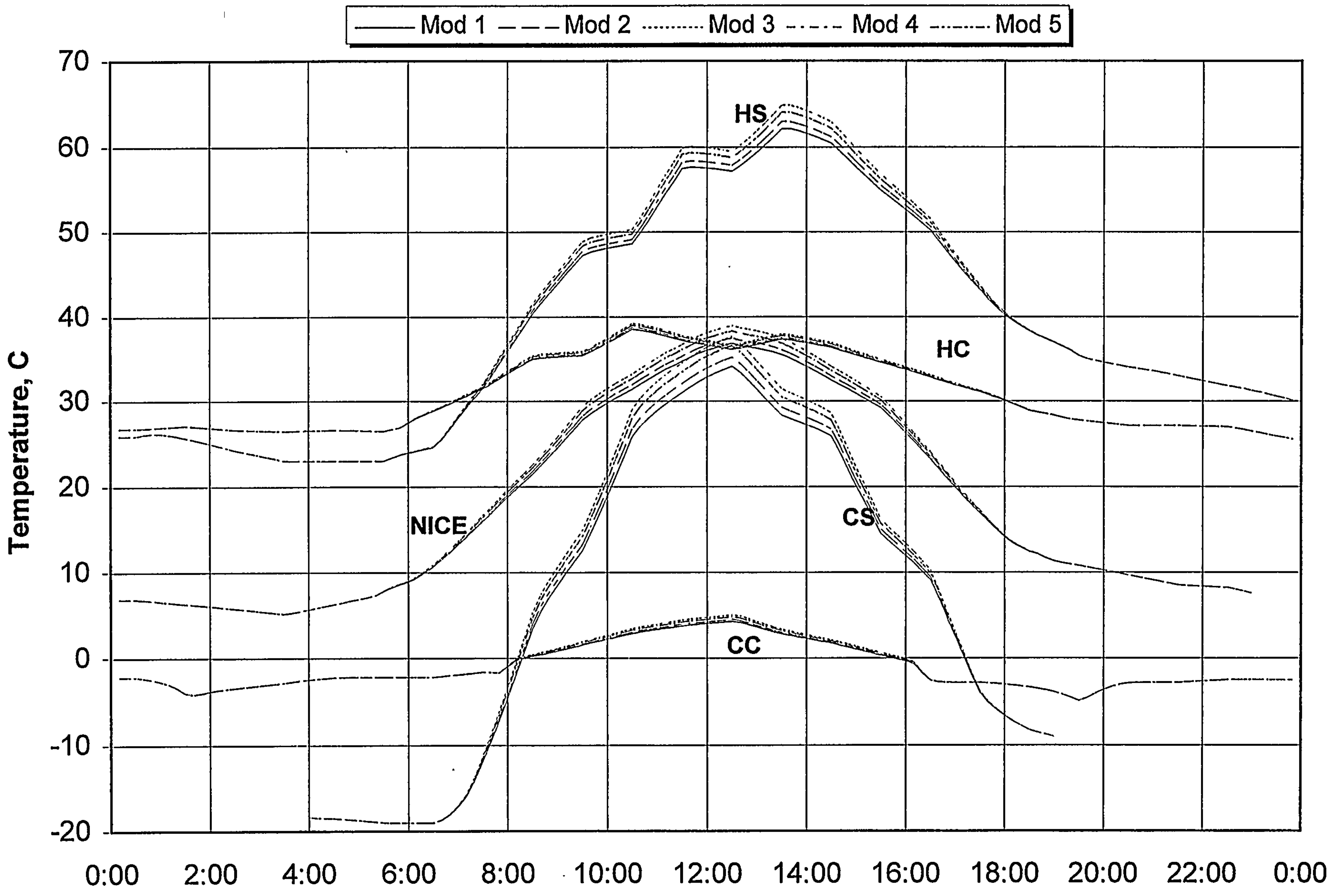
Module Energy Rating

Effective Irradiance



Module Energy Rating

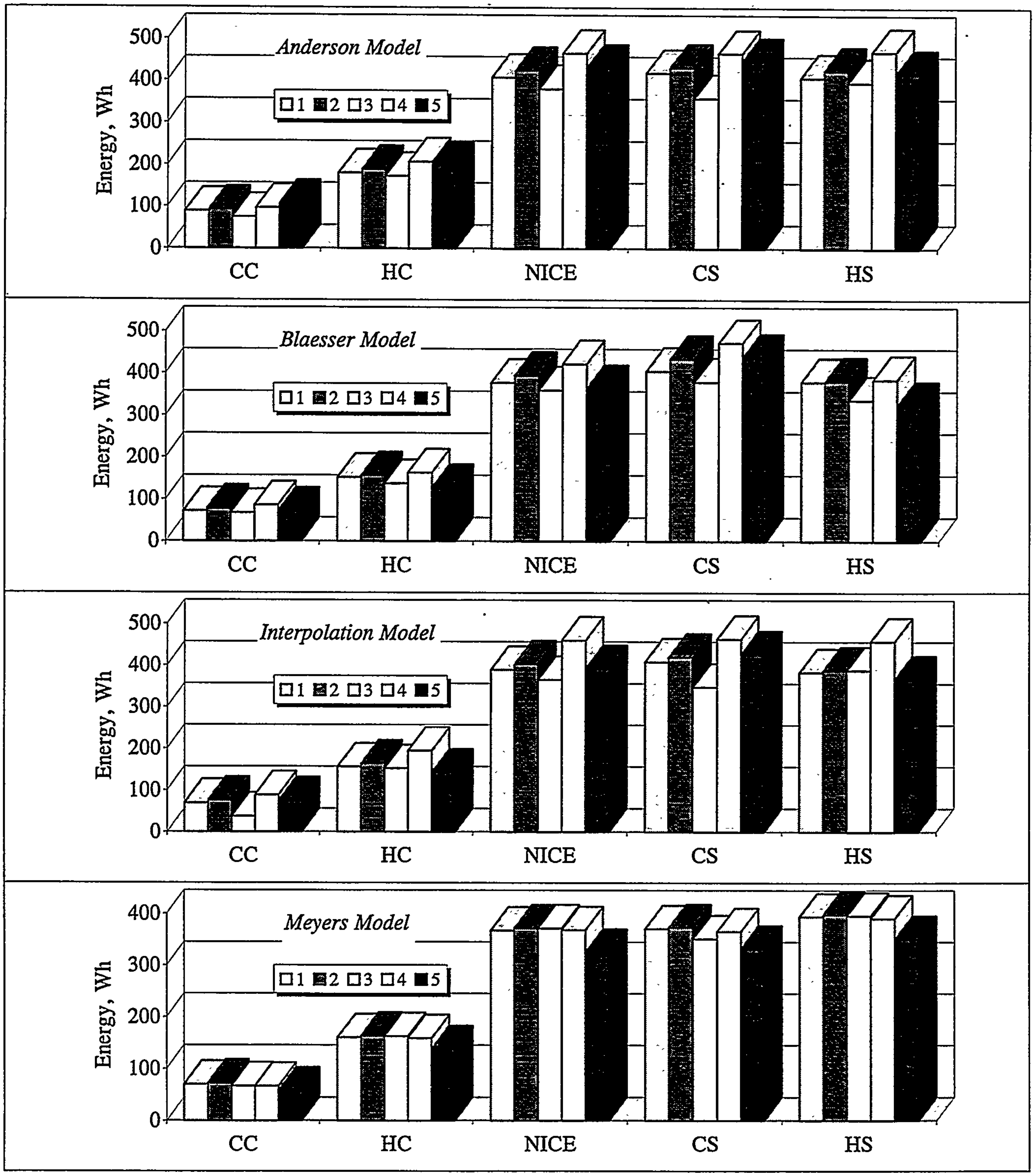
Module Tempearture



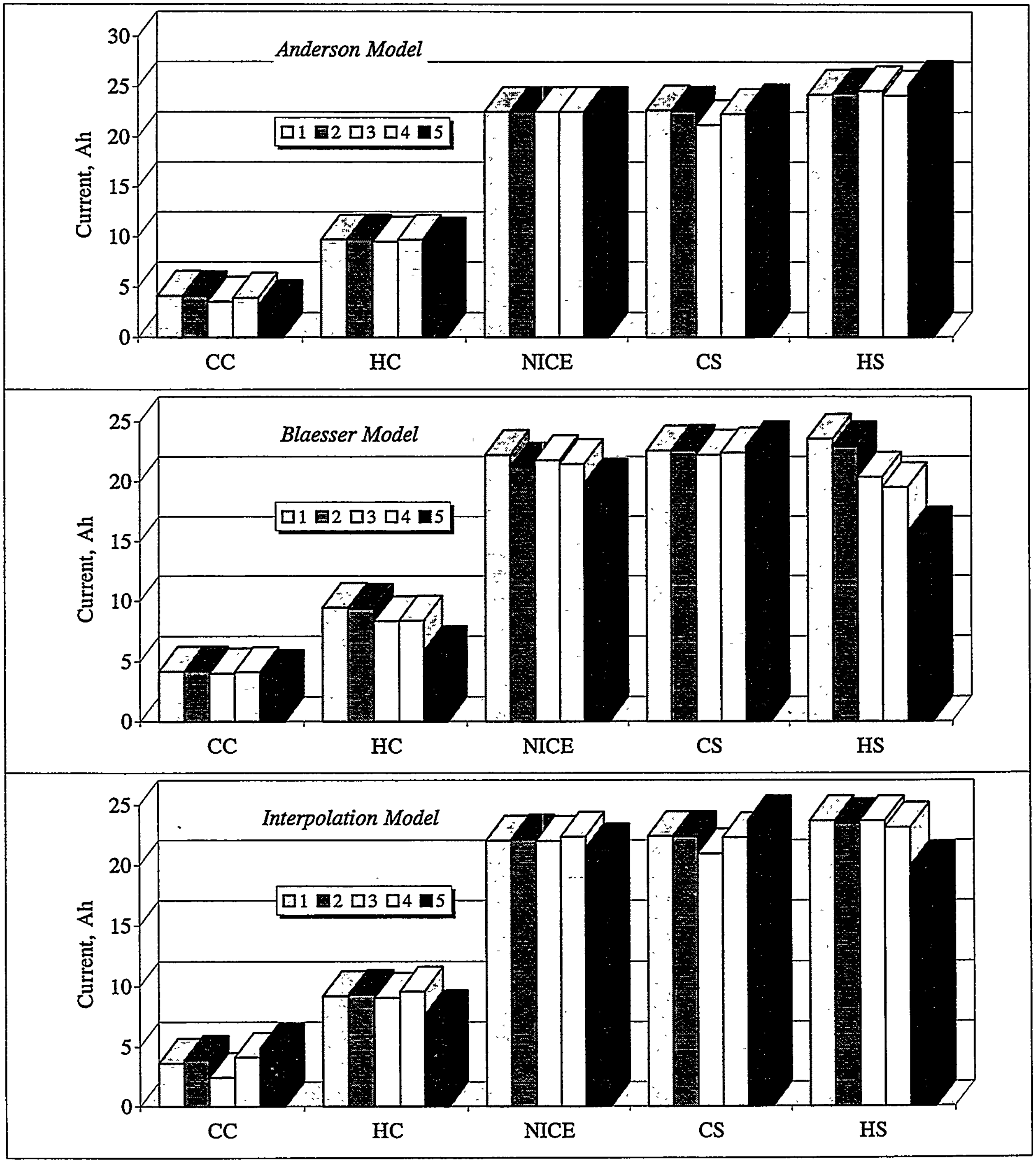
Plots Chart 1 - Plots Chart 1

Endecon Engineering - 9/7/95

Module Energy Rating



Module Energy Rating



Improved Methods for the Measurement and Modeling of PV Module and System Performance for All Operating Conditions

David L. King
Sandia National Laboratories
PV System Components Department
Albuquerque, NM

Photovoltaic Performance & Reliability Workshop
National Renewable Energy Laboratory
Golden, Colorado
September 7-8, 1995

Why are Improved Methods Needed ?

- For cells and modules we have many relevant standards, primarily at SRC (1000 W/m^2, AM$_a$=1.5, 25°C).

  ASTM E 948   ASTM E 1036   ASTM E 973   ASTM E 892   ASTM E 891.....

- Current standards don't address several system-related issues

  Variations: spectrum, angle-of-incidence, tracking or nontracking, operating temperature, max and min voltages and currents, etc.

- Discussion this meeting last year: Energy Rating or Power Model?

  SRC
  STC
  NOCT
  SOC

  PTC
  AM-PM
  RRC
  ENRA

  BULLSEYE
  UMP
  REF
  COP

  FACT
  LITE
  HIHT
  LIHT

  LILT

- My Opinion: For better system design, rating, and monitoring, *performance information for all operating conditions is needed.*

Objective

Develop improved performance model for modules and systems for all operating conditions for use in:

- module specifications (power, energy),
- system and BOS component design,
- system rating or monitoring.

The model should be “simple,” e.g. Excel spreadsheet.

(Make it easier for customers to use PV systems !$!)

Approach

- Identify and quantify the influence of dominant factors:

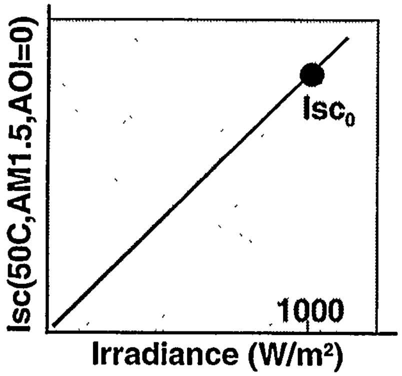
Solar irradiance	(0 - 150%)
Cell temperature	(0 - 25%)
Angle-of-incidence	(0 - 20%)
Solar spectrum	(0 - 8%, c-Si))

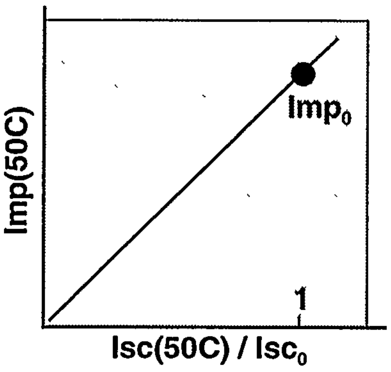
- Use outdoor test procedures to separate the effects of electrical, thermal, and optical performance.
- Use fundamental cell characteristics to improve analysis
- Combine factors in “simple” model using common variables:
    - Irradiance
    - Module temperature
    - Time of day

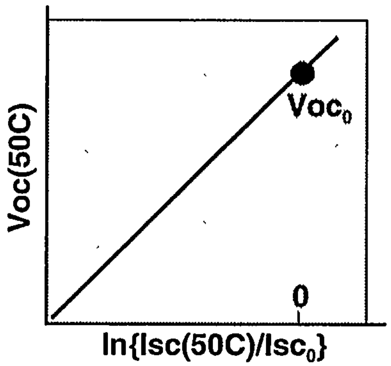
Reference Operating Conditions for PV Systems

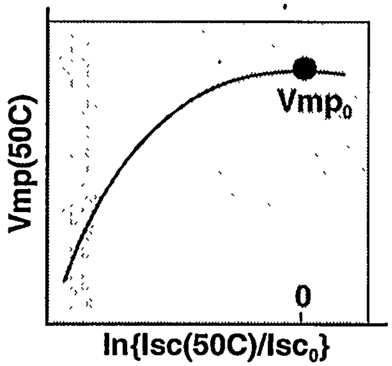
- Pick “reference conditions” in the operating range of the system!
  “Flat-plate” modules: 1000 W/m^2, AM$_a$=1.5, T$_{cell}$=50°C, AOI=0 deg

- Relate system performance parameters at other conditions to parameters at the reference conditions. For instance,

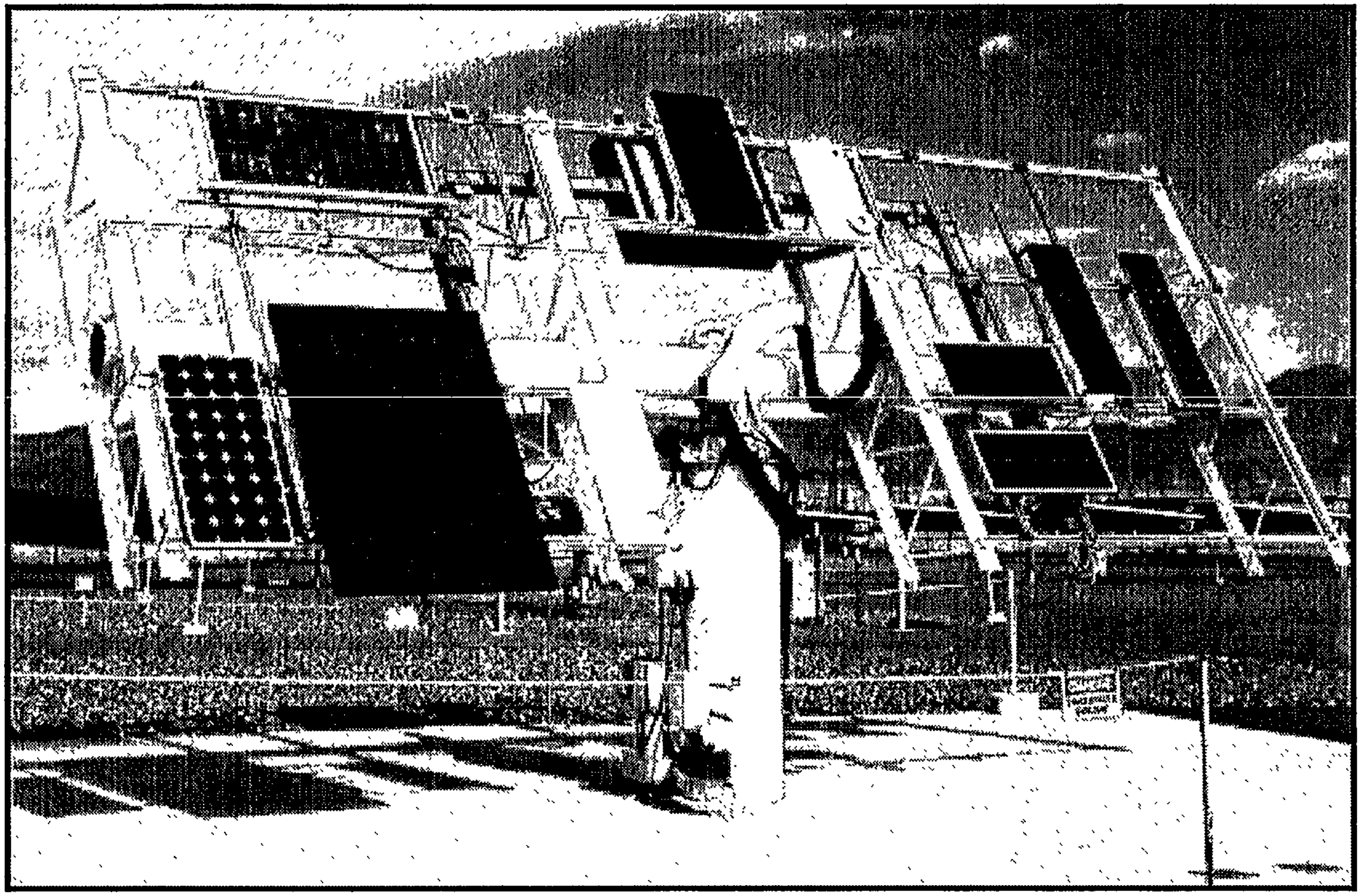




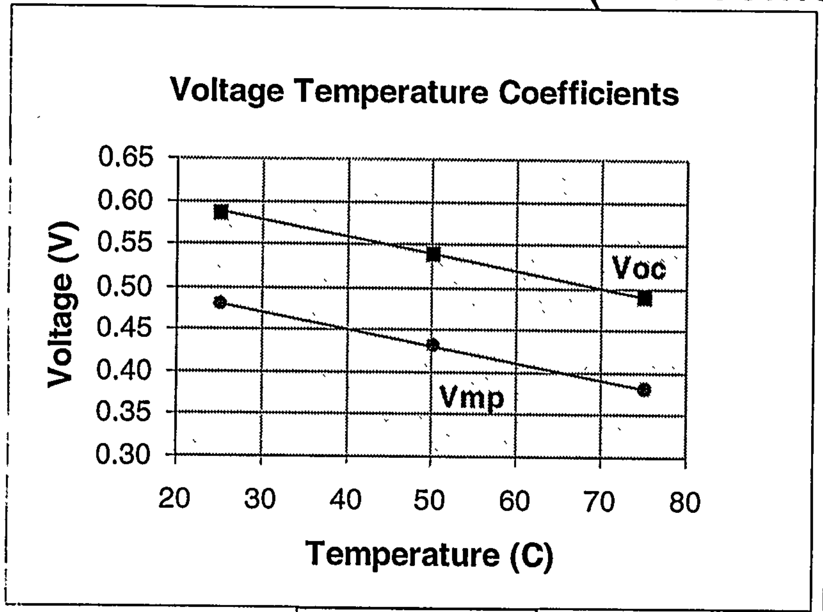


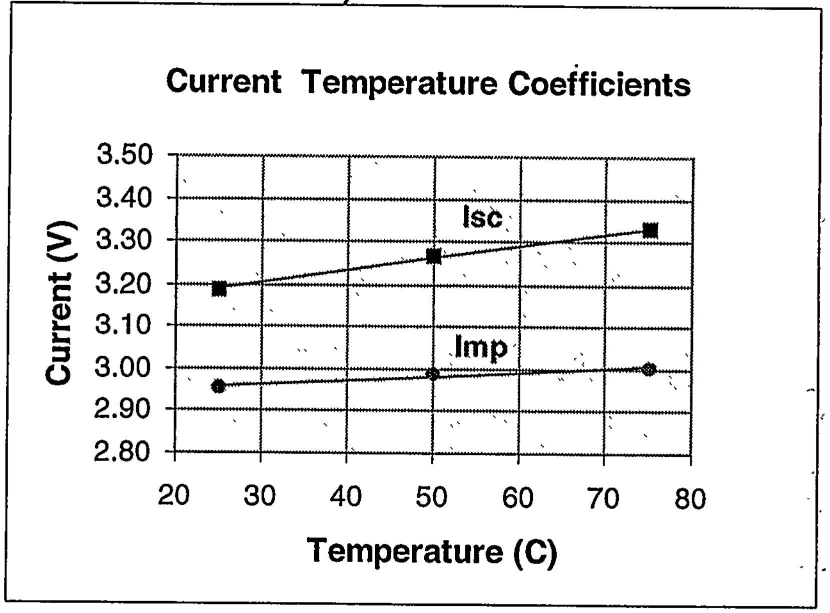


The *Tao* of PV Module Characterization



Temperature Coefficients are Important
(and sometimes abused)





$\beta_{Voc} \approx \beta_{Vmp}$

$\alpha_{Isc} \neq \alpha_{Imp}$

- Determine four basic temperature coefficients from cell and/or module testing
- Recognize that temperature coefficients for Pmp, FF, Eff are not constants, e.g.

$$\frac{dP_{mp}}{dT} = I_{mp}\frac{dV_{mp}}{dT} + V_{mp}\frac{dI_{mp}}{dT}$$

Calculated Cell Temperature

- For outdoor testing, cell temperature is best determined analytically using Isc-Voc-T relationship for the cells.

- Calculated cell temperatures can be referenced to measured back-surface temperatures during periods of “quasi-thermal-equilibrium.”

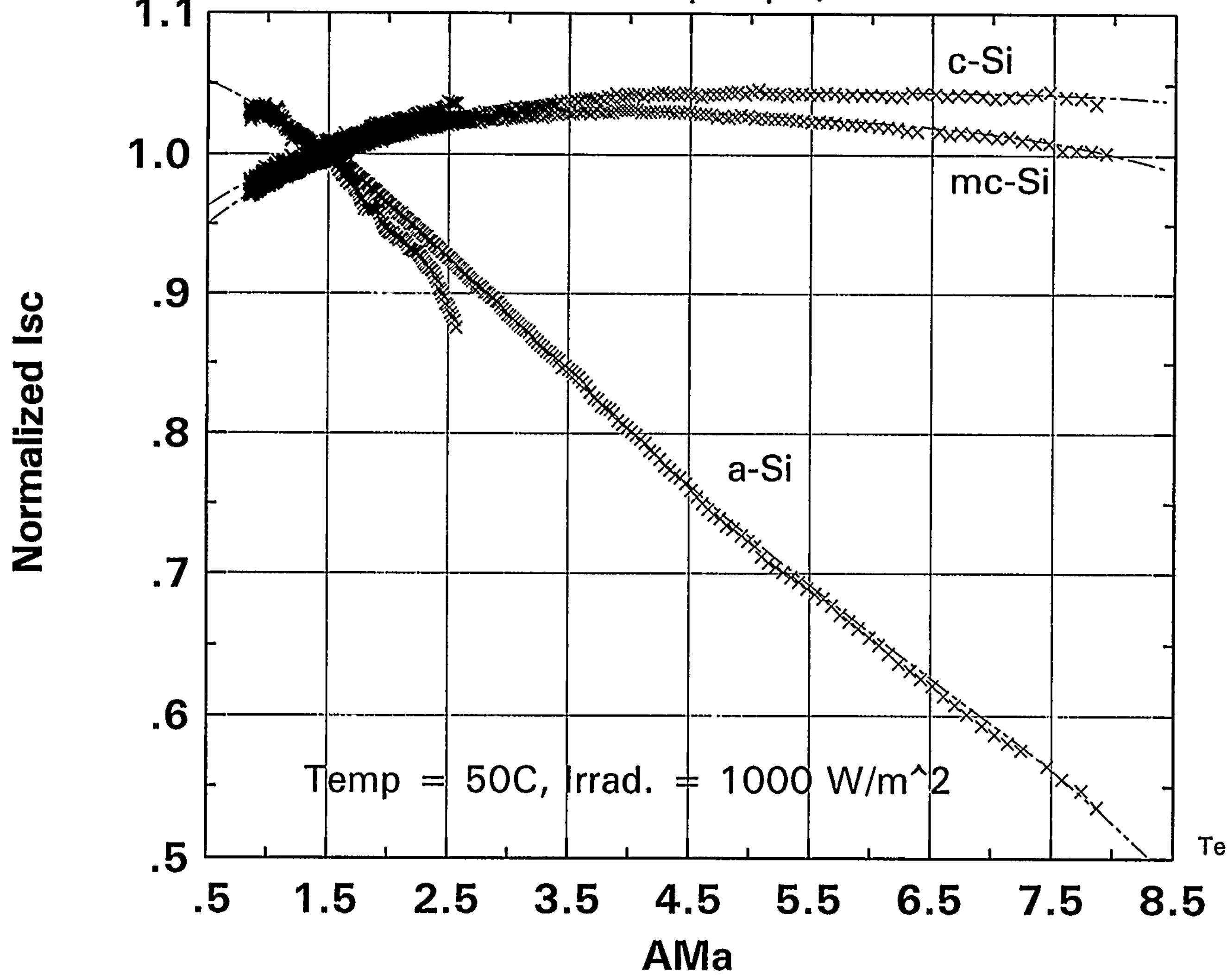
- Advantages:
  Near instantaneous response,
  Effect of module’s thermal time constant avoided,
  Provides “average” temperature for module or array,
  Module “thermal efficiency” can be assessed

- Temperature Model:

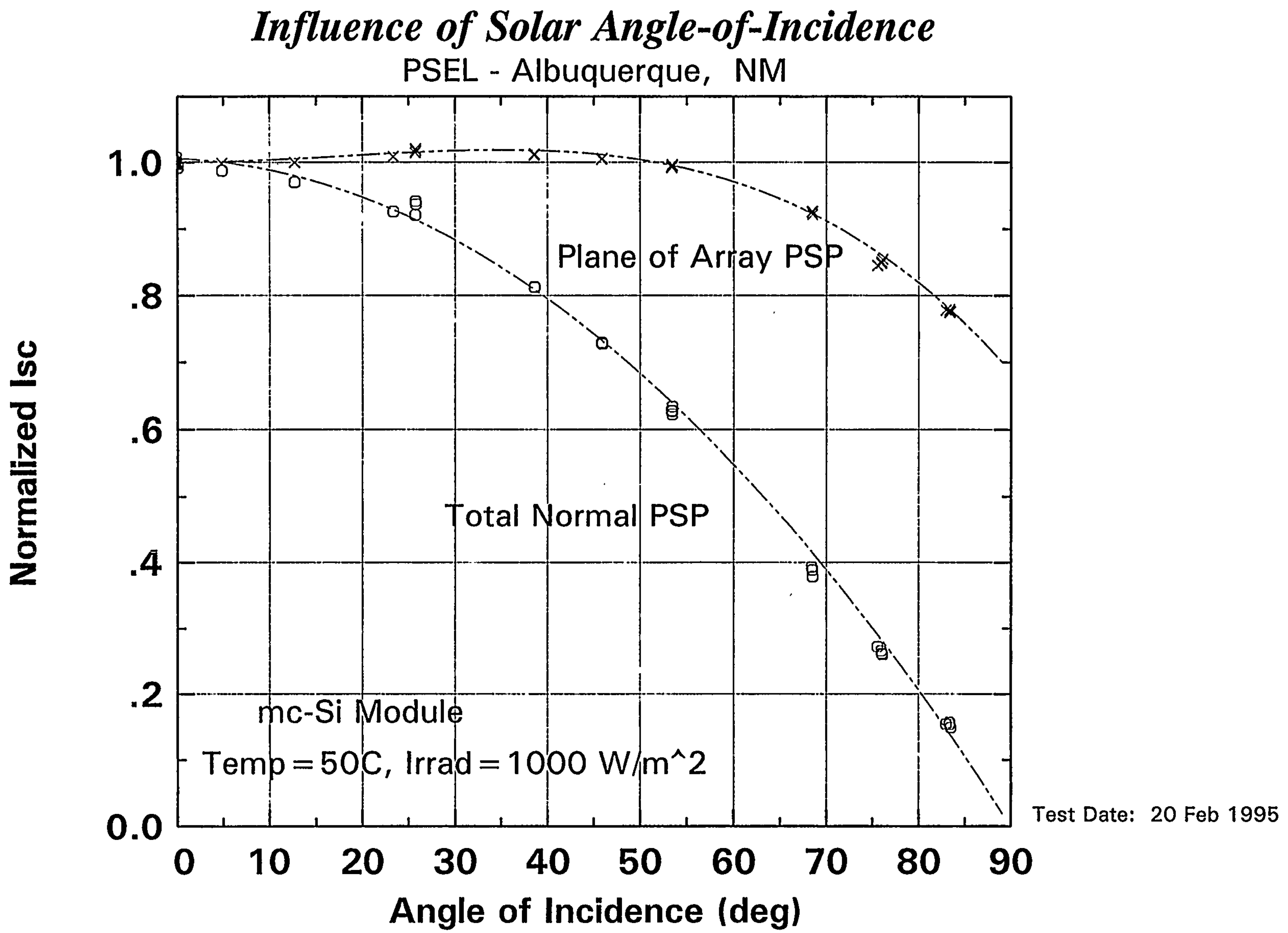
$$Voc = Voc_0 + (nkT/q)\ \ln\{Isc/Isc_0\} + \beta_{Voc}\ (T-T_0)$$

Influence of Solar Spectrum

PSEL - Albuquerque, NM



Test Date: 8 Aug 1995



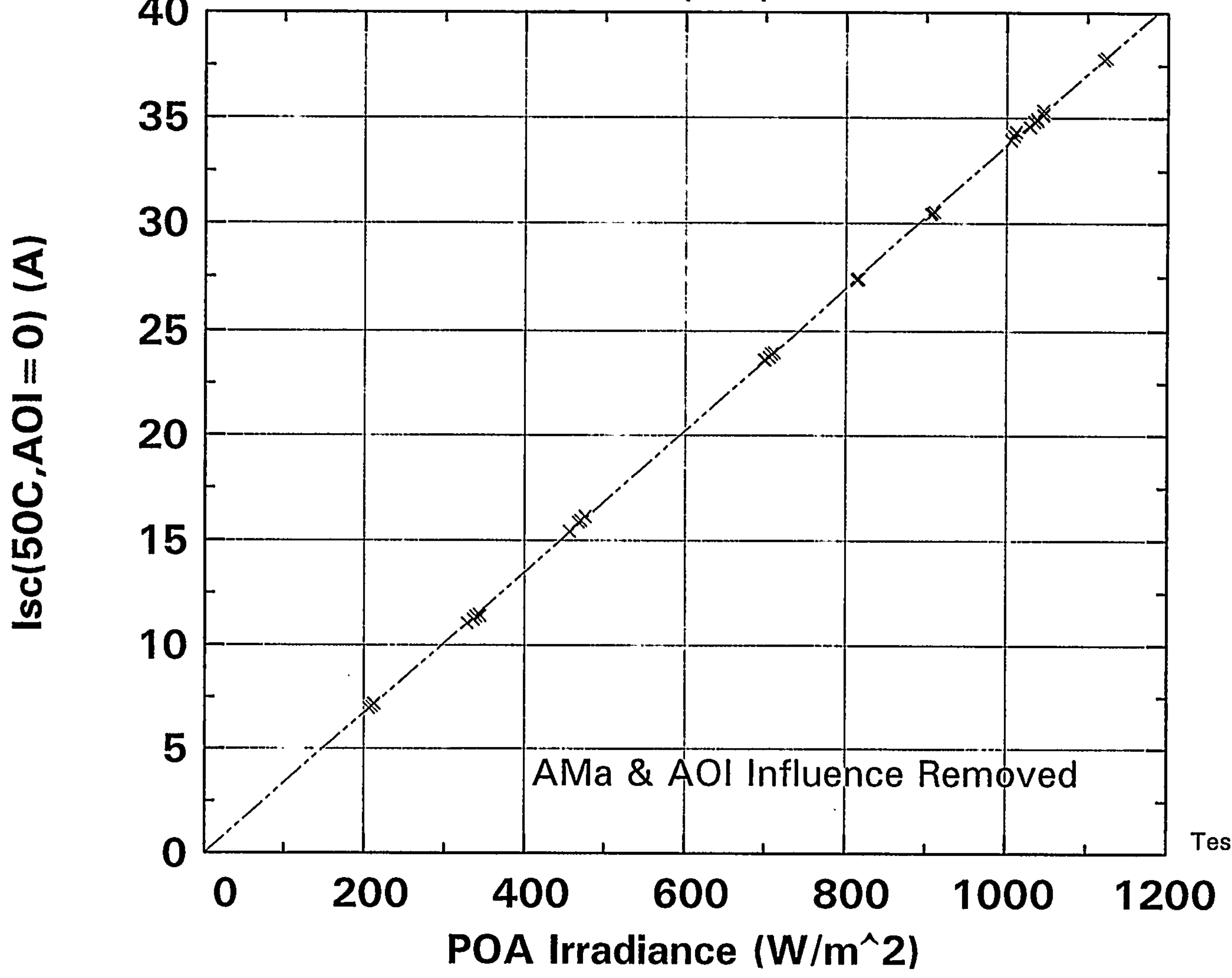
Influence of Solar Angle-of-Incidence

PSEL - Albuquerque, NM

Test Date: 20 Feb 1995

Isc Linearity for Silicon Module

PSEL - Albuquerque, NM



Test Date: 20 Feb 1995

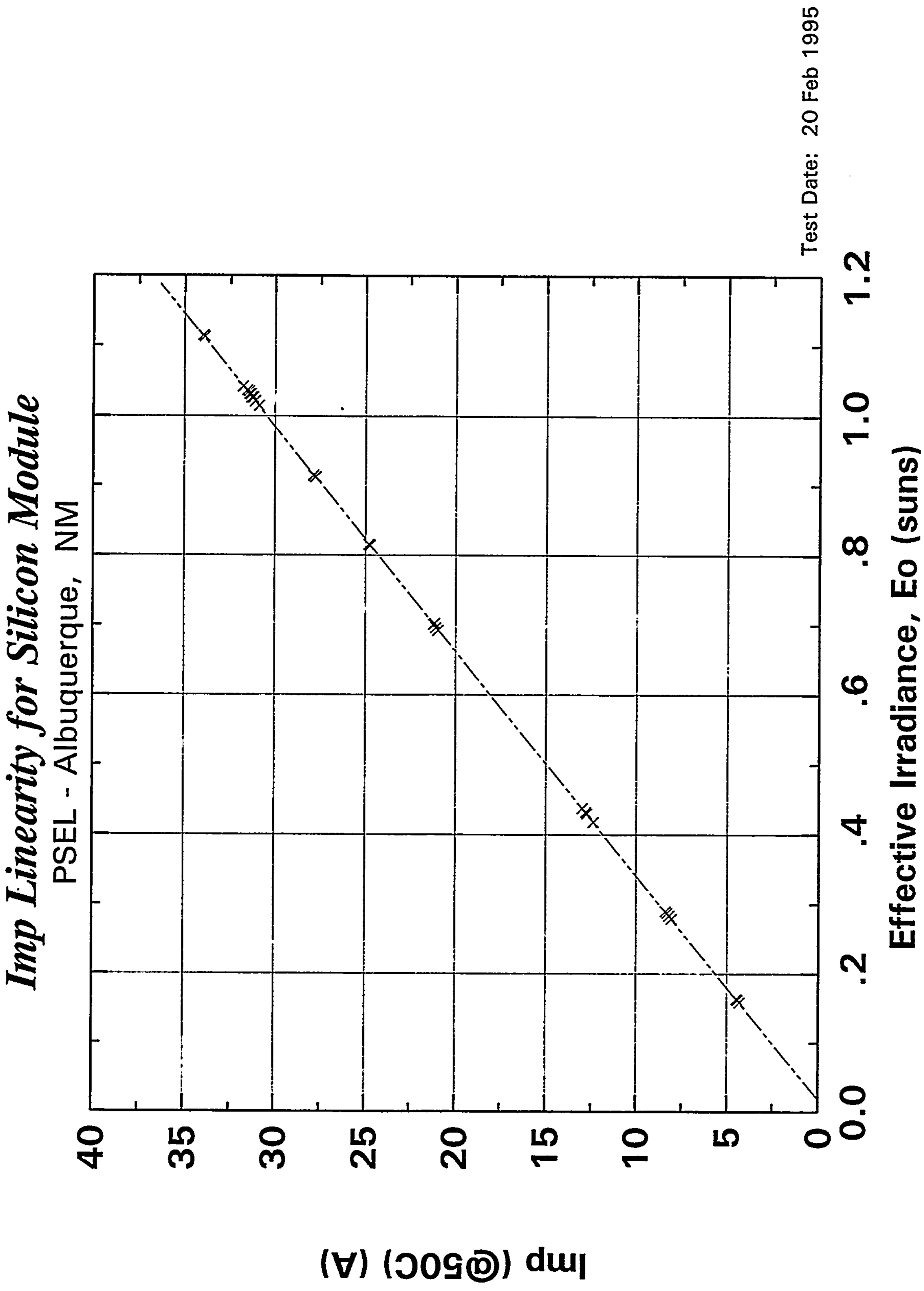
Definition: “Effective Irradiance, E_0”

From the module’s perspective:

- Isc depends on solar intensity, orientation, cell temperature, and the color of the sun. *Isc_0 determined for “reference” conditions.*
- Imp, Voc, and Vmp depend only on Isc and cell temperature! *These parameters at different conditions relate simply to the ratio* $\boxed{E_0 = Isc/Isc_0.}$

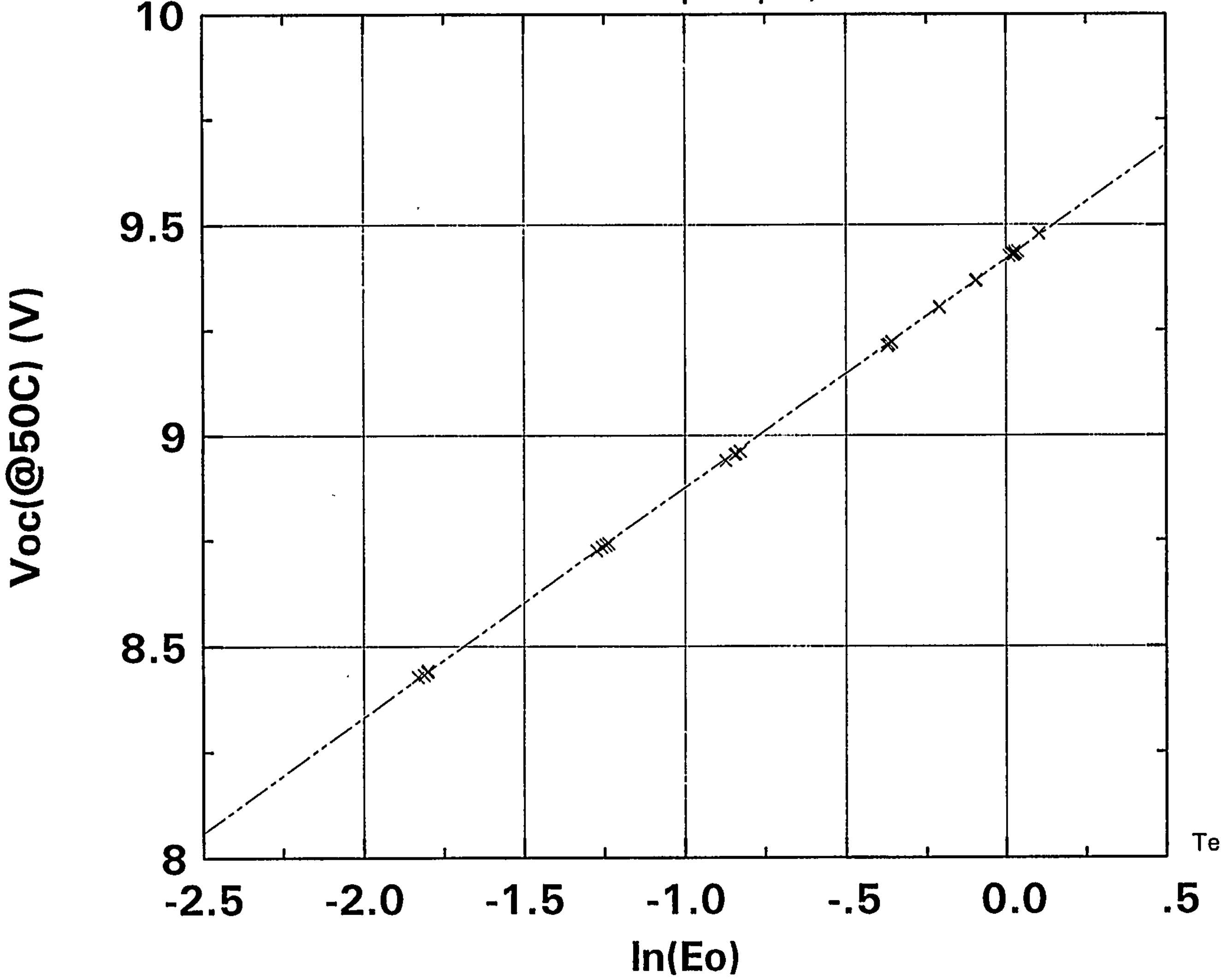
From a module user’s perspective:

- Life is more complex, Pmp relates to $
- Effective Irradiance is then $\boxed{E_0 = (E/1000)\ f_1(AMa\text{-}1.5)\ f_2(AOI)}$


Imp Linearity for Silicon Module
PSEL - Albuquerque, NM
Imp (@50C) (A)
0
5
10
15
20
25
30
35
40
Effective Irradiance, Eo (suns)
0.0
.2
.4
.6
.8
1.0
1.2
Test Date: 20 Feb 1995

Voc Linearity vs. ln(Irradiance)

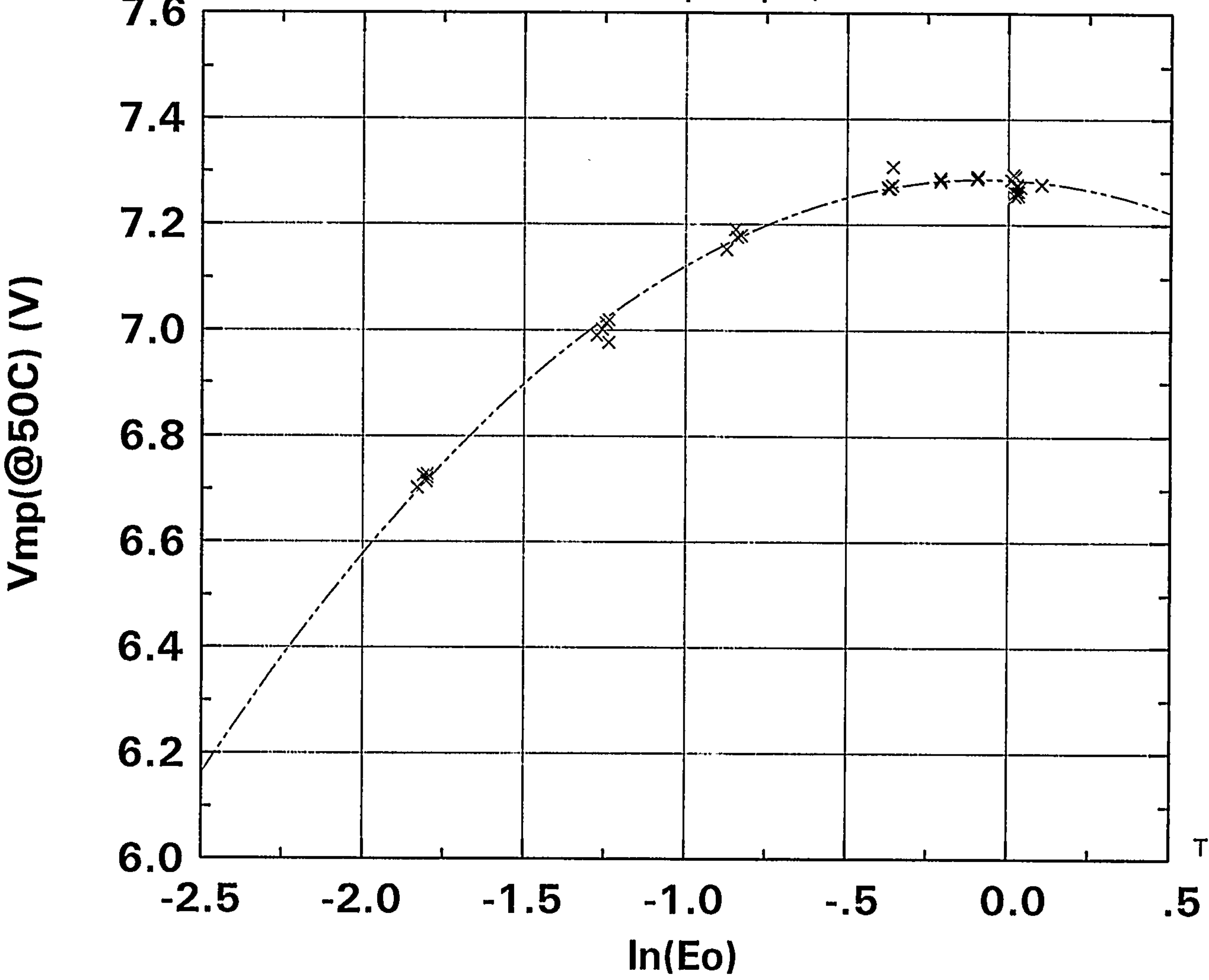
PSEL - Albuquerque, NM



Test Date: 20 Feb 1995

Empirical Relationship for Vmp

PSEL - Albuquerque, NM



Test Date: 20 Feb 1995

Modeling Equations for Module or System

$$I_{sc}(E_0,T_c) = E_0\,\{Isc_0 + \alpha_{Isc}\,(T_c\text{-}50)\}$$
$$I_{mp}(E_0,T_c) = C_1 + E_0\,\{C_2 + \alpha_{Imp}\,(T_c\text{-}50)\}$$
$$V_{oc}(E_0,T_c) = Voc_0 + C_4\,\ln(E_0) + \beta_{Voc}\,(T_c\text{-}50)$$
$$V_{mp}(E_0,T_c) = Vmp_0 + C_6\,\ln(E_0) + C_7\,\{\ln(E_0)\}^2 + \beta_{Vmp}\,(T_c\text{-}50)$$

Where:

E_0 = "Effective irradiance" = $I_{sc}(T_c$=50 °C)/ Isc_0
= (E/1000) f_1 (AM_a-1.5) f_2 (AOI)
Isc_0 = Reference I_{sc} = I_{sc}(1000 W/m^2, AMa=1.5, T_c=50 °C, AOI=0 deg)
Imp_0 = C_1+ C_2 = $I_{mp}(T_c$=50 °C, E_0=1)
Voc_0 = $V_{oc}(T_c$=50 °C, E_0=1)
Vmp_0 = $V_{mp}(T_c$=50 °C, E_0=1)
$f_1(AM_a$ -1.5) = "Air mass function," empirical
AM_a = Absolute (pressure corrected) air mass
f_2(AOI) = "Angle-of-incidence function," empirical
α_{Isc} = I_{sc} temperature coefficient, (A/°C)
α_{Imp} = I_{mp} temperature coefficient, (A/°C)
β_{Voc} = V_{oc} temperature coefficient, (V/°C)
β_{Vmp} = V_{mp} temperature coefficient, (V/°C)
C_4 = Regression coefficient (≅ No. cells in series x (nkT/q))
C_6, C_7 = Empirical regression coefficients

The Basic Steps in the Procedure

- Obtain temperature coefficients for I_{sc}, I_{mp}, V_{oc}, V_{mp}
- Obtain Isc_0, Imp_0, Voc_0, and Vmp_0 for “reference operating conditions”
- Obtain spectral (air mass) influence on Isc, “AMa Function”
- Obtain angle-of-incidence influence on Isc, “AOI Function”
- Obtain other site-dependent Isc modifiers, as required
- Calculate performance for any operating condition using concept of “Effective Irradiance” and modeling equations

Conclusions

- The techniques presented have been used effectively at Sandia's for commercial c-Si, mc-Si, and a-Si modules.
- The Southwest Technology Development Institute (SWTDI) has also done initial validation of the model using their module data archive.
- SWTDI and Sandia are developing a "System Rating Procedure" based on this approach. Endecon will help Sandia evaluate several large DOD (SERDP) systems using the procedure.
- A fixed-voltage (battery charging) condition will be added to the model.
- Guidelines for sites with heavily overcast operating conditions needed.

Highlights of the 1995
PV Standards and Codes Forum

Photovoltaics Performance and Reliability Workshop
Carl R. Osterwald
National Renewable Energy Laboratory
September 7, 1995

Overview

- Purpose
- IEEE Standards Coordinating Committee 21
- National Electric Code/CMP3 Task Group
- IEC TC82 U.S. Technical Advisory Group
- ASTM Subcommittee E44.09

NREL

Purpose

"To provide information and status of current photovoltaic standards and codes development activities in the U.S., and to provide a single time and location for working meetings of all the committees in succession."

IEEE SCC21 Highlights

- Negative ballot on the new module qualification sequence standard (PAR 1262) resolved
- Draft standard for PV power system safety, PAR 1374, reviewed
- Draft standard for field test methods of grid-connected PV systems, PAR 1373, reviewed
- Reviewed a battery qualification draft standard (PAR 1361) that uses a new Sandia testing procedure
- Two existing standards for PV battery system design and installation, 1013 and 1145, were reapproved

NEC/CMP3 Task Group Highlights

- Reported details of changes for photovoltaic systems affected in 1996 edition of NEC Article 690, "Solar Photovoltaic Systems"
- System voltages exceeding 600V will be allowed for installations other than single- and two-family dwellings.

IEC TC82 USTAG Highlights

- Seventeen international PV standards published to date
- Steve Chalmers elected as Technical Advisor for the USTAG, replacing Robert D'Aiello (expired term)
- Roster of the USTAG updated
- Time available for circulation of draft standards to national committees reduced to 2 - 5 months by IEC
- Thin film module qualification standard to begin voting in March 1996
- First drafts of module safety and PV device linearity standards available

ASTM E44.09 Highlights

- Revisions of E 948, E 1021, E 1362, and E 1462 passed subcommittee ballot
- Draft standard on wet module insulation integrity testing passed subcommittee ballot
- Draft standard on module mechanical integrity discussed and revised
- Multi-junction device performance testing draft discussed and revised
- New revision of E 1036 on module performance testing reviewed that is now being balloted
- Three existing standards to be revised in near future: E 927, E 973, and E 1171

RELIABILITY SESSION

Chair: Jack Stone

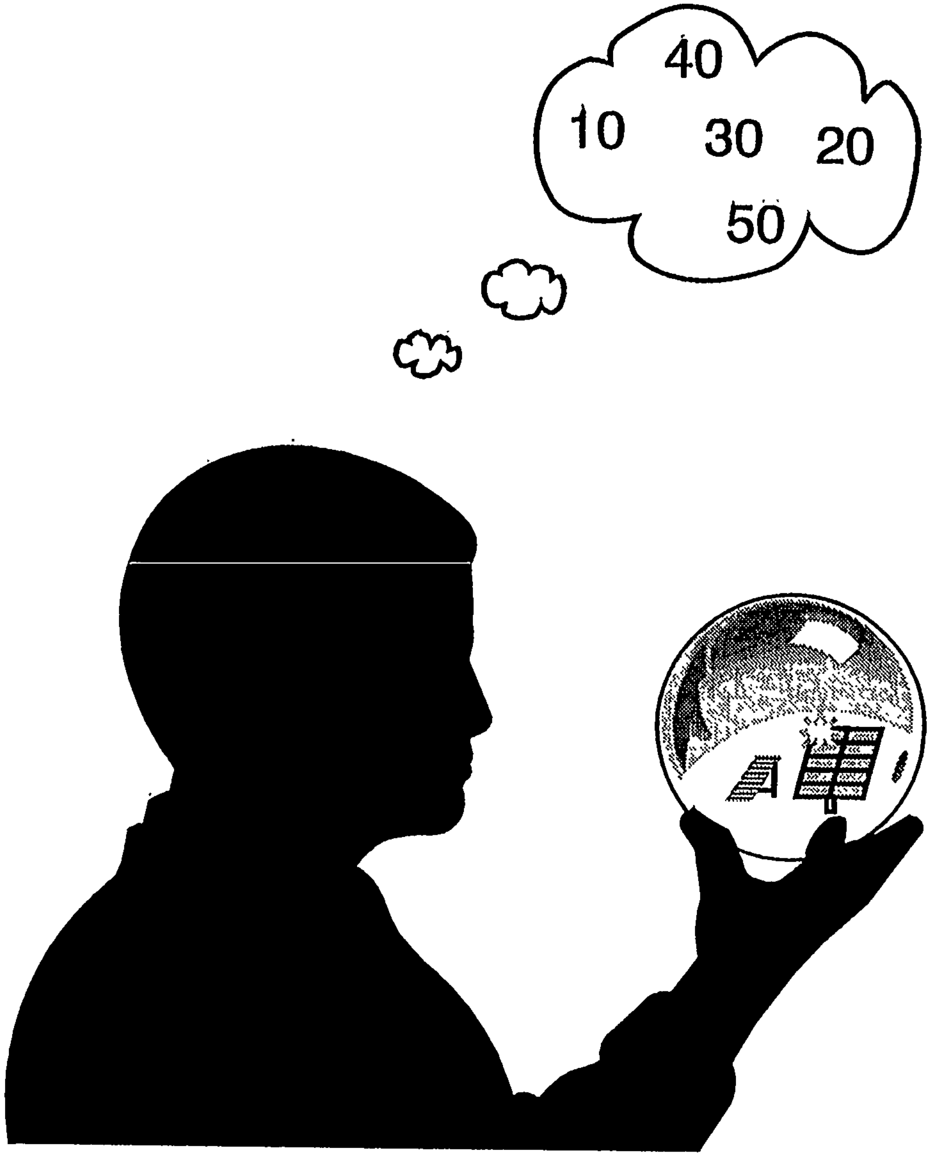
An OVERVIEW of SERVICE LIFETIME PREDICTION (SLP)

Gary Jorgensen

NATIONAL RENEWABLE ENERGY LABORATORY

September 7, 1995

SERVICE LIFETIME PREDICTION (SLP)



- A critical need for SLP exists in a wide variety of technologies
- SLP is a complex problem requiring significant resources
- Accurate, reliable SLP *is possible* if carefully performed

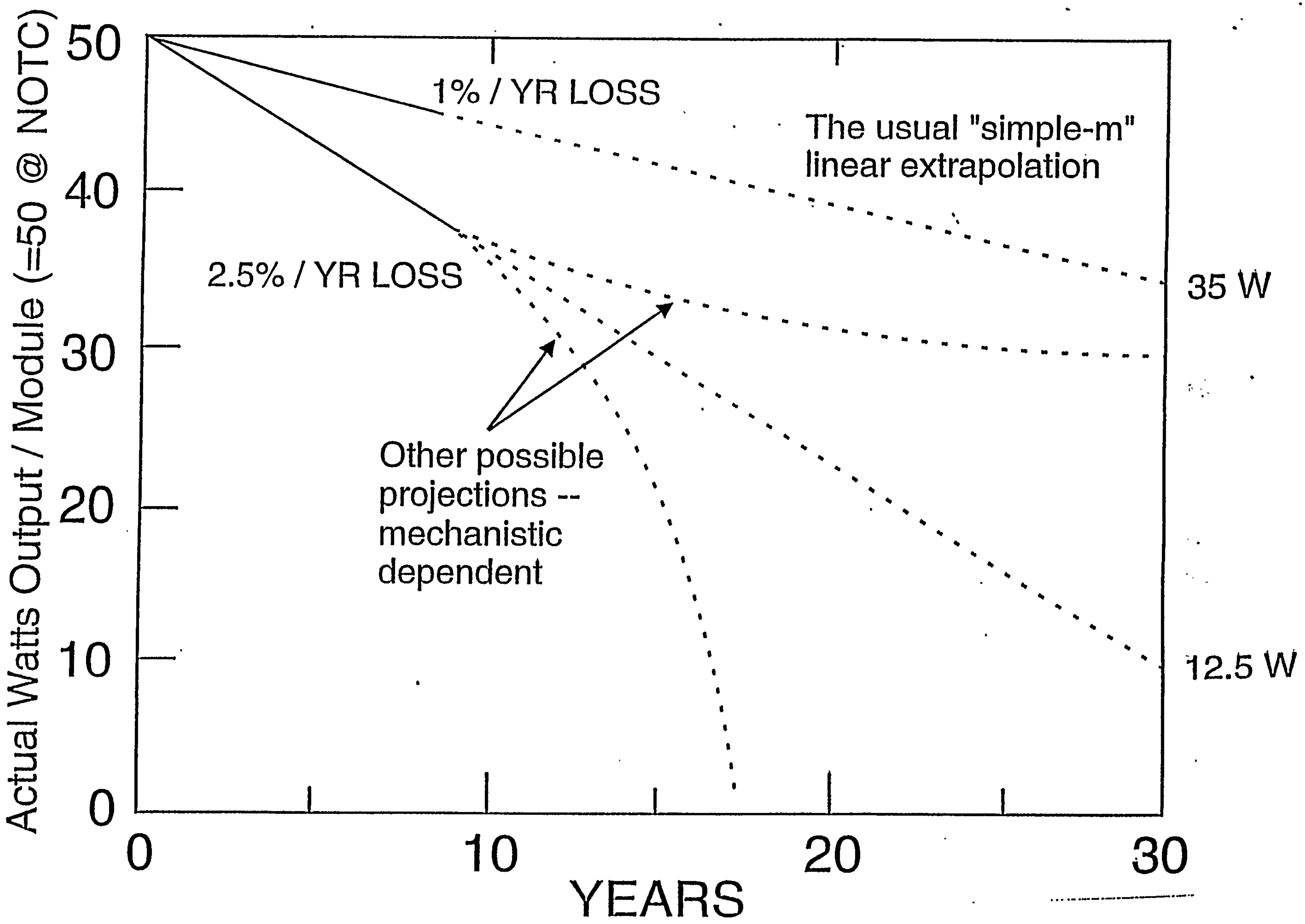
OUTLINE

- Importance of SLP
- Technologies that *need* SLP
- Facilities and Expertise required for SLP
- Objectives
- Approach
- Difficulties and Remedies
- Stress Factors
- Modeling Performance vs. Stresses
- Concluding Remarks

WHY IS SERVICE LIFETIME PREDICTION IMPORTANT?

- Emerging advanced multilayer renewable energy devices are expected to exhibit significantly increased service lifetimes; the use of real-time weathering alone is not viable for devices with 20-30 year lifetimes
- Many companies are, or soon will be, at a critical juncture in terms of marketing products whose projected lifetimes are uncertain without SLP
- Without confident knowledge of service lifetime, warranties will have high risks associated with them
- Life cycle cost projections require accurately known service lifetimes

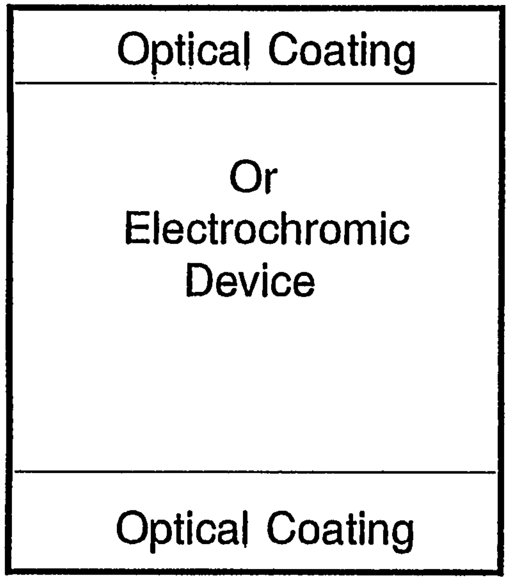
WHY IS SERVICE LIFE PREDICTION IMPORTANT?



WHO NEEDS to MAKE SERVICE LIFETIME PREDICTIONS?

- Renewable energy devices
  - — PV modules
  - — Solar Mirrors
  - — Electrochromic windows
  - — Flat plate collector glazings and absorbers
  - — Photoelectrochemical cells
- Coating applications
  - — Protective/decorative coatings
  - — Interior lighting applications
  - — Polymer based coatings for vehicles, homes, etc.
- Other technologies
  - — Aerospace
  - — Medical
  - — Electronics

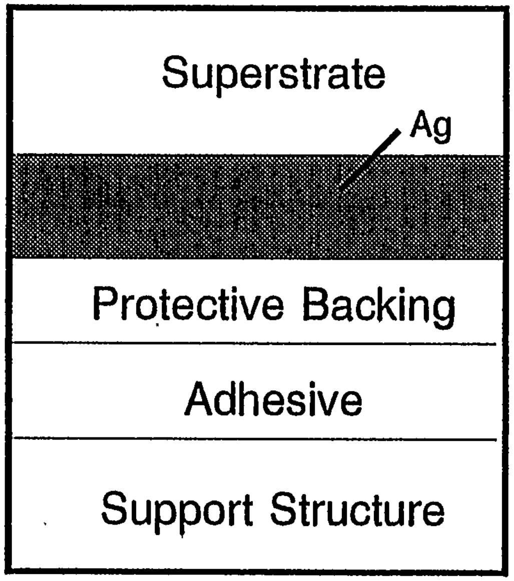
EXAMPLES of MULTILAYER RENEWABLE ENERGY DEVICES
for which SLP is NEEDED


Optical Coating

Or
Electrochromic
Device

Optical Coating

Transmitters


Superstrate

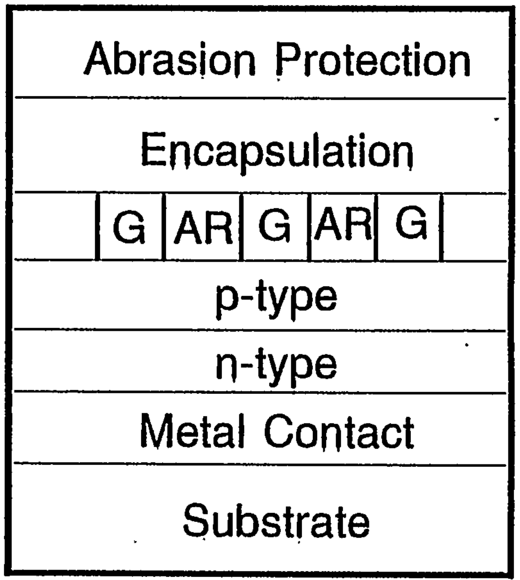
Ag

Protective Backing

Adhesive

Support Structure

Reflectors


Abrasion Protection

Encapsulation

G | AR | G | AR | G

p-type

n-type

Metal Contact

Substrate

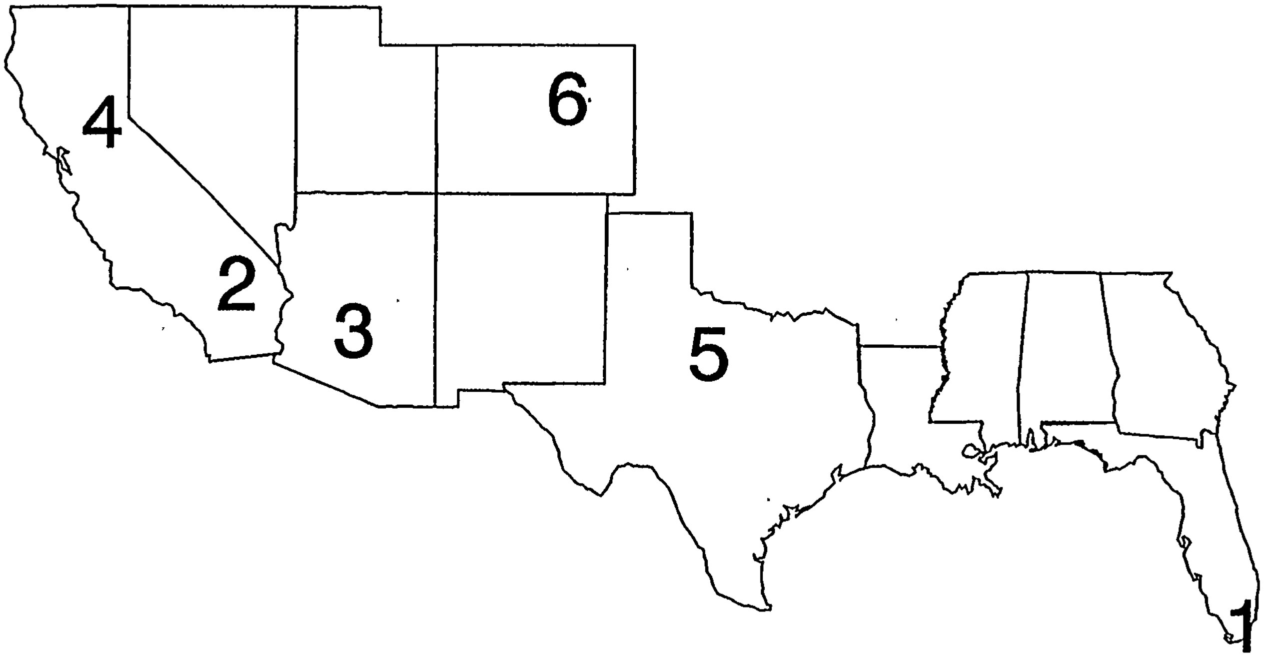
PV Cells

FACILITIES and EXPERTISE REQUIRED for SLP

- Ability to accurately characterize performance
- Ability to accurately characterize environmental stresses
- Geographically diverse network of fully instrumented outdoor test sites
- Carefully controlled laboratory exposure chambers (accelerated testing)
- Analytical capabilities to investigate degradation mechanisms
- A coordinated approach to data collection, management, and analysis
- Staff experienced in operating equipment and acquiring relevant data
- Knowledge of appropriate theoretical models and statistical techniques

NREL's Outdoor Exposure Test Network

1. Miami, FL	Hot / Humid
2. Daggett, CA	Hot / Dry
3. Phoenix, AZ	Hot / Dry
4. Sacramento, CA	Warm / Humid
5. Abilene, TX	Warm / Mild
6. Golden, CO	Cool / Mild



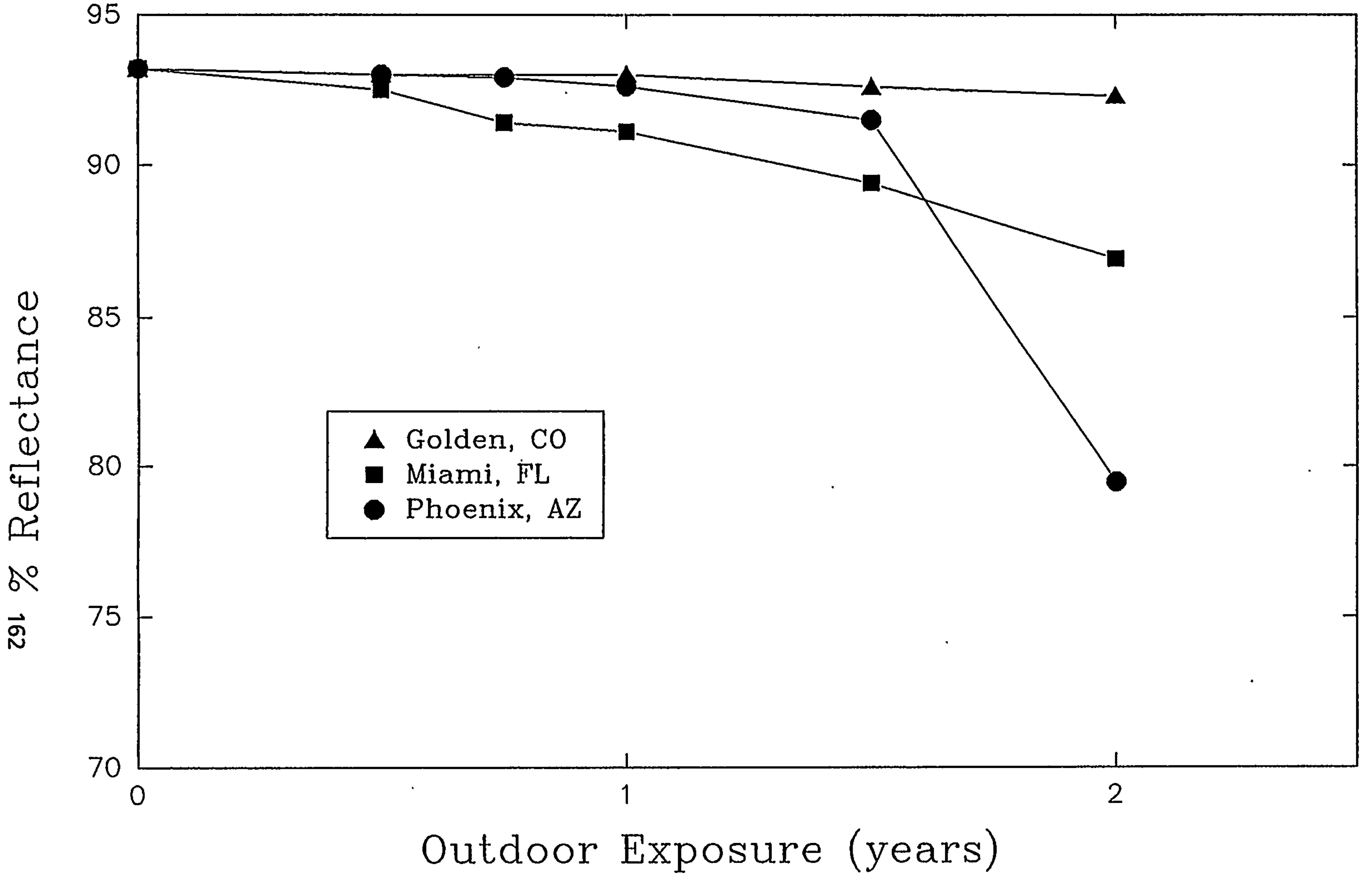
European Outdoor Exposure Test Sites

1. Cologne, Germany
   Warm / Humid

2. Almeria, Spain
   Hot / Mild

OBJECTIVES of SLP

- Develop a general methodology for accurate service life prediction (SLP) based upon correlations between accelerated exposure testing and outdoor weathering data
- Demonstrate and substantiate the methodology using existing and new data
- Understand / address site-specific effects of environmental service stresses

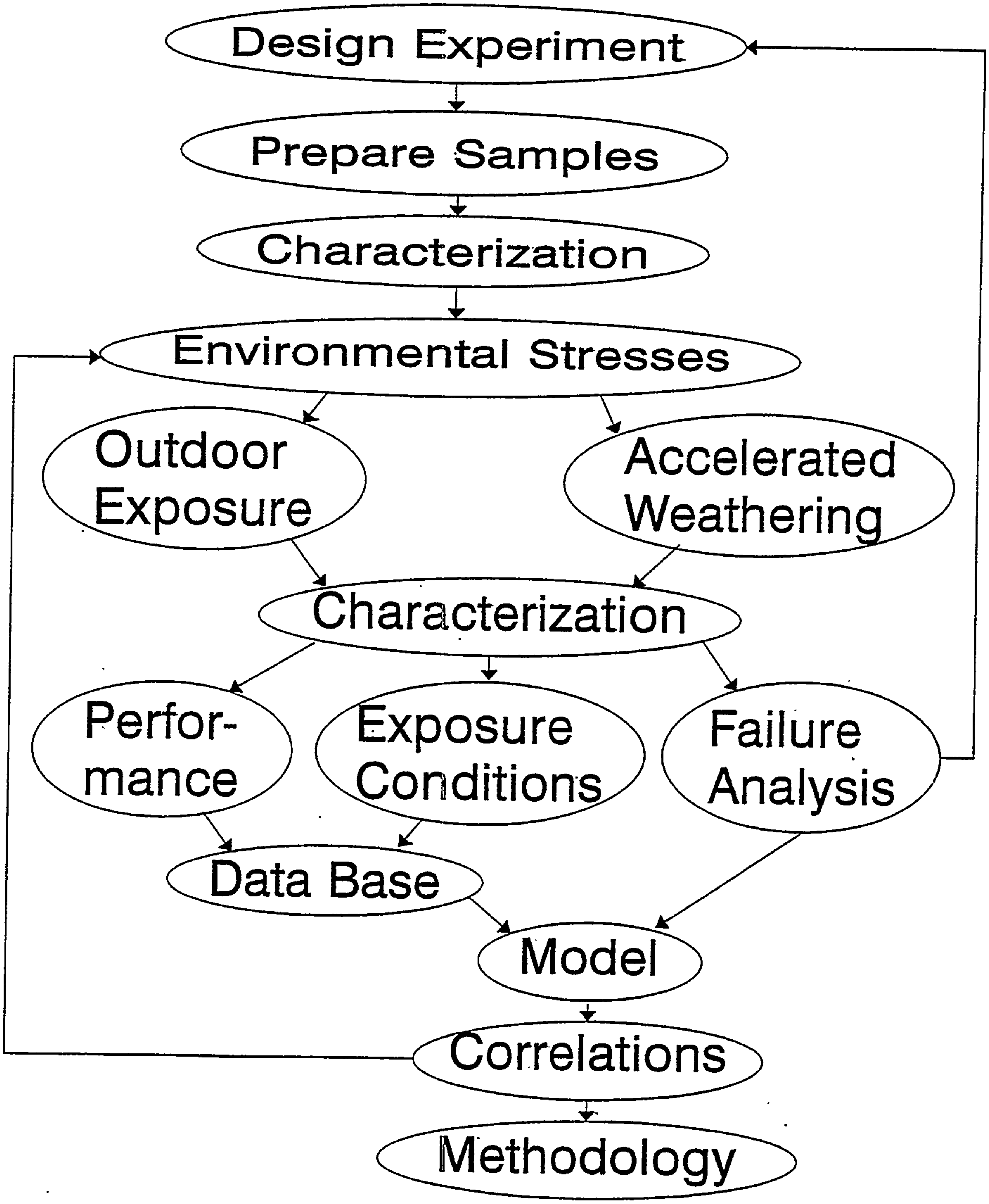


Solar-weighted hemispherical reflectance of ECP-305
on aluminum substrate as function of exposure site

TECHNICAL APPROACH to SLP

- Postulate candidate models for predicting "real" service life from accelerated test results
- Establish/build a quantitative data base of exposure stresses (both outdoor and accelerated) vs. material responses (performance measurements as a function of degradation)
- Obtain correlations between outdoor and accelerated exposure data, thereby identifying and quantifying the important stress factors relevant to particular materials/devices
- Perform analytical investigations of exposed samples to understand degradation mechanisms and their relationship to weathering, and to guide experimental design
- Use results of the measurement data base and degradation analyses to revise models

SLP Methodology Development

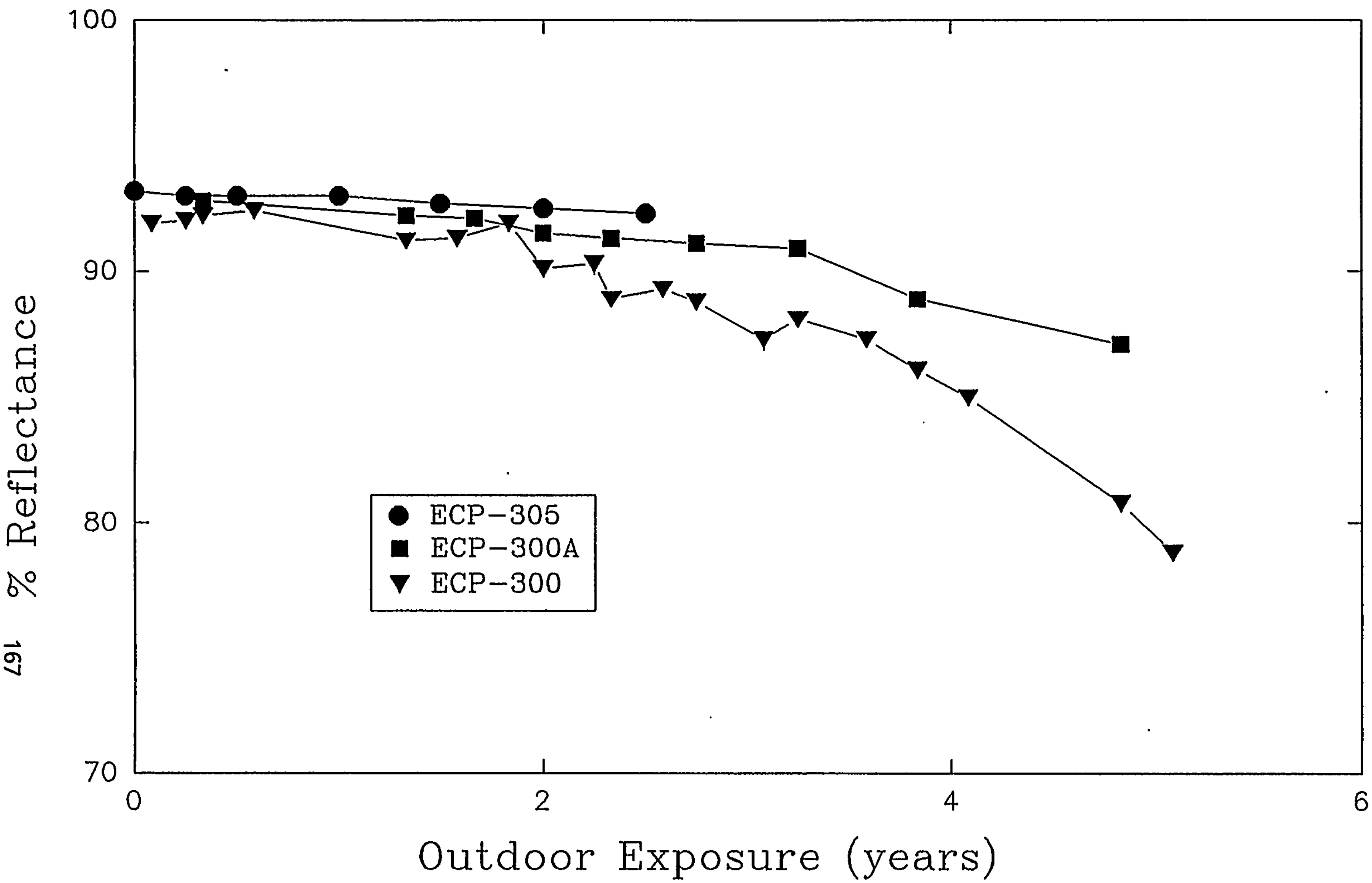


DIFFICULTIES of SLP and POSSIBLE REMEDIES

• Cost constraints associated with testing	• Use optimal Design of EXperiments (DEX)
• Complexity of data / results	• Good data base tools and statistical analysis
• Uncertainty between Accelerated Lifetime Testing (ALT) and "normal stress" failures	• Analytical characterization facilities
• Identification and characterization of important stresses	• DEX; stress monitoring capabilities
• Proper characterization of degradation and failure	• Ability to make accurate performance measurements
• SLP may be material and site specific	• Robust, general methodology

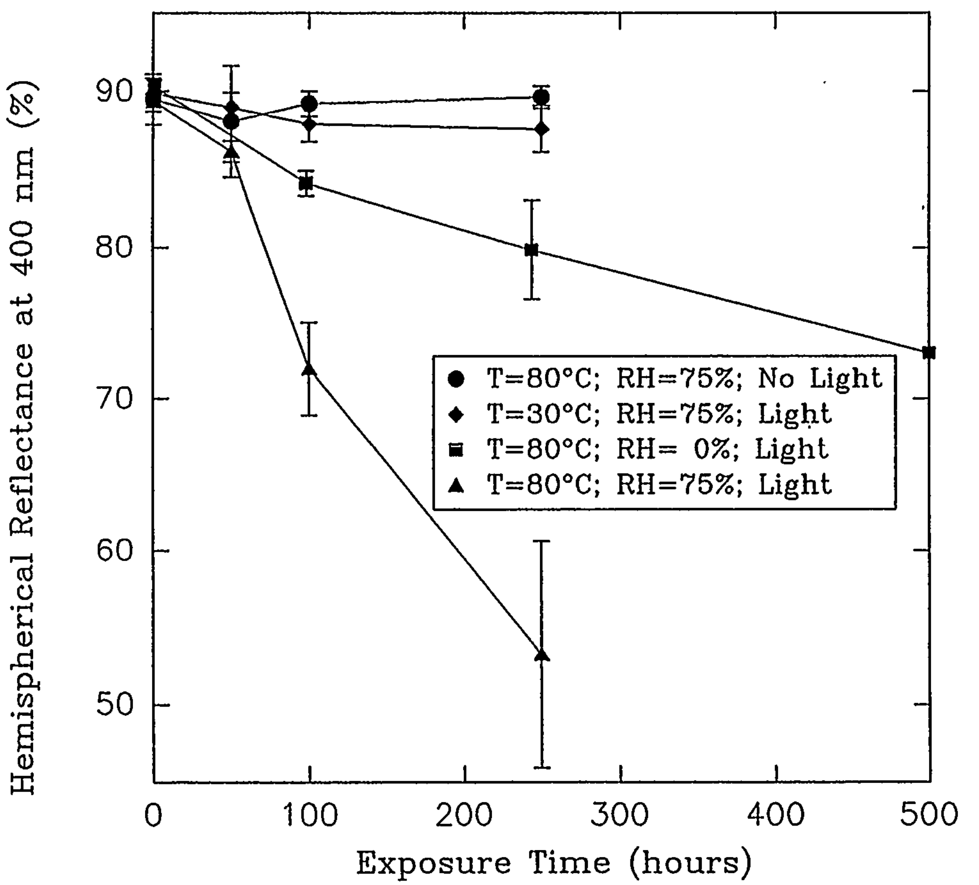
POSSIBLE STRESS FACTORS

- Harmful radiation
  - — Total broad-band, $I_{PSP}(\lambda=250\text{-}2500\ nm)$
  - — Total UV $I_{TUVR}(\lambda=290\text{-}385\ nm)$
  - — Narrow-band UV-B, $I_{UV\text{-}B}(\lambda=290\text{-}320\ nm)$
- Temperature, T
- Moisture
  - — Relative humidity, RH
  - — Rain
  - — Time of wetness
- Pollutants
  - — SO_x
  - — NO_x
  - — Suspended particulates
- Cycling
  - — Thermal
  - — Irradiance
  - — Wet / dry
- Hail



Solar−weighted hemispherical reflectance for exposure in Golden, CO as a function of material type

Effect of Stresses on Performance for
ECP-300A Exposed in Solar Simulator



MODELING PERFORMANCE vs. STRESSES

The synergistic effects described above suggest that the change of performance, ΔP, depends on the three stresses $L_{UV\text{-}B}$ (irradiance), T, and RH. A general expression for the change in performance over time can be given by [Jorgensen, Kim, and Wendelin]:

$$\Delta\rho(t) = A \int_0^t L_{UV\text{-}B}(\tau)\, T(\tau)^{-B}\, e^{-[E/T(\tau)]}\, e^{RH(\tau)[C+D/T(\tau)]}\, d\tau \qquad (1)$$

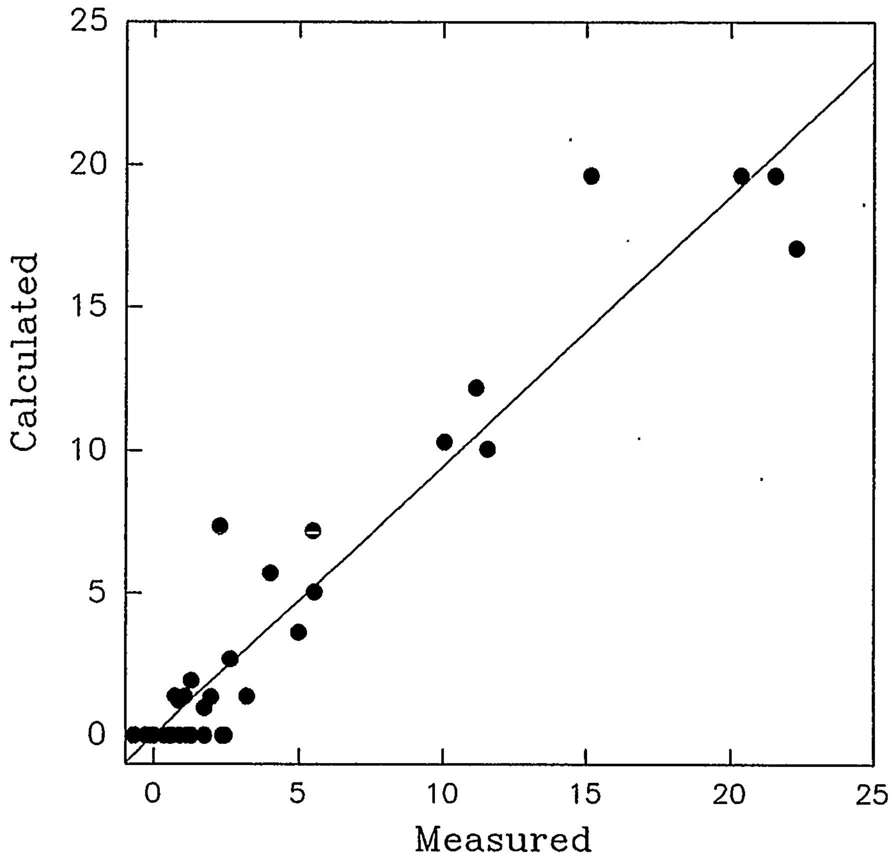
For laboratory controlled experiments, in which the important (elevated) stress factors are time independent variables (e.g., $L_{UV\text{-}B}(t) = L_{UV\text{-}B}$, $T(t) = T$, and $RH(t) = RH$), Eq 1 simplifies to:

$$\Delta\rho(t) = A\,(L_{UV\text{-}B} \cdot t)\, T^{-B}\, e^{-(E/T)}\, e^{RH[C+(D/T)]} \qquad (2)$$

and the change in performance after some cumulative dose of UV-B irradiance, $I_{UV\text{-}B}$, will be:

$$\Delta\rho = A\, I_{UV\text{-}B}\, T^{-B}\, e^{-(E/T)}\, e^{RH[C+(D/T)]} \qquad (3)$$

Measured vs. Calculated Change in Reflectance



CONCLUDING REMARKS

- **A critical need for SLP exists in a wide variety of technologies**
- **SLP is a complex problem requiring significant resources**
- **Accurate, reliable SLP *is possible* if carefully performed**

Lessons Learned from 15 Years of PV System Testing

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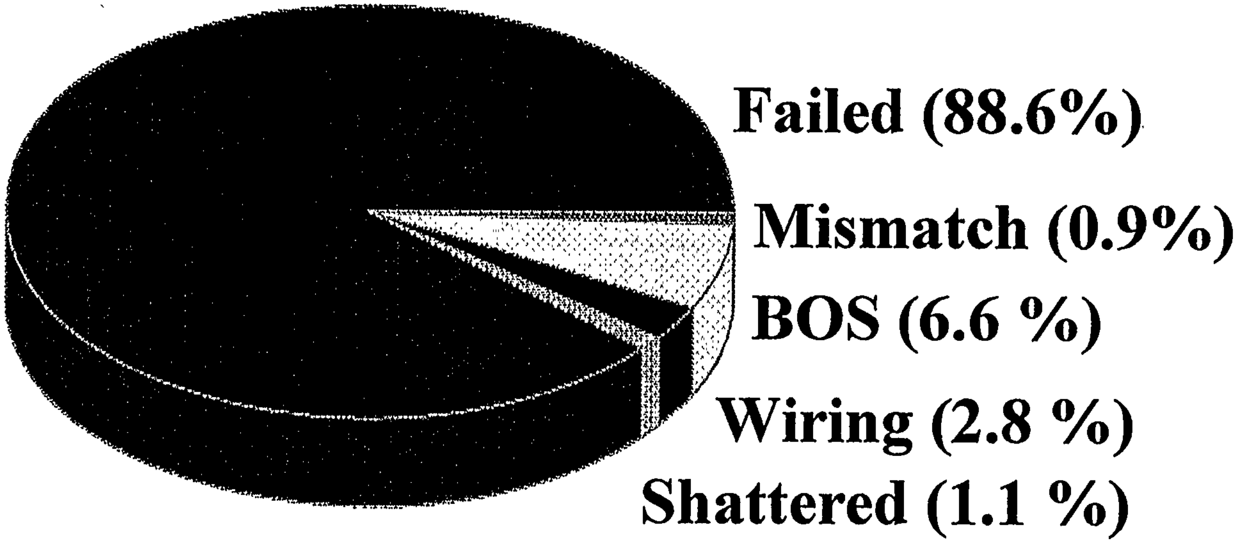
Southwest Technology
Development Institute

Geographic Locations of Tested PV Systems

Southwest Technology
Development Institute

Pre Block V
Total Number of Modules Tested 19,956
Non-producing Modules 10,143

Failed	8,985
BOS	674
Wiring	280
Shattered	112
Mismatch	92

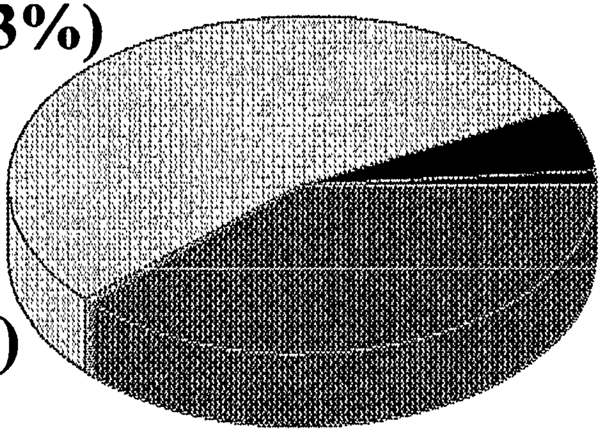


Southwest Technology Development Institute

Block V

Total Number of Modules Tested 68,739

Non-producing Modules 4,463



Shattered	24
Failed	58
Wiring	276
Mismatch	1,682
BOS	2,423

Southwest Technology Development Institute

SWRES / SNL-DAC
10-Year Module Degradation Study

	1985	1986	1987	1988	1989	1990	1991	1992	DEGRADATION PER YEAR
AUSTIN PV300			288	274	267	268			1.7%
FOND DU LAC		2.1	2.0	1.7	1.6				1.6%
GEORGETOWN	270			210					6.8%
JOHN LONG			181		171			161	2.3%
NEWMAN PS	16.9			15.8		13.8			3.9%
SMUD PV1	1050	990			947				2.1%
SMUD PV2		988	926		931				1.8%
WP&L MUNI									1.9%
WP&L RES		2.0		1.9	1.8				1.5%
WP&L SOC			1.8	1.8	1.6	1.8		1.8	4.7%

Conclusions

- Module Reliability is Improving
- Proper Installation is Essential to Ensure Reliability
- Reliability problems that develop over time are best dealt with in two ways:
  - Complete Characterization of New or Innovative Designs
  - Development and Use of Accelerated Outdoor Exposure Testing Methods

Analysis Techniques Used On Field Degraded Photovoltaic Modules

By

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PO Box 5800
Albuquerque, NM 87185-0753

Introduction

Sandia National Laboratories' PV System Components Department performs comprehensive failure analysis of photovoltaic modules after extended field exposure at various sites around the world. Many of these modules are sent to us because of observed and/or suspected electrical degradation. Sandia maintains a full spectrum of analytical techniques in support of its defense projects, and the photovoltaic program at Sandia uses these resources as needed to help identify the cause of the degradation. This report focuses only on ultrasonic inspection, microscopic inspection, infrared inspection, and module encapsulant adhesion testing. These analytical techniques are used to make solder fatigue life predictions for PV concentrator modules, identify cell damage or current mismatch, and measure the adhesive strength of the module encapsulant. The results help identify the causes of module degradation and provide technical support to the module manufacturers so that they can improve the reliability of their product.

Ultrasonic Inspection

There are two major methods of ultrasonic inspection: the transmission method and the pulse-echo method. As the names imply, the transmission method measures the ultrasonic energy passing through a test sample, and the pulse-echo method measures the ultrasonic pulse reflected back from defects in the test sample. This technique has been used to identify design and manufacturing problems before module production. After modules are fielded, cell assembly debonding can also be monitored over time using the same techniques (see Figure 1).[1]

The transmission method, which measures only signal attenuation, can only provide information on the size and X-Y location of defects. The sample defects identified by ultrasound are usually voids, cracks, nonuniformities, and debonded laminate structures. The transmission method is limited in sample thickness by the ultrasound attenuation in the material under test; it does not have a minimum sample thickness limitation. Its main advantage is that data interpretation is much less complicated because there are no reflected echoes, just transmitted ultrasound energy.

The pulse-echo method, which is the most frequently used, can locate defects in the Z-axis in addition to measuring the size and the X-Y-axis position. This method measures Z-axis location by measuring the transit time of the reflected pulse. The X-Y location for

This work is supported by the Photovoltaic Energy Technology Division,
US Department of Energy, contract DE-AC04-945AL85000

both methods is established by an X-Y position indicator while the ultrasonic transducer is moved across the sample. Sample thickness is theoretically limited only by the distance the pulse can travel before another pulse is initiated, usually 6 meters. From a practical standpoint, sample thickness is always considerably less than the theoretical limit because of signal attenuation. The minimum sample thickness is limited by the ability of the test equipment to measure the transit time of the echo.

Ultrasound Test Data

Scan data for the pulse-echo method is presented in three forms, called A-scans, B-scans, and C-scans. The A-scans, which are the most widely used data format, provide a quantitative display of signal amplitudes and time-of-flight data on an oscilloscope screen. The A-scans are used to analyze the type, size, and location of flaws. B-scans display time-of-flight data along a line on the surface of the sample. This data is plotted and used to show size, shape, orientation, and depth of large flaws. C-scans map out signal amplitude and time-of-flight data over the testpiece surface. C-scan data is used to identify defects using a plan view of the testpiece at specific interfaces.

The data in Figure 2 demonstrates the use of the ultrasound technique to detect bond degradation. Nine C-scans and one through-transmission image are displayed from a five-layer stack containing a PV concentrator cell, solder, ceramic insulator, solder, and an aluminum heat spreader. The data shows significant bond degradation at the aluminum/ceramic interface after 250 thermal cycles (-40 to 110°C). As seen in the first row of C-scans, debonding is indicated by the increased pulse-echo signal (dark image) at the aluminum/ceramic interface. The drop in pulse-echo signal at the ceramic/cell interface also indicates debonding at the first interface. It is difficult to make conclusions about the bond at the second interface because most of the pulse-echo is reflected at the debonded first interface. If the first aluminum/ceramic interface were good, then the second interface could be evaluated more effectively for debonding. The third row of pulse-echo scans shows bond degradation throughout the entire cell stack as a function of thermal cycles. The top pulse-echo image is very consistent with the last through-transmission image.

Metallurgical Cross Section and Scanning Electron Microscopy

A metallurgical cross section and Scanning Electron Microscopy (SEM) were used to measure solder-fatigue crack-growth in a concentrator module cell assembly after 29 months of field use. This destructive analytical technique was necessary because no pre-installation ultrasound scans were available to compare with the field-degraded cell assembly. The only way to measure solder fatigue was with direct microscopic inspection of the fatigue crack (see Figure 3 and 4).[2,3]

Metallurgical cross sections require the cell assembly to be removed from the PV module and cut in half to expose the 0.025-mm (1 mil) thick solder bond between the cell and copper heat spreader. This is a delicate process and usually requires a special diamond saw to minimize damage to the cell assembly. After all excess material from the cell assembly is removed, the cross section is potted in epoxy for mechanical support and ease of polishing. Polishing dissimilar materials, especially lead solders, requires special polishing compounds and procedures. The 62.5Pb-36.1Sn-1.4Ag eutectic solder alloy has a microstructure that coarsens and elongates when it is exposed to the cyclic strains that cause solder fatigue. Solder fatigue occurs in this cell assembly at the cell-to-copper heat spreader and is caused by daily temperature cycles and the large thermal expansion differences between the silicon (2.6-ppm/°C) and copper heat spreader (16.7 ppm/°C). The effect of solder fatigue is clearly seen in the SEM photos in Figure 5. The Photo #3 microstructure is coarsened and elongated compared with Photo #4. Photo #4 was taken at the center point of the solar cell where cyclic strain was negligible. Photos #1 through #3 were taken from the outer edge of the cell inward to about 1.2 mm.

The SEM images were taken in compositional backscatter mode, which enhances the visibility of the solder microstructure. In this imaging mode a special detector collects electrons that are backscattered from the input electron beam. The number of backscattered electrons increases with higher mass elements, thus making the lead look lighter and the tin look darker.

The percentage area under the cell where the solder had cracked was calculated using the measured crack length on both edges of the solar cell. It was calculated that between 4 and 12% of the area under the cell was debonded due to cracks. This one field degradation measurement was then compared with identical solder fatigue test samples that were cycled under controlled conditions in a temperature cycle chamber. Before and after through-transmission ultrasound scans were used to measure the percent of debonded area in the solder fatigue samples. The fatigue test results are in Figure 6 and show fatigue crack growth for 0 to 80°C, 0 to 100°C, -40 to 110°C, and -50 to 150°C cycles. The one fielded cell assembly solder fatigue measurement after 870 "natural" diurnal cycles resulted in slightly over half the debonded area as the same data point on the 0 to 80°C fatigue curve (see Figure 6).

Infrared Imaging

Infrared imaging of PV modules has proven to be a very useful tool in identifying mismatched cells, cracked cells, and high-resistance contacts caused by failed solder bonds. The infrared camera's spectral bandpass is between 3 and 5 microns and uses a Hg/Cd/Te detector at 77°K. Liquid nitrogen is used to cool the detector and it has a dewar hold time of more than 3 hr. The camera's field of view is 15° vertical and 20° horizontal with a temperature sensitivity of 0.4 to 0.1°C and a spatial resolution of 0.5°/pixel. The entire system consists of a scanner, control electronics, video cassette recorder, and video processing software. Newer infrared cameras do not require the liquid nitrogen, their spatial resolution is closer to 0.1°/pixel, and their image processing is more user friendly.

An infrared scan of a PV module in short-circuit condition is shown in Figure 7. The image indicates that three cells are operating about 5 to 15°C hotter than the rest of the module, and one hot spot is present where a high-resistance solder bond is located. The other cells adjacent to the hot spot are also hotter than normal and they may also have high-resistance contacts or be electrically mismatched with the other cells. In a short-circuit condition, a few cells are typically in reverse bias resulting in internal heating and a temperature higher than the surrounding cells.

Encapsulant Adhesion Test

After 8 to 10 years in the field, loss of adhesion between ethylene vinyl acetate (EVA) and silicon cells has been observed in modules from different manufacturers. In all cases, the modules showing adhesion failure had passed JPL Block V testing at the time of manufacture. This raised concern that the JPL Block V thermal cycle and humidity/freeze tests were unable to identify this particular failure mechanism. In order to answer these questions, a quantitative adhesion test was needed. Sandia has developed a test procedure that will measure EVA adhesive strength to the solar cell.

The test procedure uses either field-degraded modules and/or test modules that have been exposed to environmental testing. First the module is prepared by removing the frame and clamping the glass laminate to a milling machine table. An end-mill is used to remove the Tedlar™ and machine down to the solar cell. A 6-mm diameter cell sample is isolated using a diamond core drill. Care must be taken not to damage the isolated cell fragment or the tempered module glass. Once all EVA residue is removed from the backside of the cell, a stud is epoxied to the cell sample. A load cell mounted in the end-mill is then attached to the stud for the pull test. These procedures quantify the adhesive strength between the top cell surface and the EVA encapsulant (see Figure 8 and 9).

Test results on new modules indicated EVA-to-cell adhesive strengths near 620 NT/cm^2 (900 lb./in^2). Work is in progress to measure the effects of environmental aging. In addition to the adhesive strength of the EVA-to-cell interface, the extracted cell sample is available for numerous analytical techniques such as Auger, X-Ray Photoelectron Spectroscopy, and Scanning Electron Microscopy (see Figure 10).

Summary

The above analytical techniques have helped Sandia identify the cause of different module degradation mechanisms: these include solder fatigue, cell damage or current mismatch, and EVA to cell adhesion loss. In all cases, the information obtained was provided to the module manufacturers to assist in improving the reliability of their product.

References

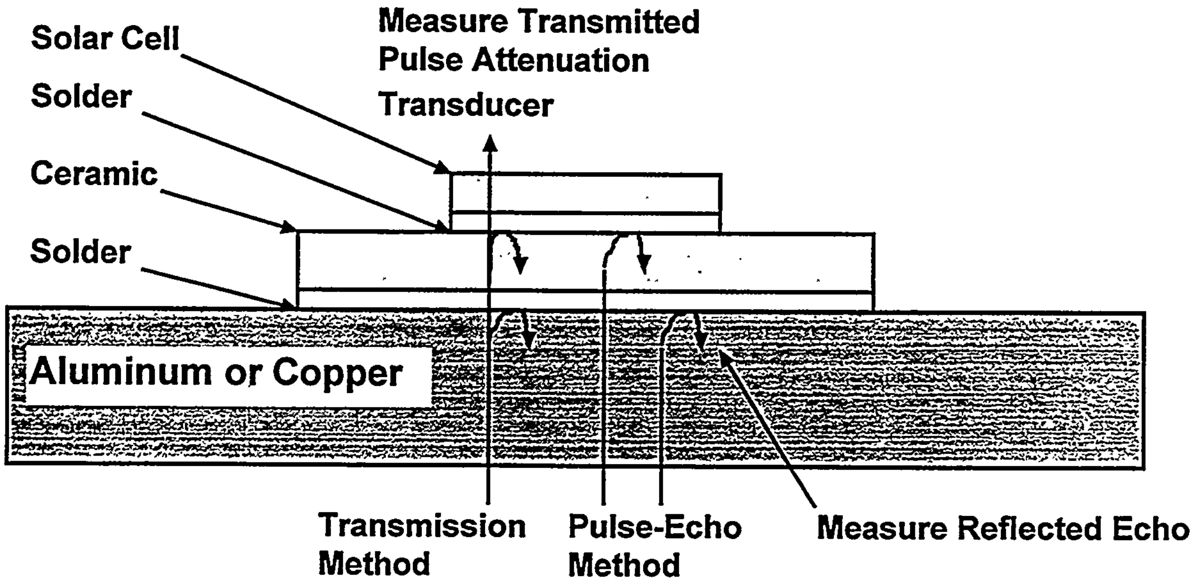
1) **Nondestructive Evaluation and Quality Control,** Metals Handbook Ninth Edition, Vol. 17, American Society For Metals.

2) Joseph I. Goldstein , **Scanning Electron Microscopy and X-Ray Microanalysis,** A Text for Biologists, Materials Scientists, and Geologists, , Plenum Press, 1981.

3) D.R. Frear, W.B. Jones, K.R. Kinsman, **Solder Mechanics, A State of the Art Assessment,** Minerals, Metals & Materials Society, 1991.

Figure 1

Ultrasound Of PV Concentrator Cell Assembly

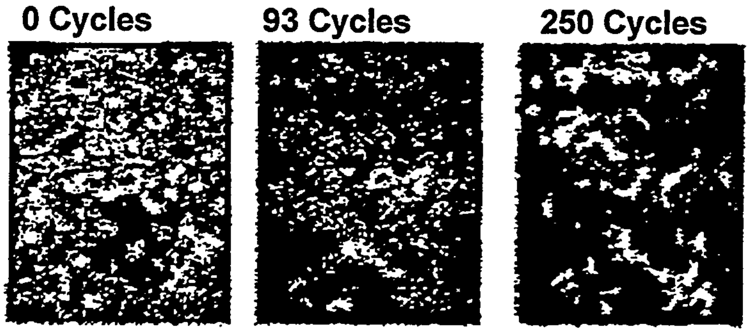


Sandia
National
Laboratories

Figure 2

Nondestructive Ultrasonic Inspection Of PV Concentrator Cell Assemblies

Pulse-Echo Amplitude At Aluminum/Ceramic Interface



Gray through Black Levels Indicate Poor Bond At This Interface

Pulse-Echo Amplitude at Ceramic/Silicon Interface

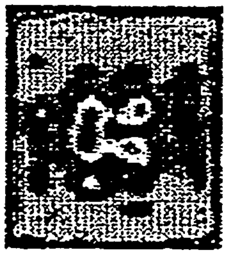
Gray through Black Levels Indicate Good Bonds up to this Interface

Pulse-Echo Amplitude at Top Of Silicon

Gray through Black Levels Indicate Good Bonds Throughout The Cell

% Debonded 67% 84% 96%

Through Transmission Image



Gray = No Bond At One Or More Interfaces

90%

Figure 3

PV Concentrator Cell Assembly

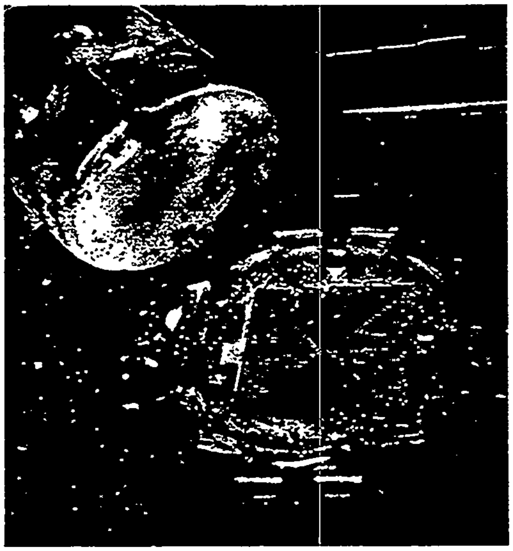


Figure 4

Solder Fatigue In Cell Assembly After 29 Months

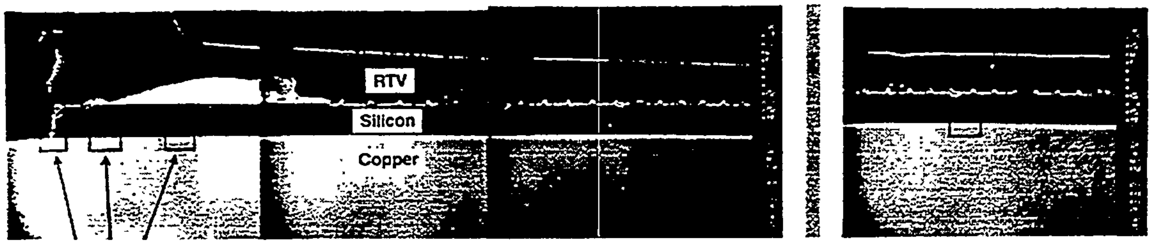


Photo # 1, 2, 3

Photos of Fatigue Crack Zone
Crack Length 1.2 mm

Photo # 4

Sandia
National
Laboratories

Figure 5

Solder Fatigue In Cell Assembly After 29 Months

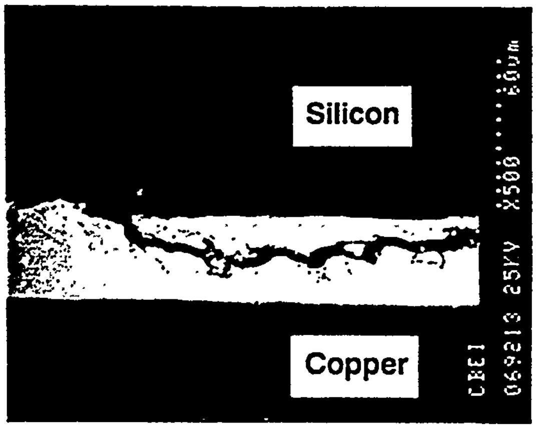


Photo #1
Cell Edge
Fatigue Crack Initiation

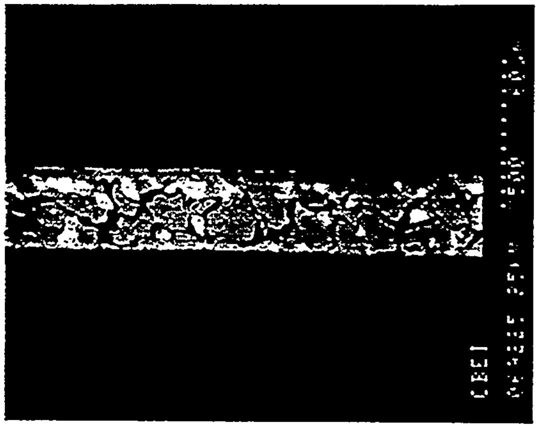


Photo #2
Fatigue Crack Growth

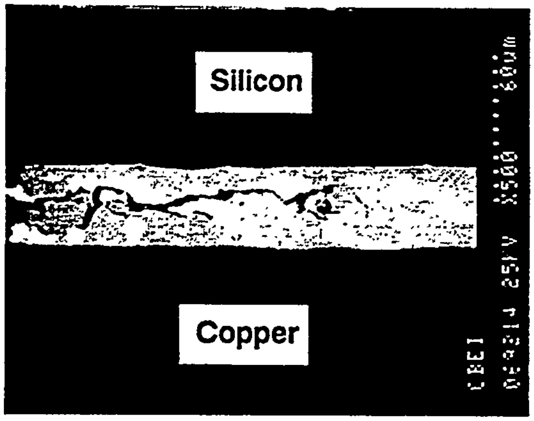
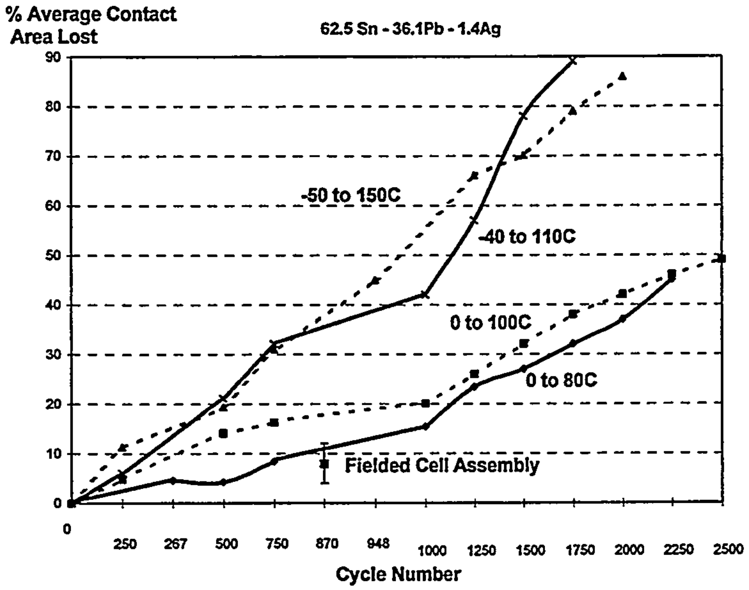


Photo #3
Fatigue Crack Extinction

Photo #4
Cell Center - Undisturbed

Sandia
National
Laboratories

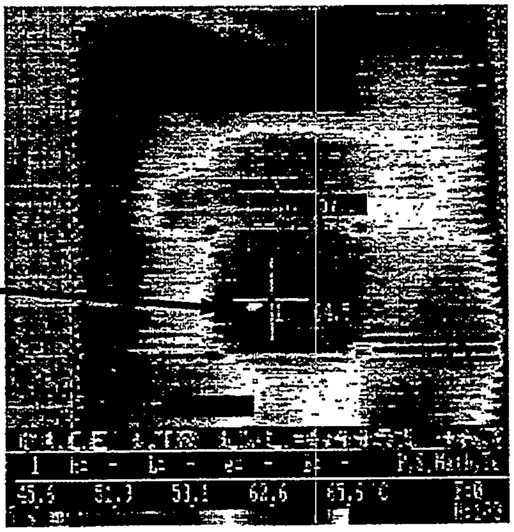
Figure 6



Solder Fatigue As A Function Of Thermal Cycling

Figure 7

Infrared Image Of An Aged Crystalline Silicon Module



Hot Spot From Solder Bond Failure

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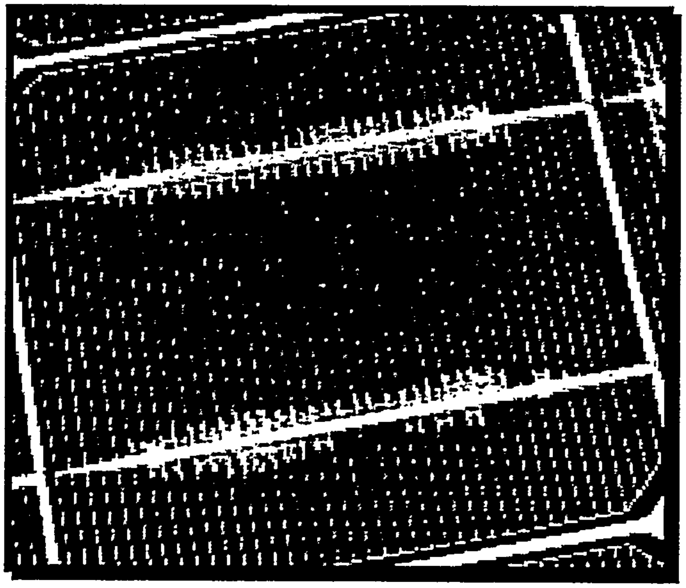
National
Laboratories

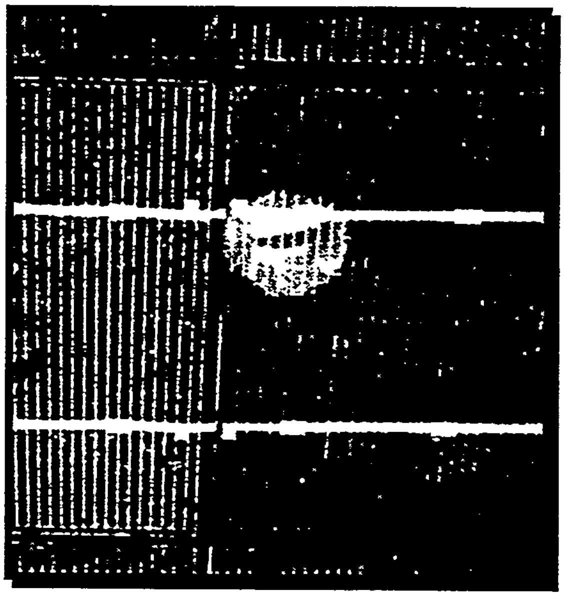
Figure 8

ENCAPSULANT ADHESION

(A Durability Issue)

- ~10-yr. field exposure can result in loss of adhesion at EVA interfaces
- Extent varies, but the problem is common to several manufacturers
- Method developed to quantify adhesion strength at interfaces before and after field exposure or accelerated aging tests

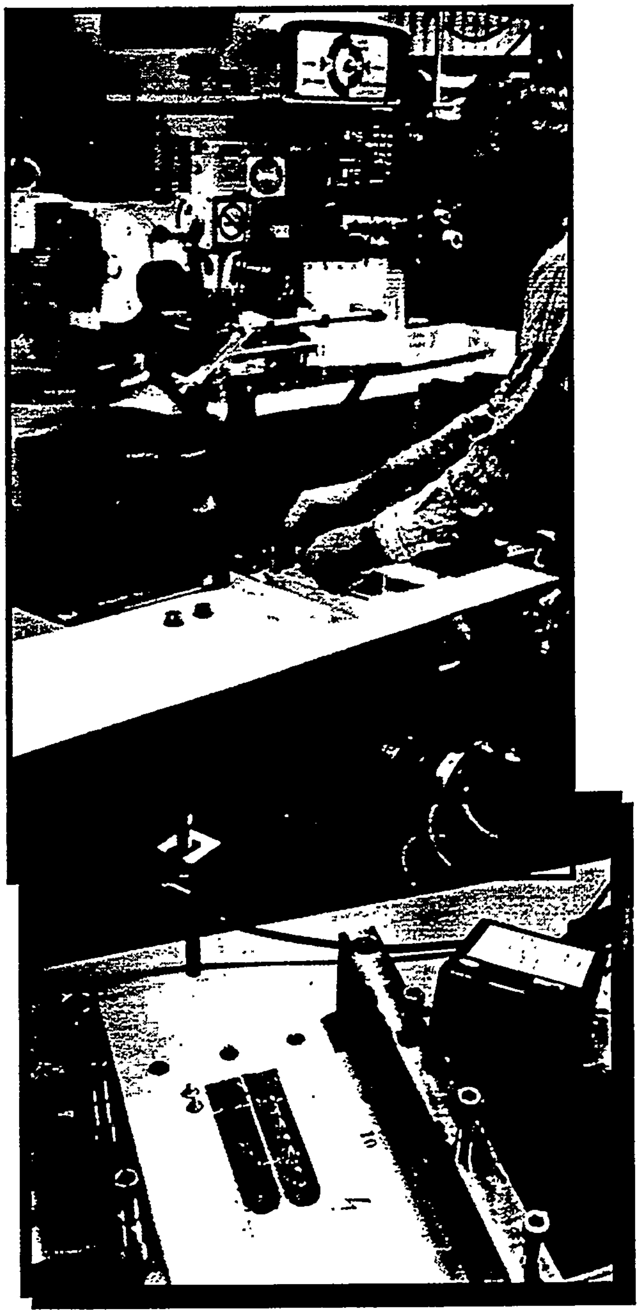




Sandia National Laboratories

Figure 9

ADHESION STRENGTH TESTING



Procedure

- Overcome reluctance to hurt a module
- Isolate samples using a milling process
- Bond pull tabs to samples
- Measure tensile stress at failure
- Perform analytical tests (Auger, XPS, SEM, etc.)
- Also solder-bond and EVA samples

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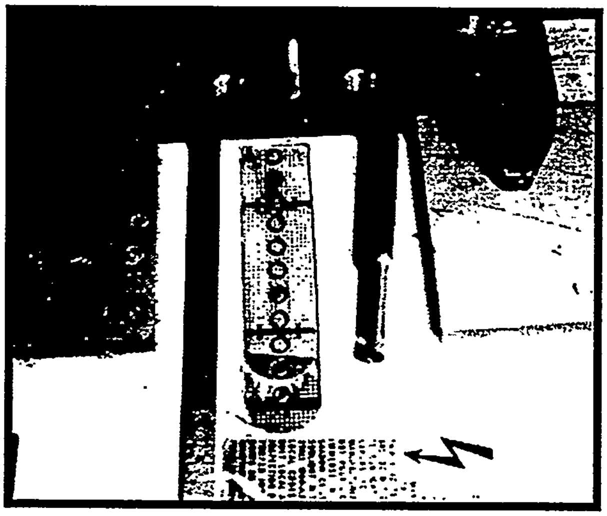
National
Laboratories

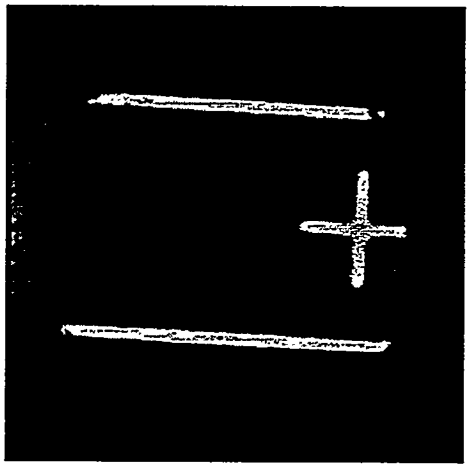
Figure 10

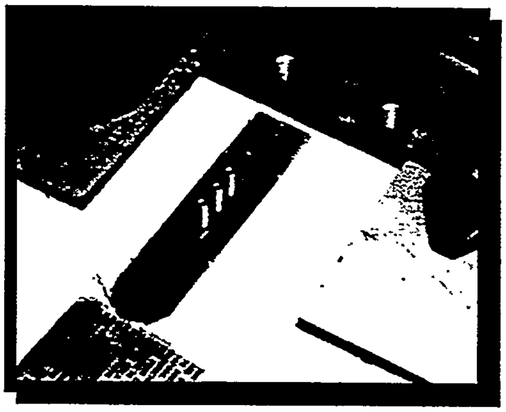
ADHESION STRENGTH TESTING



Results

- Repeatable process
- Failure force proportional to sample area
- ~900 lb/in^2 required for failure in new module
- Work in progress to relate failure stress to aging





Sandia
National
Laboratories

Analysis Techniques Used On Field Degraded Photovoltaic Modules

By

Thomas D. Hund and David L. King

Sandia National Laboratories
Albuquerque, NM

Sandia
National
Laboratories

This work is supported by the Photovoltaic Energy Technology Division,
US Department of Energy, contract DE-AC04-945AL85000.

Introduction

- **Sandia Maintains A Full Spectrum Of Analytical Techniques In Support Of Its Defense Projects**
- **The PV System Components Dept. Accesses These Resources**

Analysis Techniques

- Ultrasonic Inspection
- Microscopic Inspection (Metallurgical Cross Section And SEM)
- Infrared Inspection
- Adhesive Strength Of Module Encapsulant

Measured Effect

- Solder Fatigue
- Cell Damage Or Mismatch
- EVA To Cell Adhesion Strength

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Ultrasonic Inspection

• Transmission Method

- Measures Ultrasonic Energy Passing Through Sample
- Provides information On X-Y Location Of Defects
- Sample Thickness Limited by Ultrasound Attenuation
- No Minimum Thickness Limitations
- Much Less Complicated Than Pulse-Echo Method

• Pulse-Echo Method

- Measures Ultrasonic Energy Reflected Back From Defects In Sample
- Provides information On X-Y-Axis And Z-Axis Location Of Defects
- Sample Thickness Limited by Ultrasound Attenuation And Pulse Timing
- Minimum Thickness Is Limited By The Test Equipment's Ability To Measure Transit Time Of The Pulse-Echo

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Metallurgical Cross Section And Scanning Electron Microscopy

• Metallurgical Cross Section

- Measured Fatigue Crack Growth
- Provides Real Information On Field Cycle Life
- Sample Is Removed From Module And Cut In Half
- Requires Special Handling And Processing
- Destructive Test
- Costly

• Scanning Electron Microscopy

- Provides A High Magnification Detailed Picture Of Solder Microstructure For Failure Analysis
- Identified Solder Fatigue Microstructural Characteristics
- Requires Special Sample Handling And Processing In The Laboratory
- Costly

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Infrared Imaging

* Measured Hot Spots On Backside Of Module
* Identified Mismatched Cells, Cracked Cells, And High Resistance Solder Bonds
* Equipment Is Easy To Setup And Operate
* Has Good Temperature Sensitivity With Limited Spatial Resolution
* Non-Invasive Test
* Equipment Is Costly

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Laboratories

Summary

The Module Degradation Mechanisms That Have Been Identified Or Measured

- ⇒Solder Fatigue
- ⇒Cell Damage/Mismatch
- ⇒EVA To Cell Adhesive Strength

This Work Was Conducted In Support Of PV Module Manufacturers To Improve The Reliability Of Their Product

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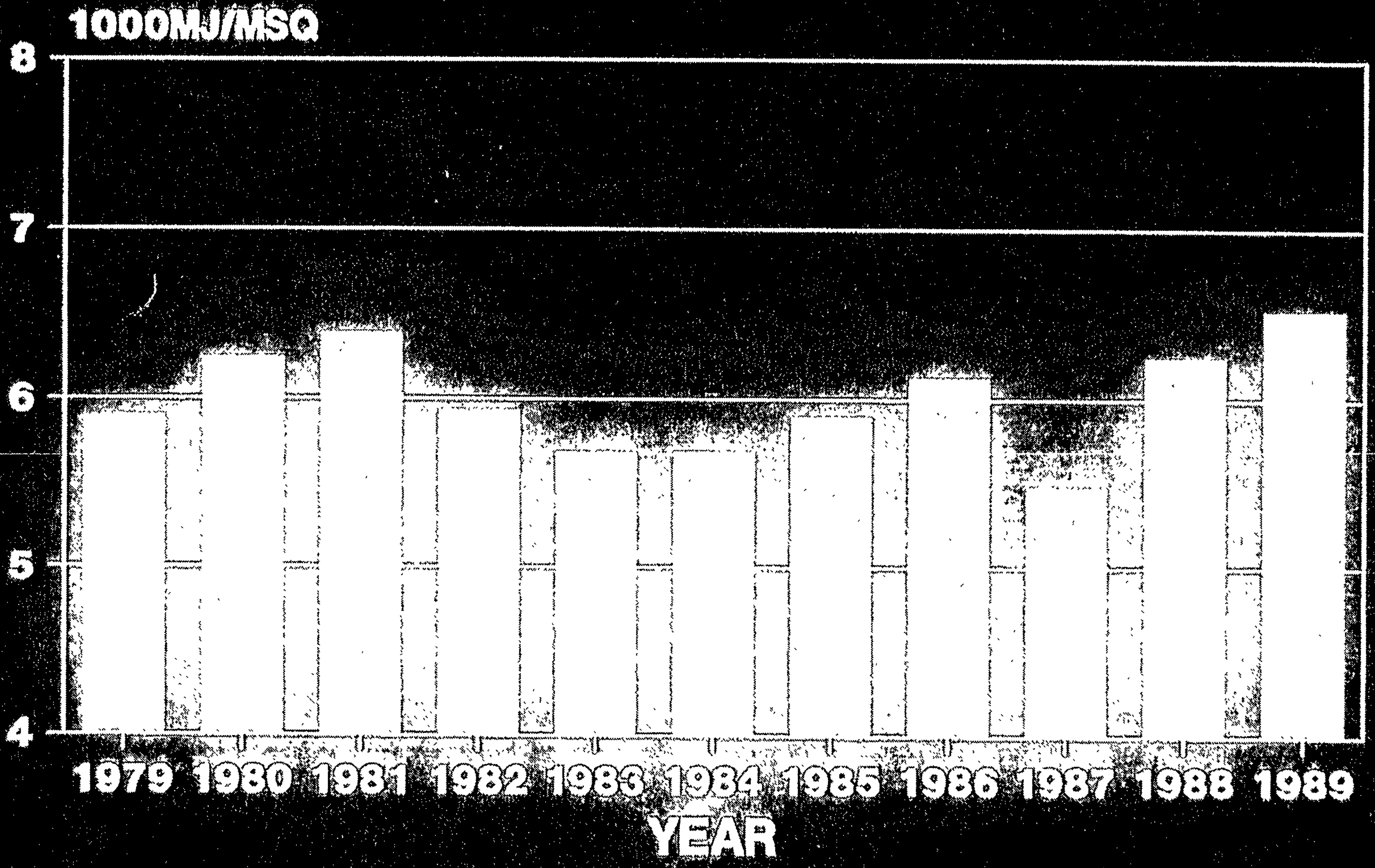
National
Laboratories

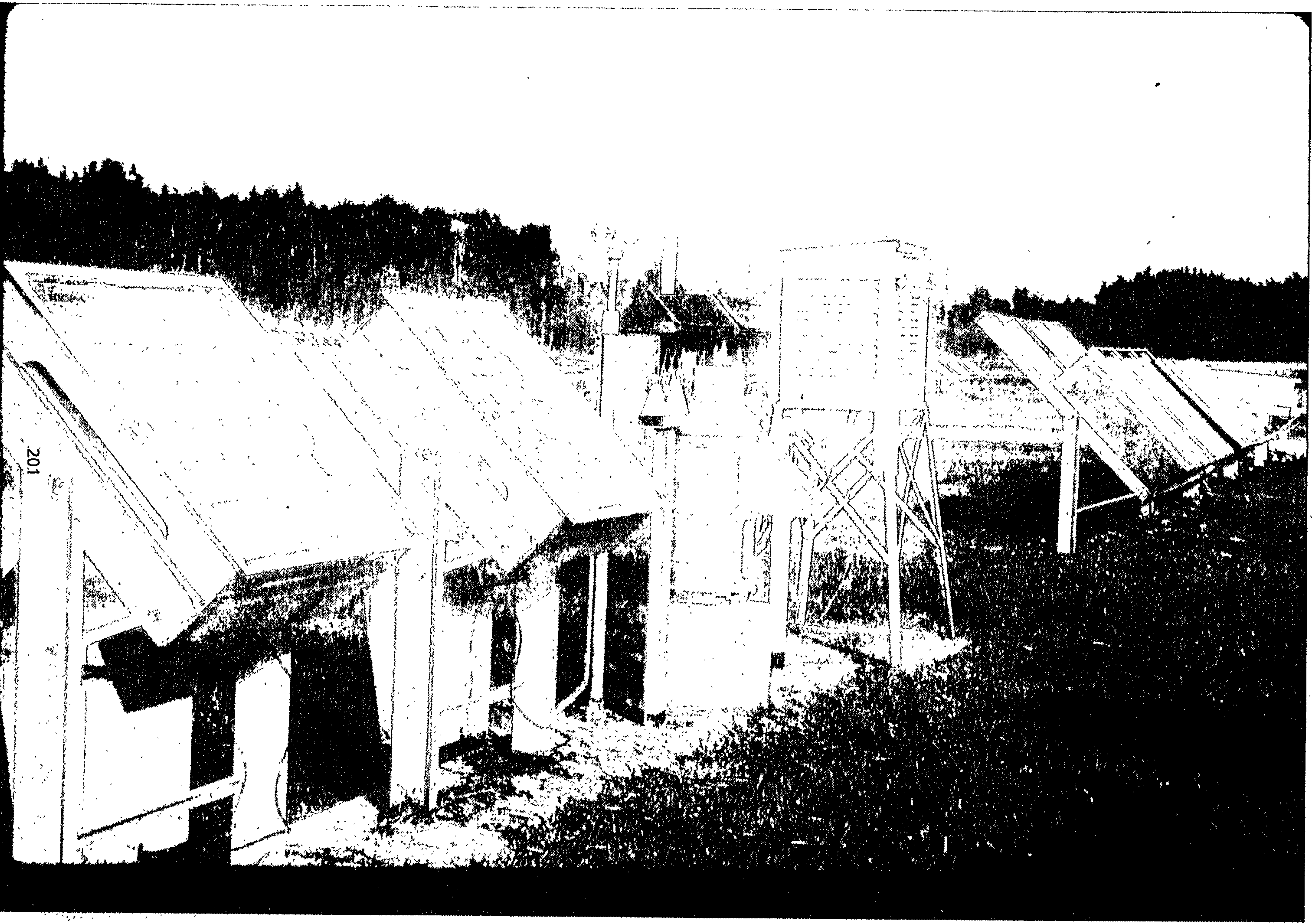
Correlation of Indoor Accelerated Testing with Outdoor Field Testing Related to Weathering of Materials

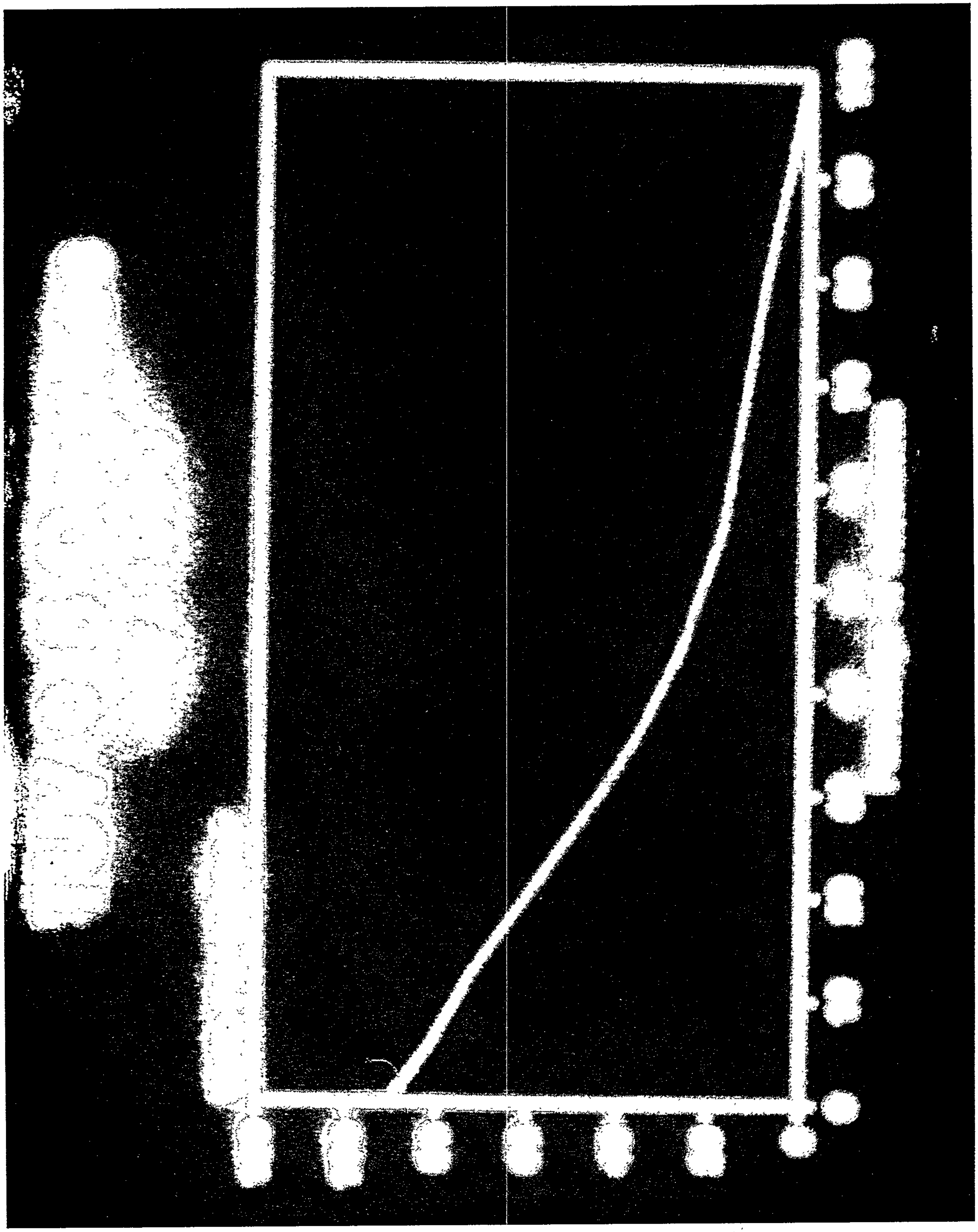
Leslie Jacques (Crewdson)
South Florida Test Service

TOTAL RADIATION FOR PAST 10 YEARS
DIRECT 45 DEGREES SOUTH

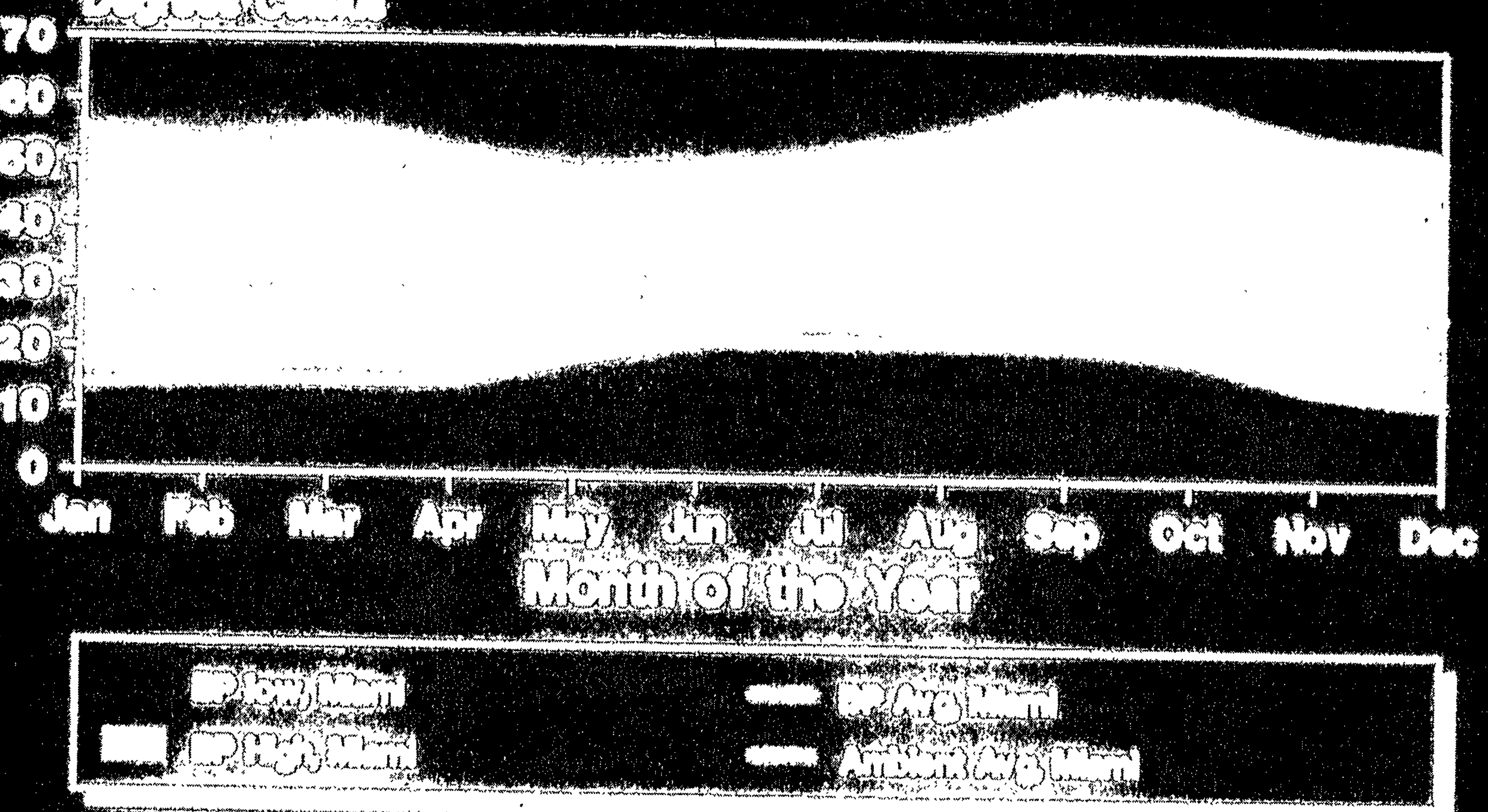


SOUTH FLORIDA TEST SERVICE

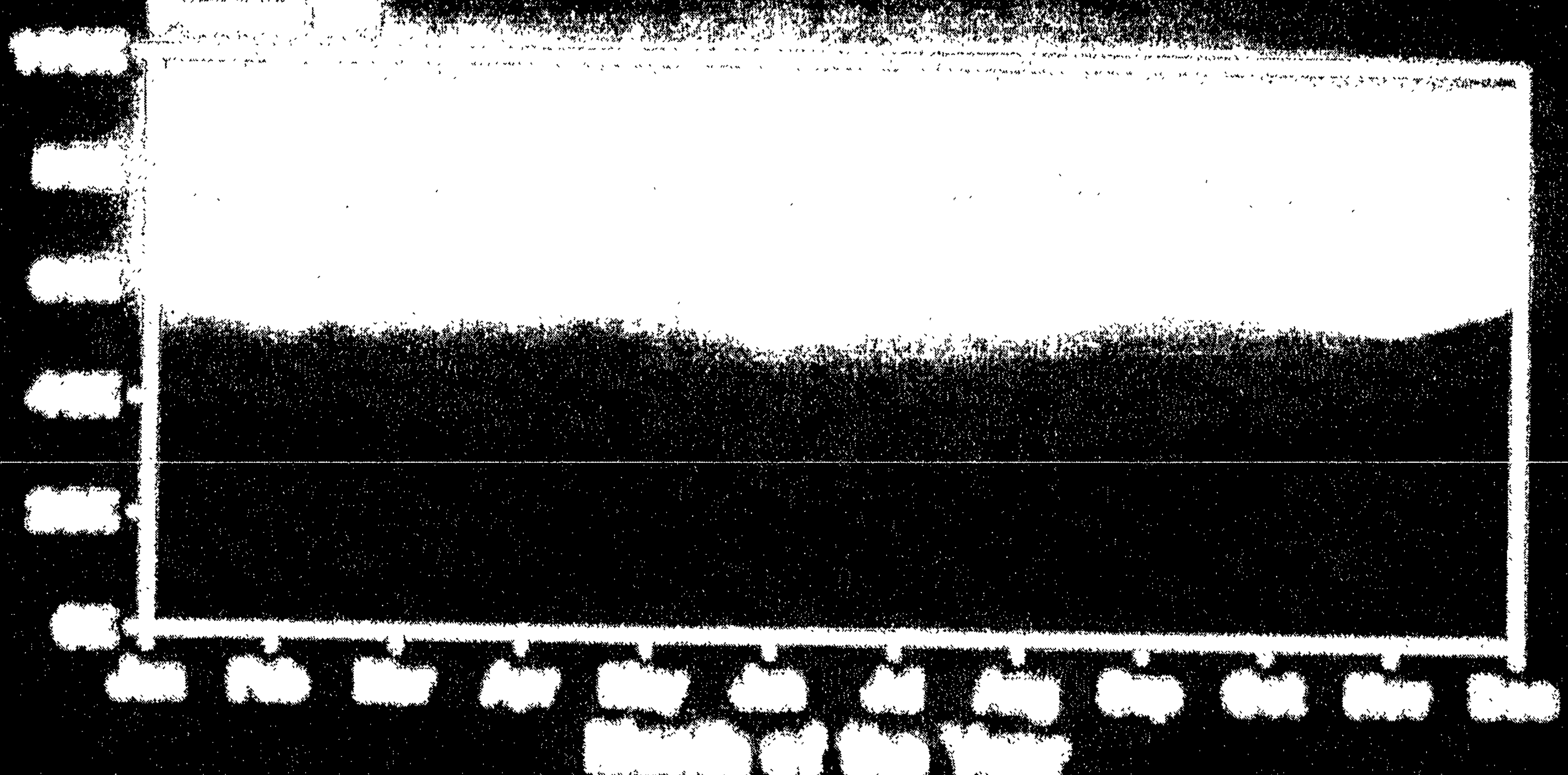




Black Panel vs Ambient Temperatures
Miami Florida 1990

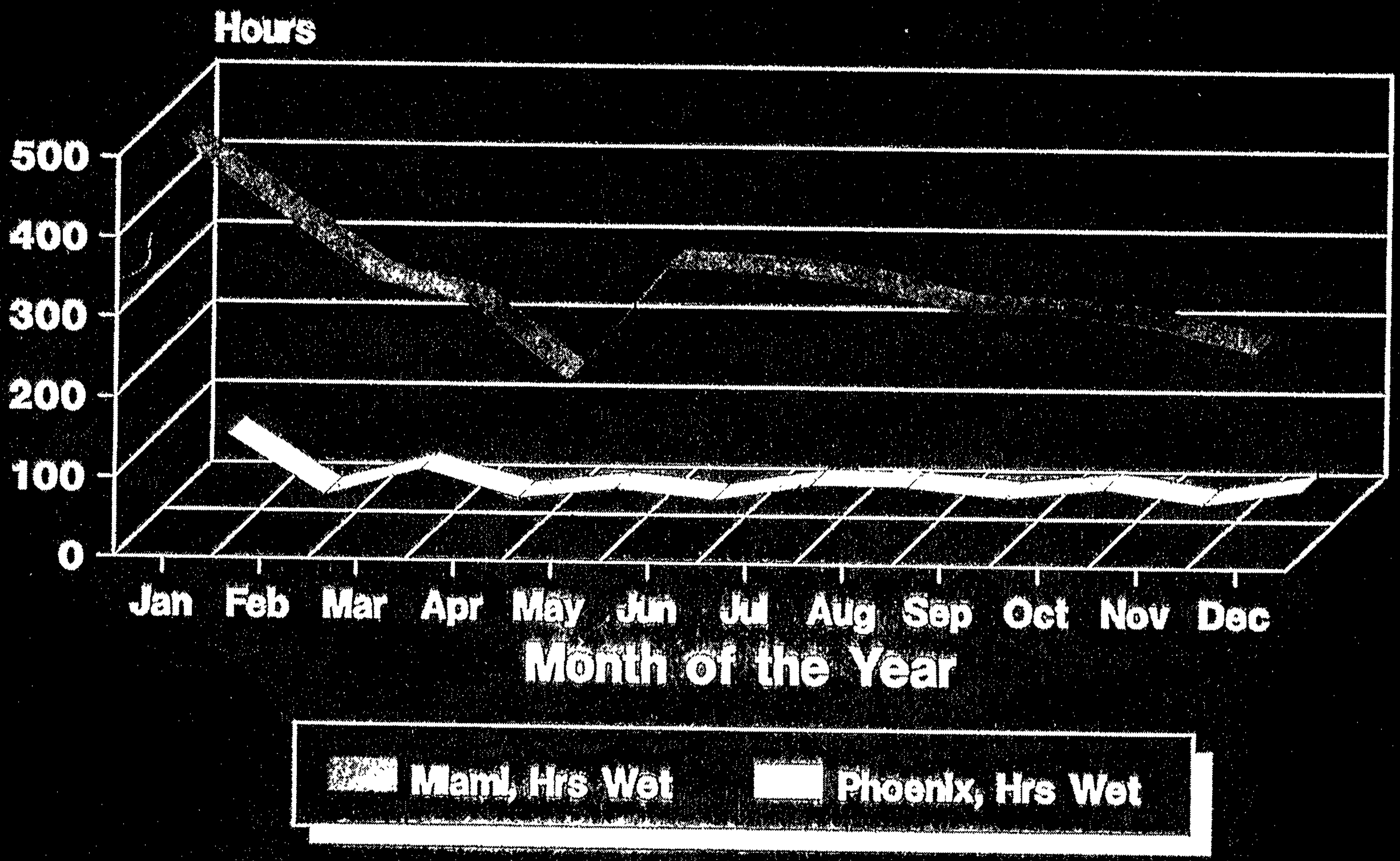


South Florida Test Service

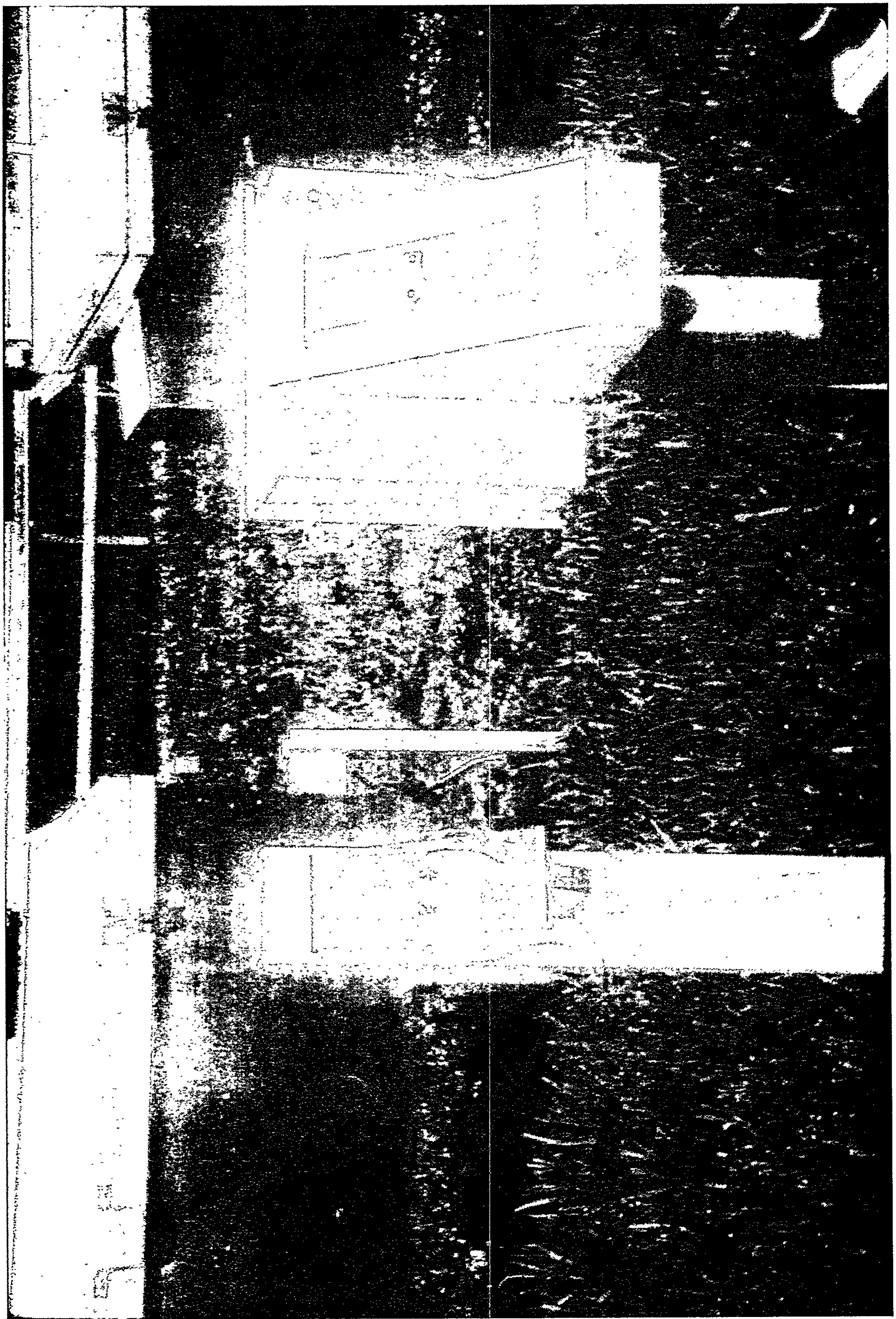


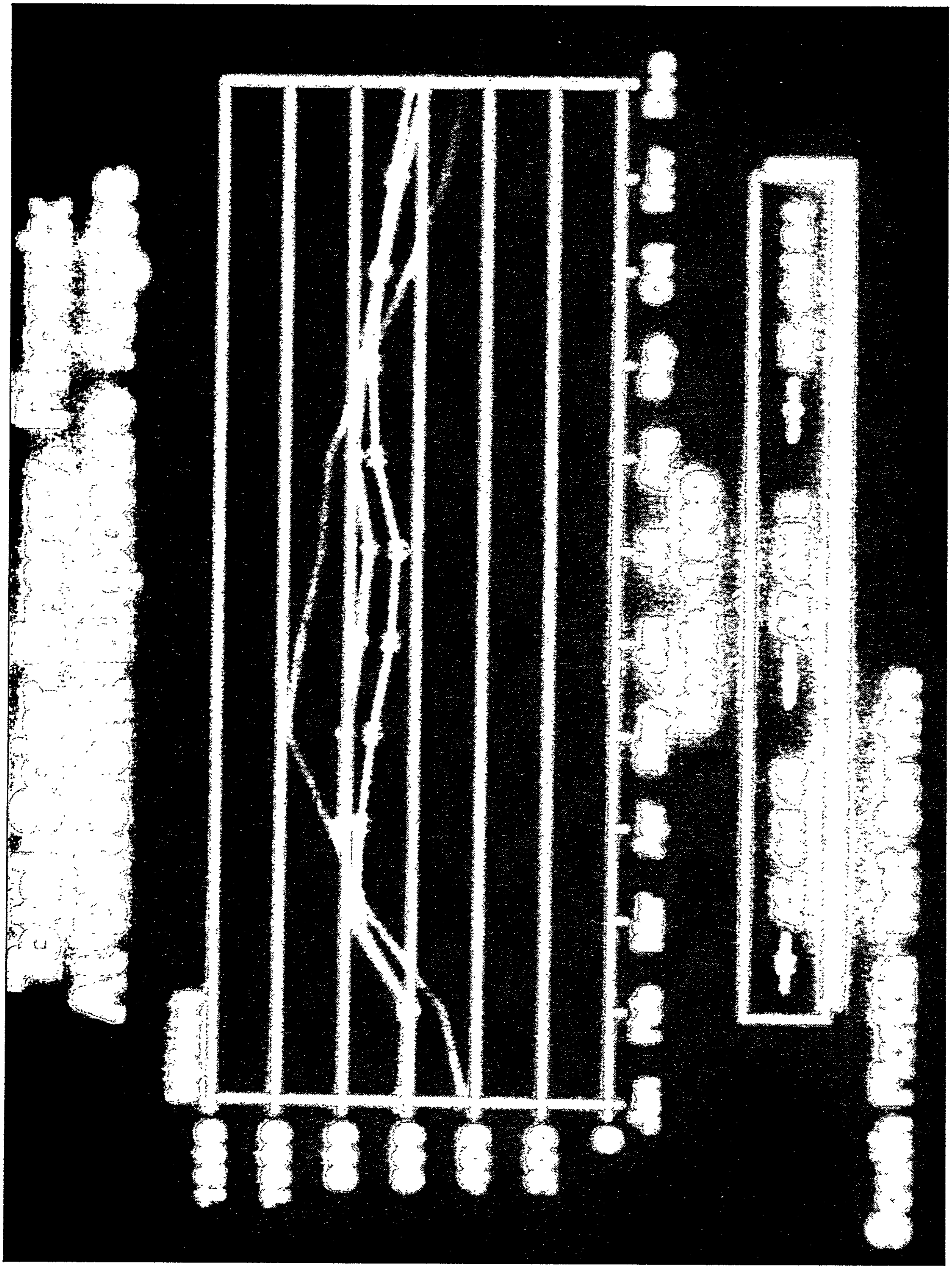
South Florida Test Service

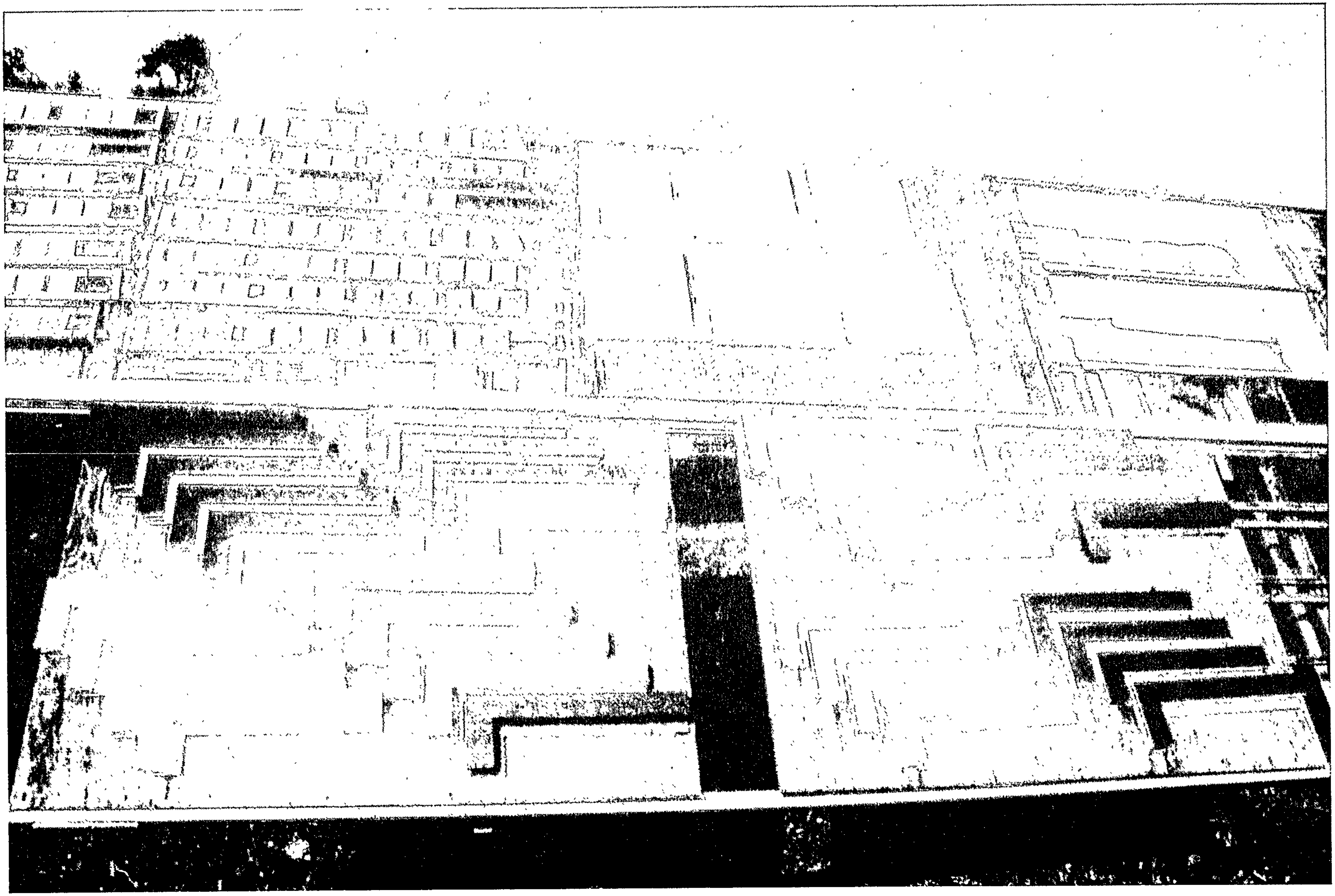
Monthly Total Hours Of Wetness
Miami and Phoenix 1989

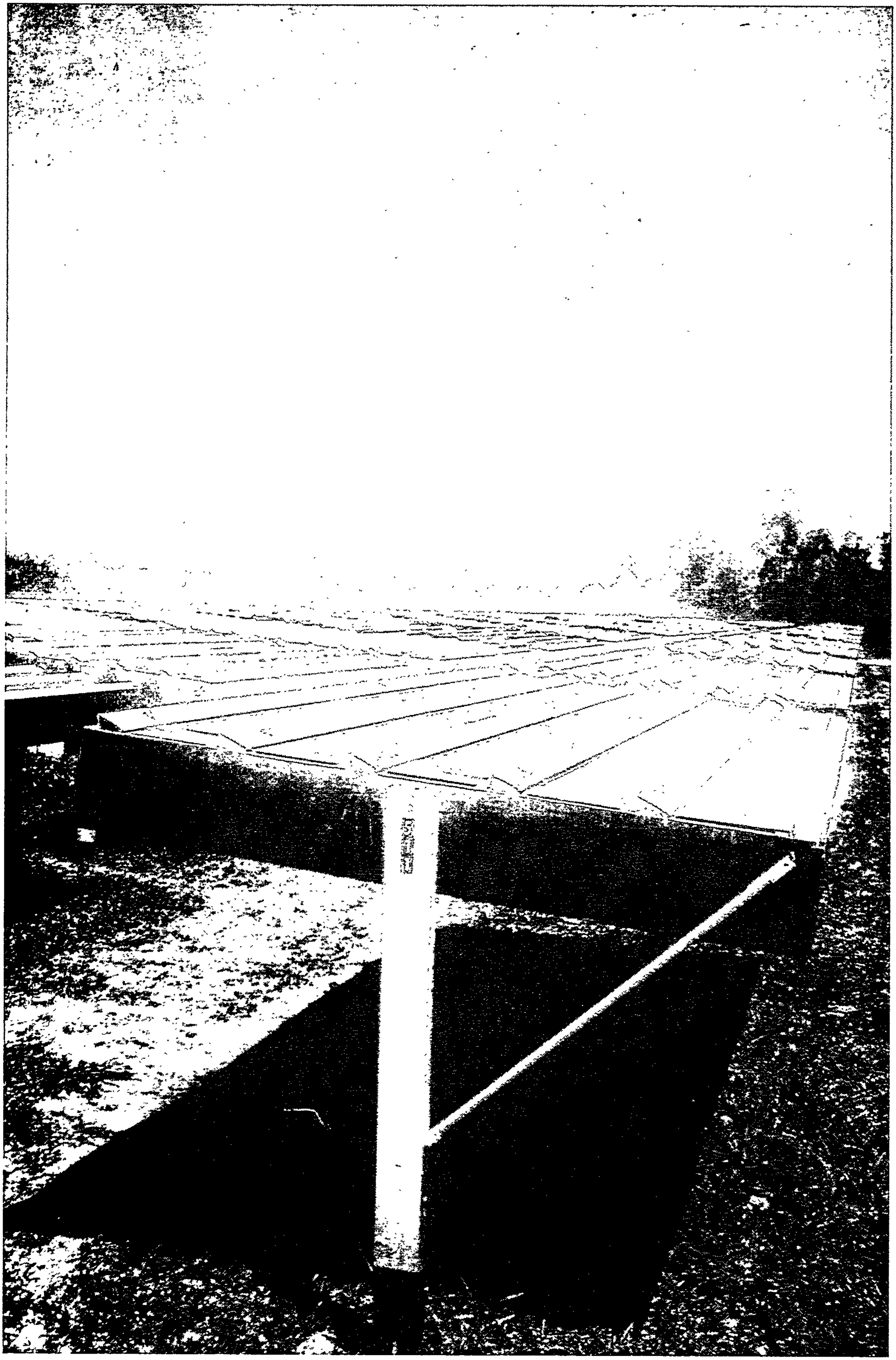


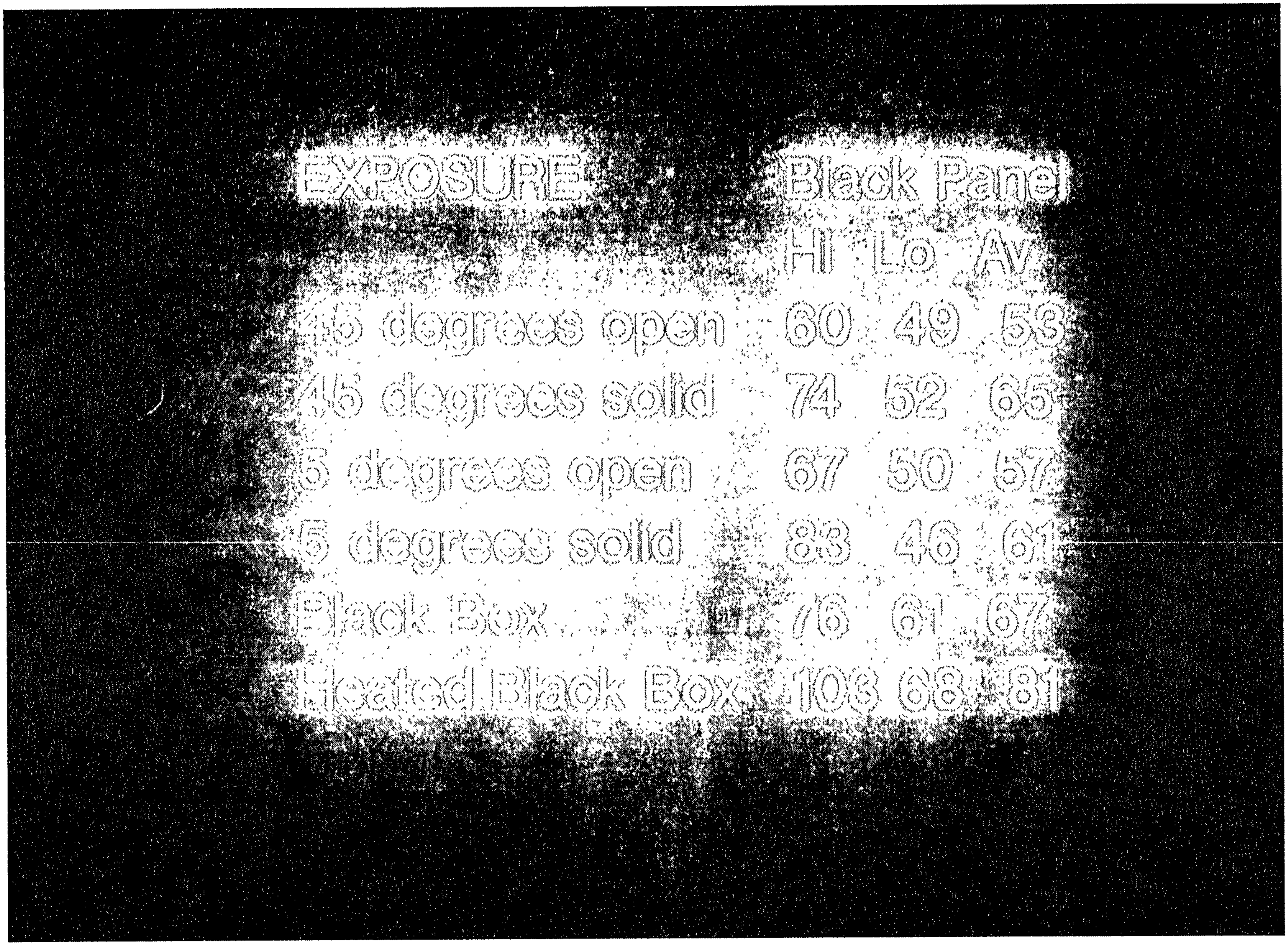
South Florida Test Service



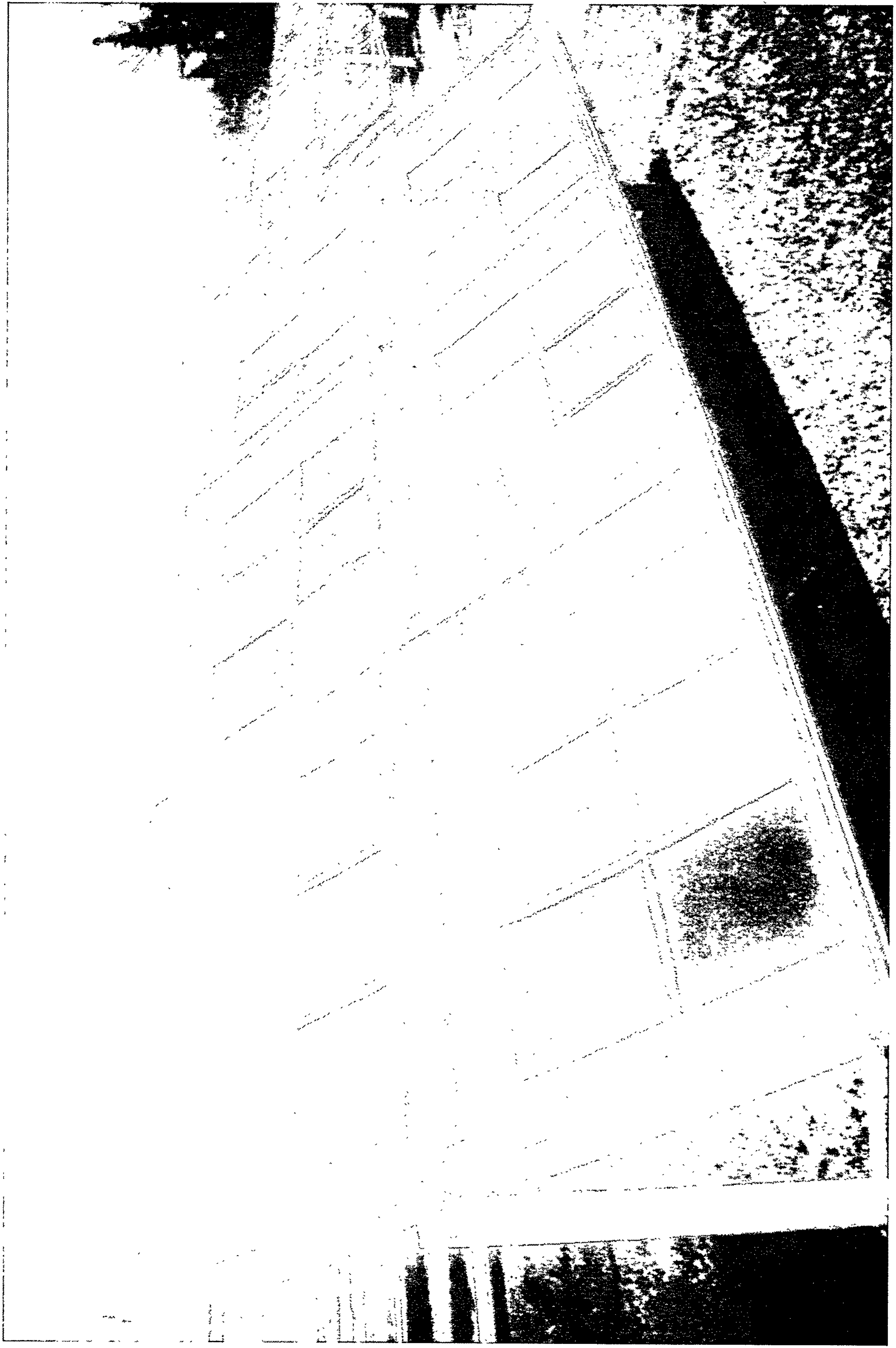


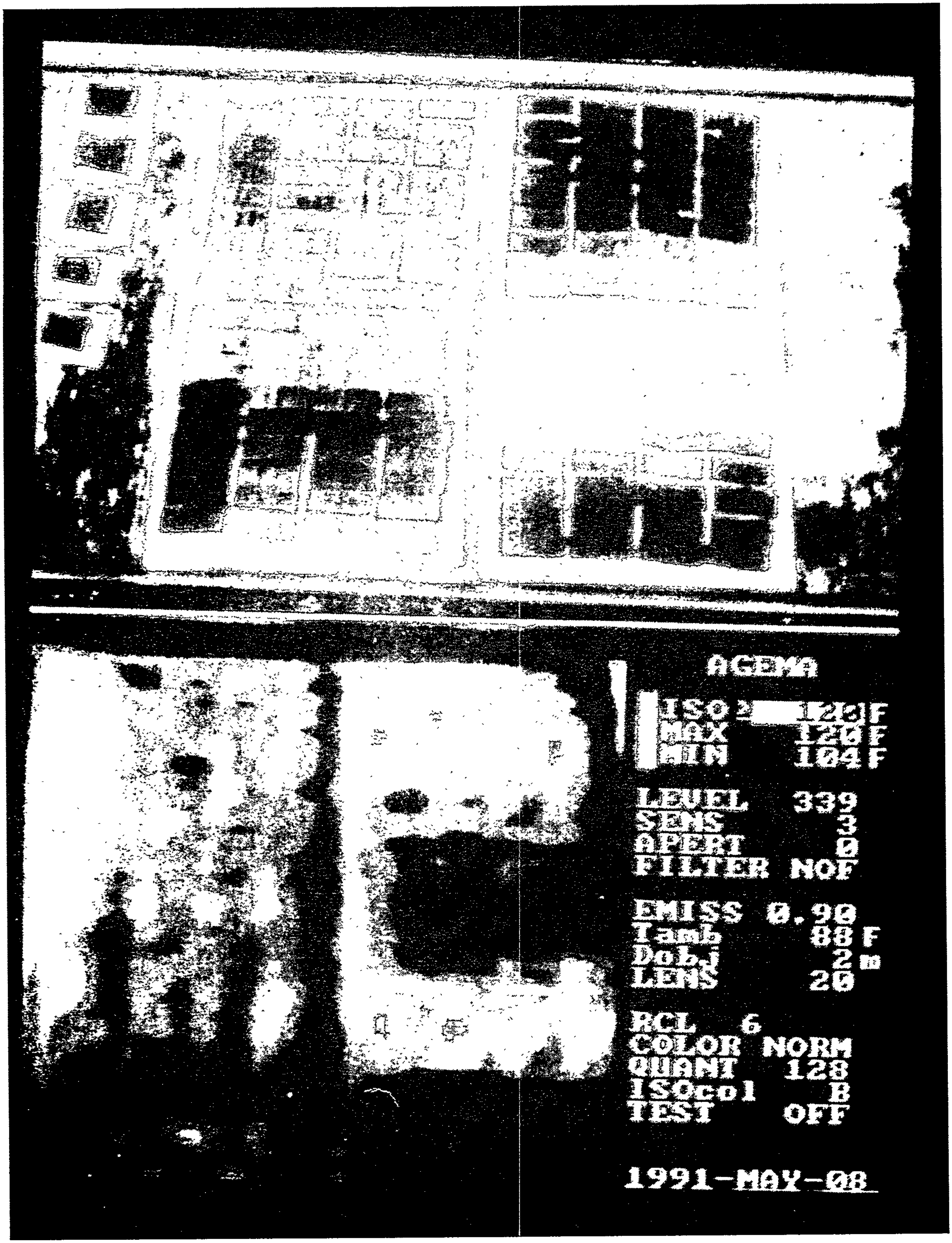






EXPOSURE	Black Panel Hi	Lo	Av
45 degrees open	60	49	53
45 degrees solid	74	52	65
5 degrees open	67	50	57
5 degrees solid	83	46	61
Black Box	76	61	67
Heated Black Box	103	68	81





AGEMA

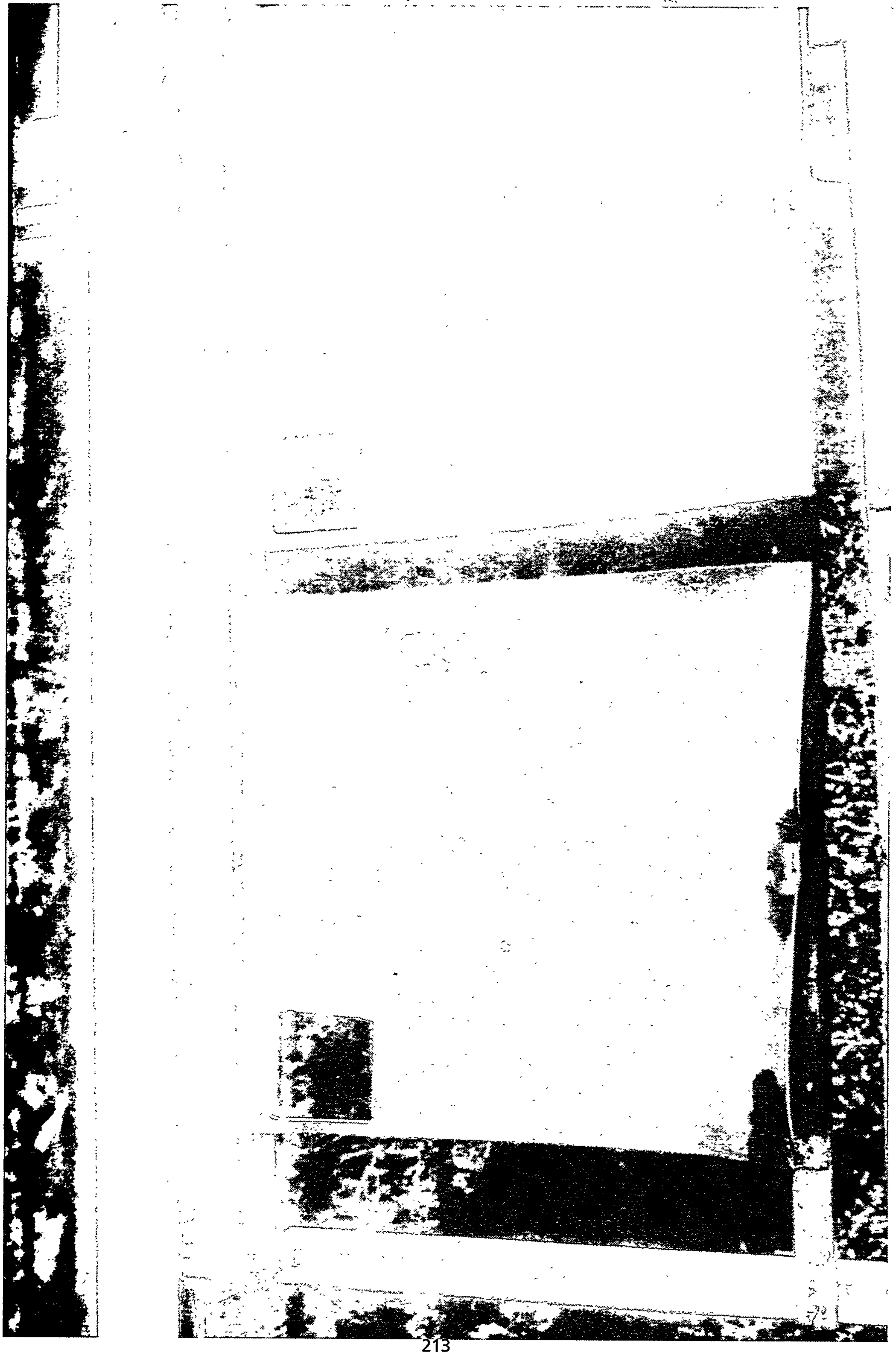
ISO² 120F
MAX 120F
MIN 104F

LEVEL 339
SENS 3
APERT 0
FILTER NOF

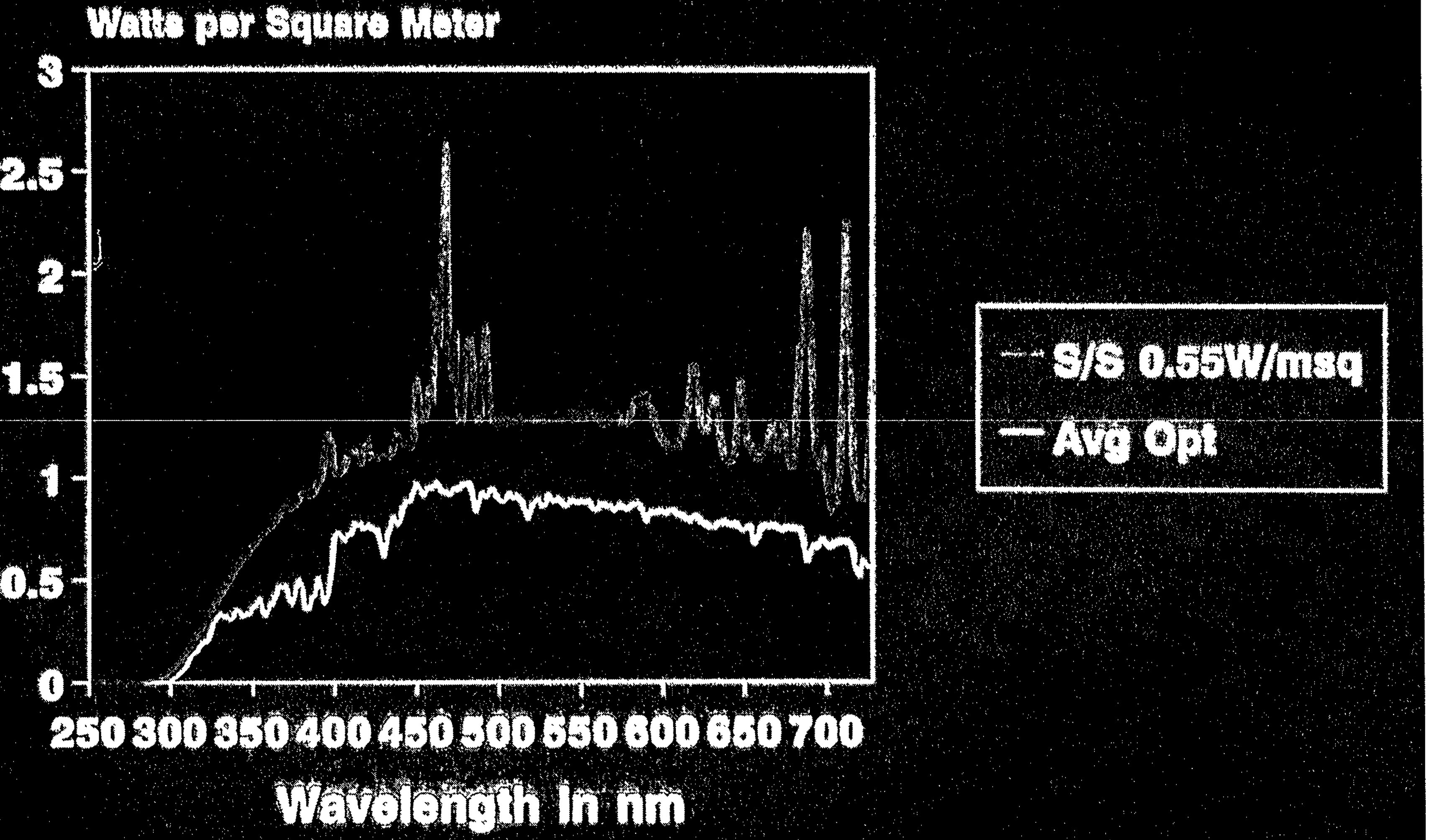
EMISS 0.90
Tamb 88 F
Dobj 2 m
LENS 20

RCL 6
COLOR NORM
QUANT 128
ISOcol B
TEST OFF

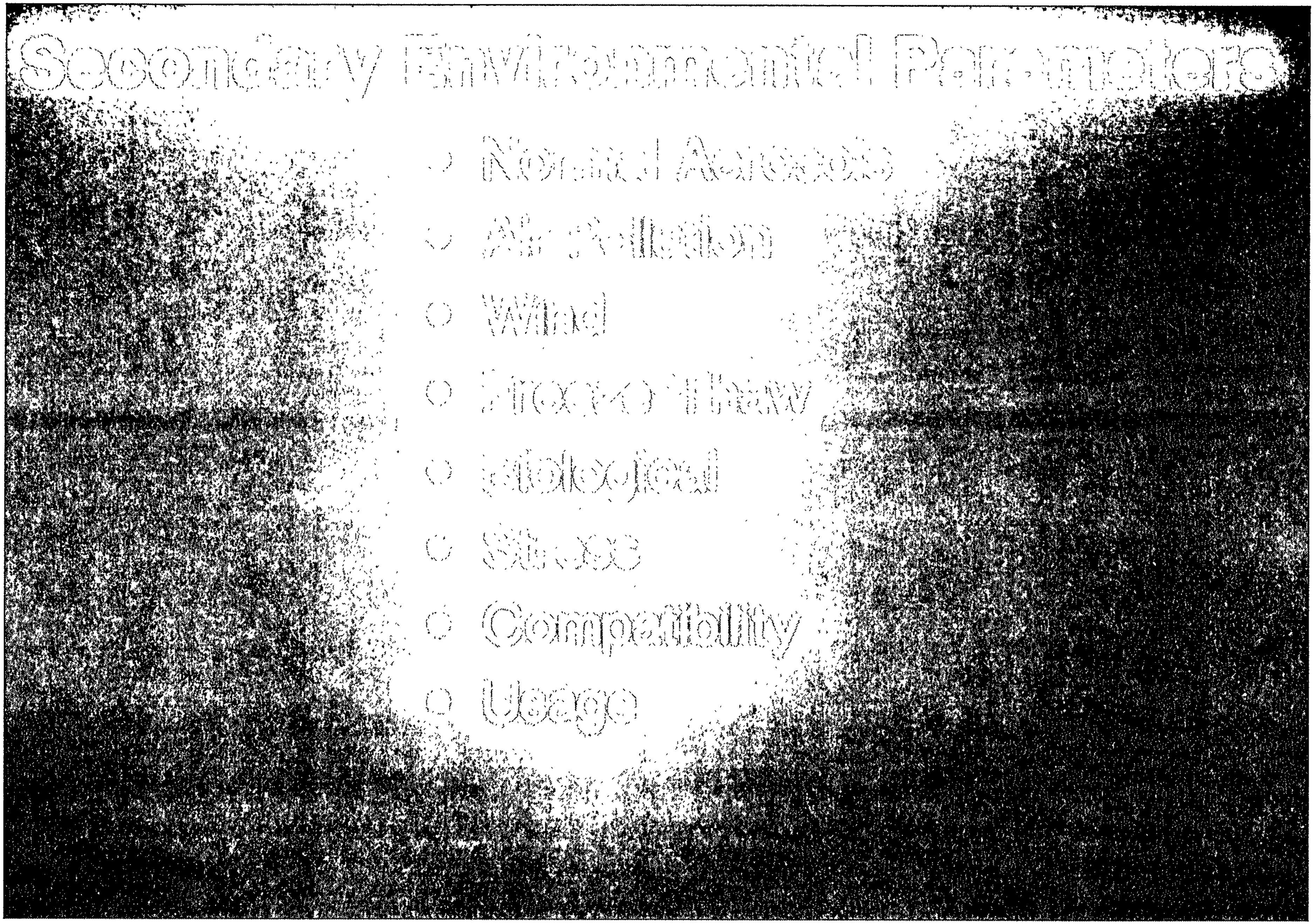
1991-MAY-08



Comparison of Experimental Test XSS and Miami Average Optimum Daylight



Type 'S' inner and type 'S' outer filters



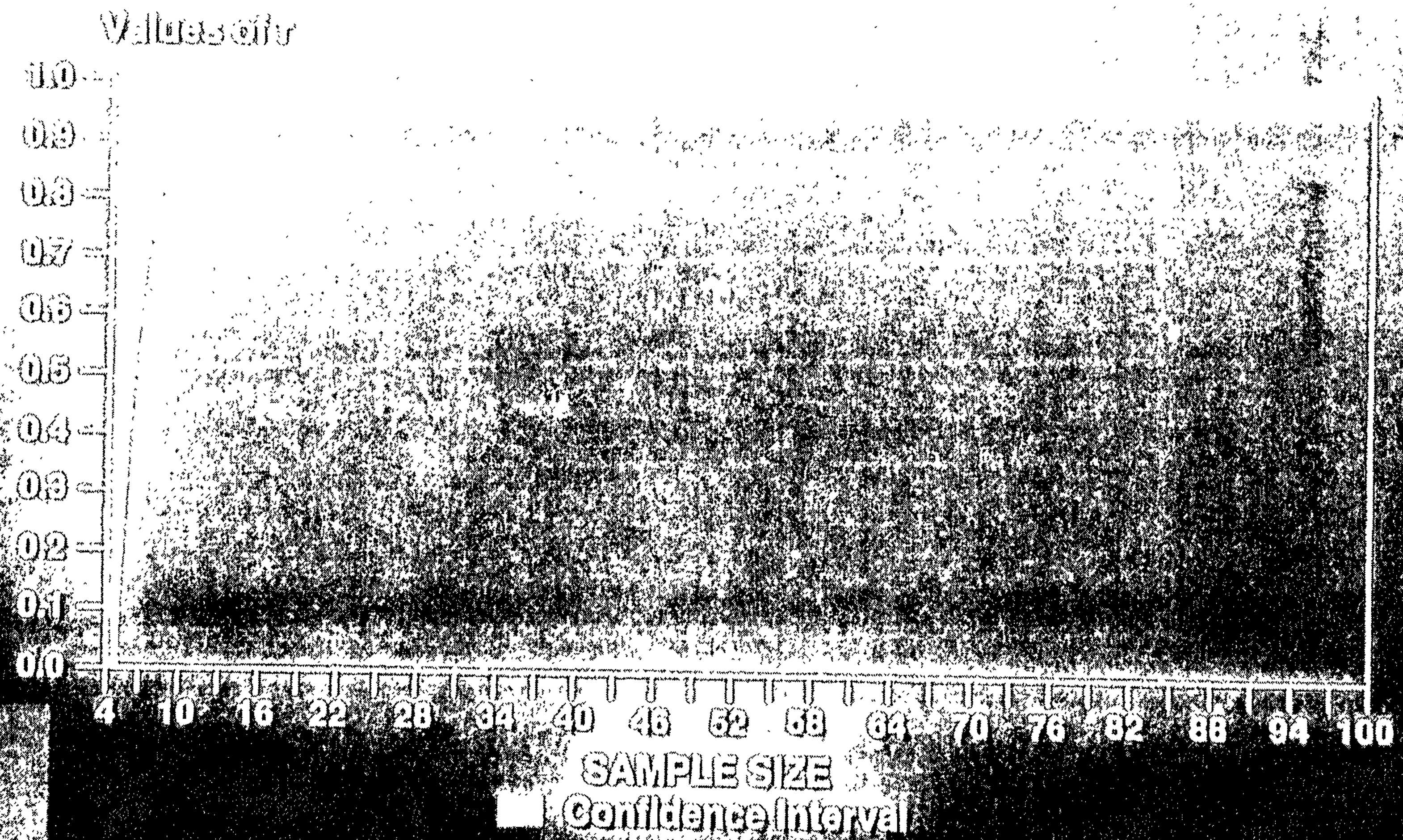
Secondary Environmental Parameters

- ○ Normal Aerosols
- ○ Air Pollution
- ○ Wind
- ○ Freeze / Thaw
- ○ Biological
- ○ Stress
- ○ Compatibility
- ○ Usage

Primary Environmental Parameters

- ○ Radiant Energy
  - Quality
  - Quantity
- ○ Temperature
  - Ambient
  - Black Panel
- ○ Humidity
- ○ Moisture
  - Rainfall
  - Condensation

RELATIONSHIP BETWEEN THE SAMPLE SIZE AND CONFIDENCE INTERVAL OF A CORRELATION COEFFICIENT OF 0.97



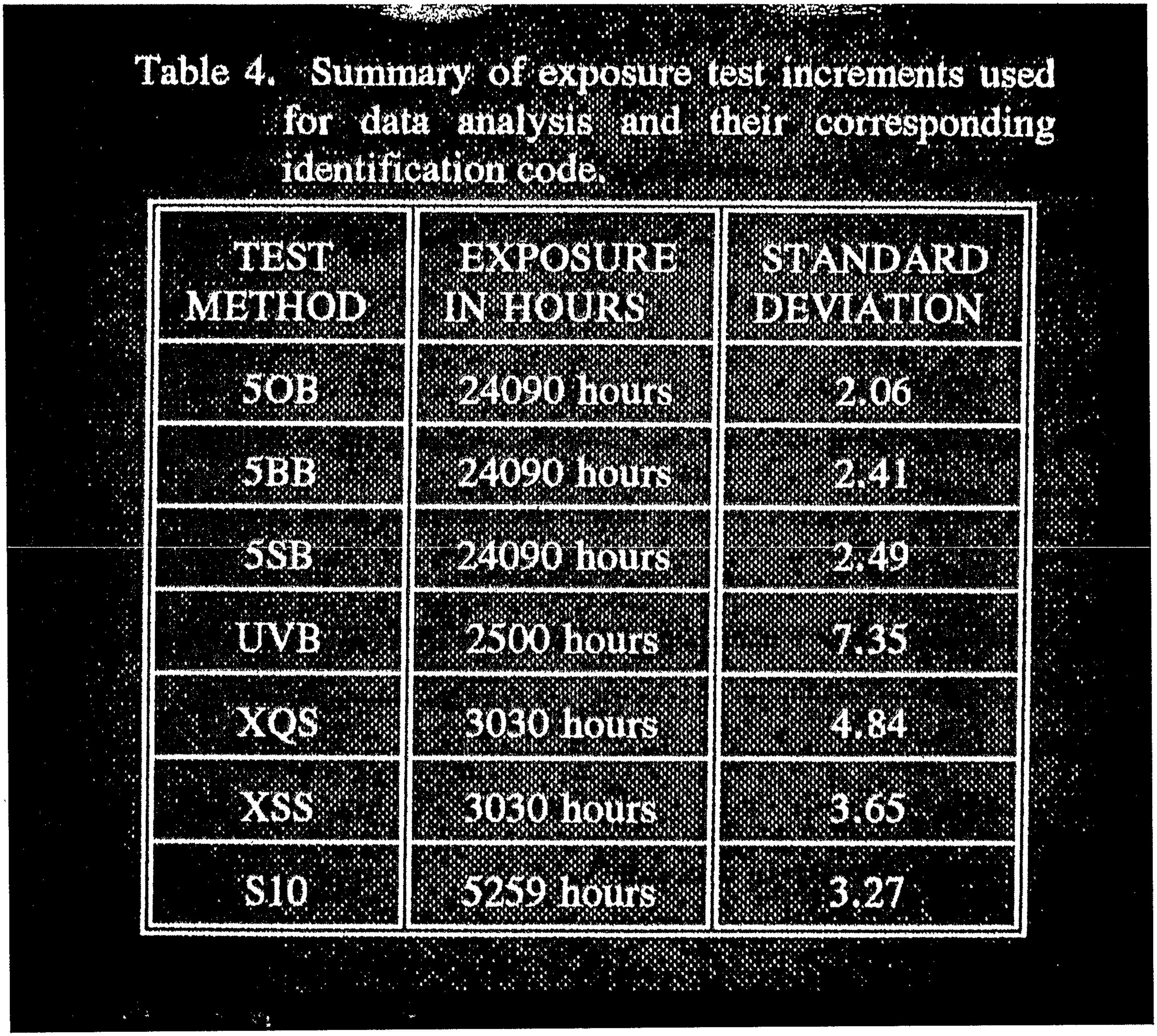
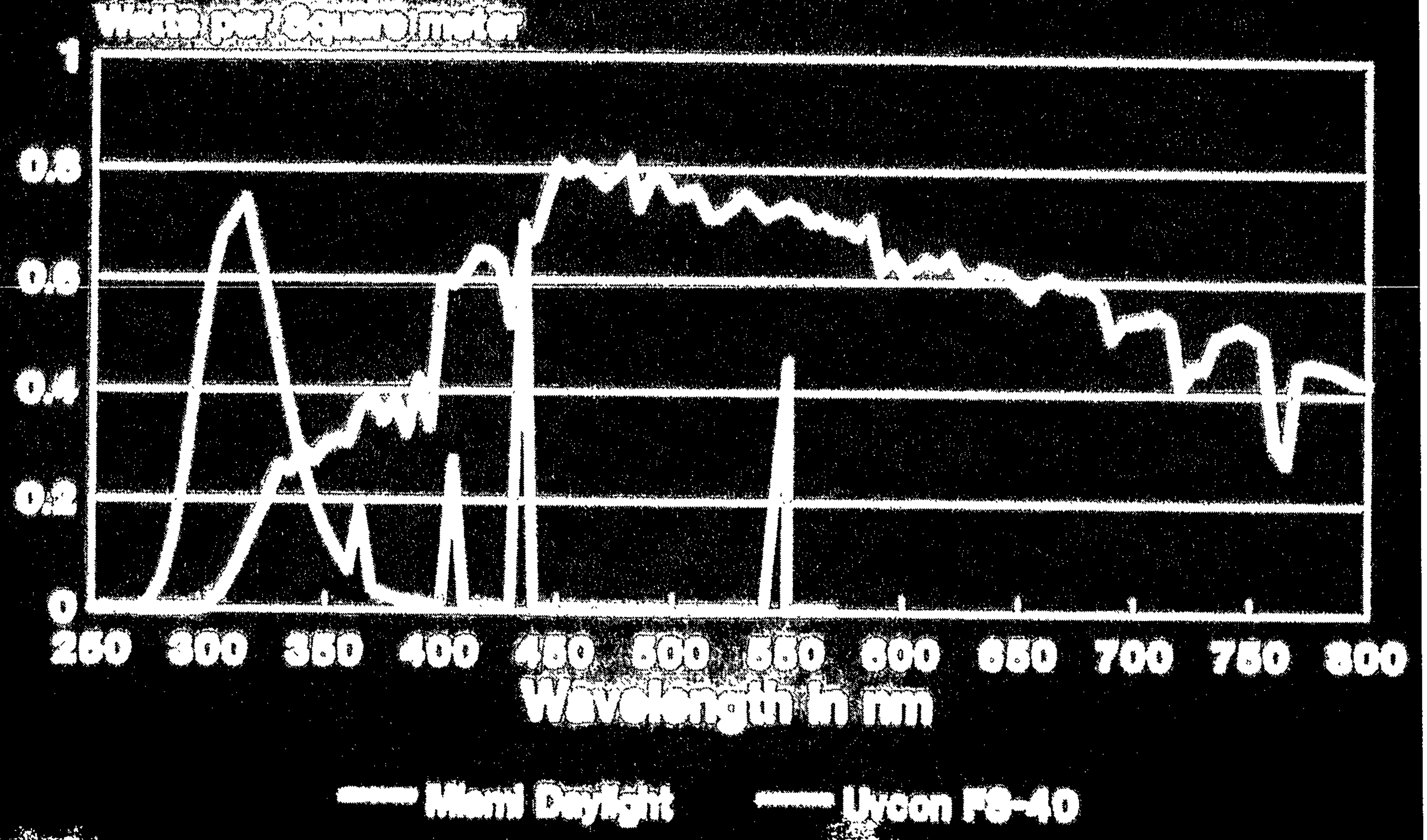


Table 4. Summary of exposure test increments used for data analysis and their corresponding identification code.

TEST METHOD	EXPOSURE IN HOURS	STANDARD DEVIATION
5OB	24090 hours	2.06
5BB	24090 hours	2.41
5SB	24090 hours	2.49
UVB	2500 hours	7.35
XQS	3030 hours	4.84
XSS	3030 hours	3.65
S10	5259 hours	3.27

'Average Optimum Miami Daylight' Vs Uvcon With FS-40 Lamps



SAE J1960 TEST CONDITIONS

Black Panel Temperature
Light cycle 70°C±2°, Dark Cycle 38°C±2°C

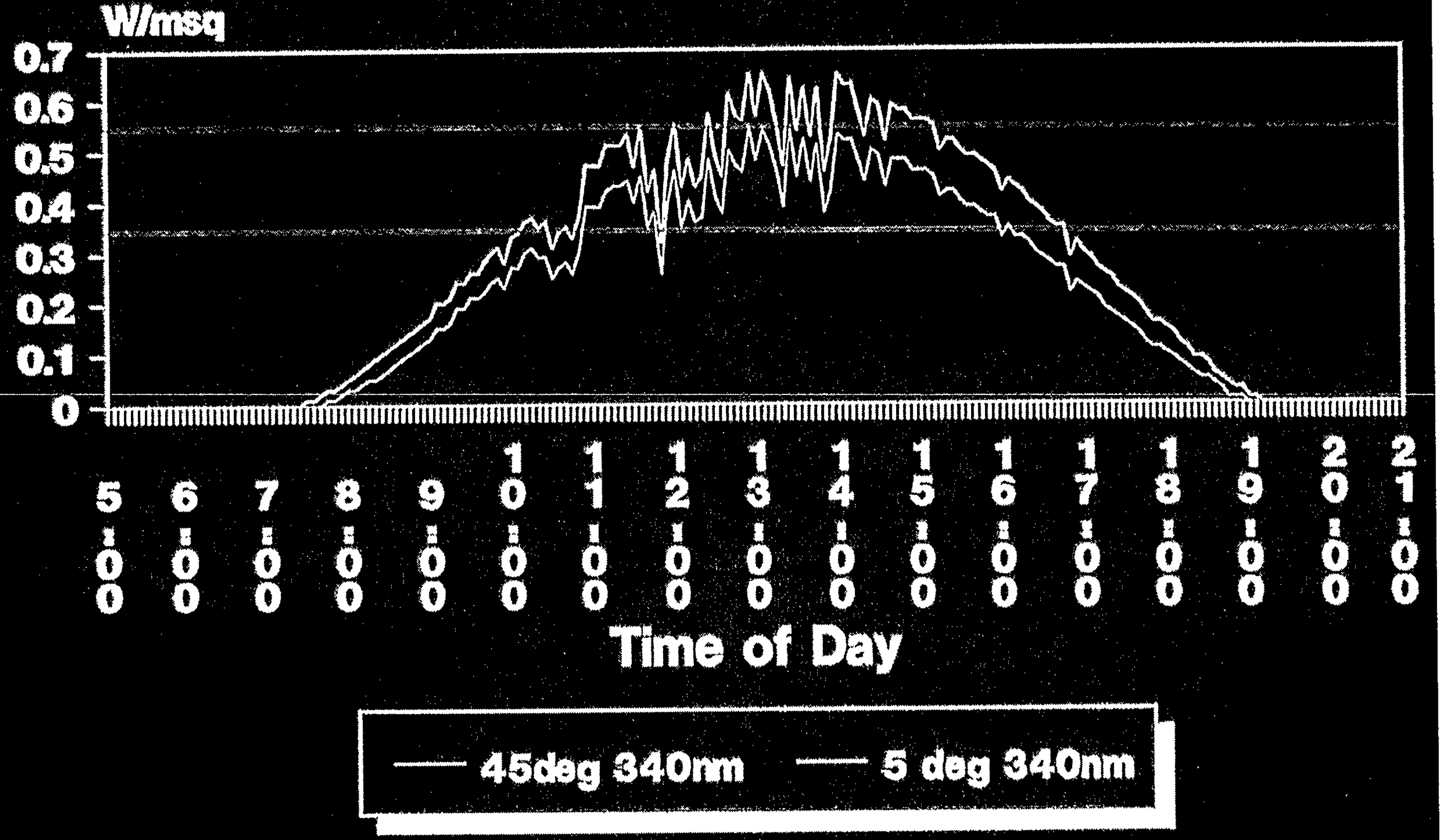
Ambient Temperature
Light Cycle 47°C±2°C, Dark Cycle 38°C±2°C

Relative Humidity
Light Cycle 50%±5%, Dark Cycle 95%±5%

Light Source
Xenon Lamp, 0.55w/msq @340nm, Quartz inner Type 'S' Outer Filters

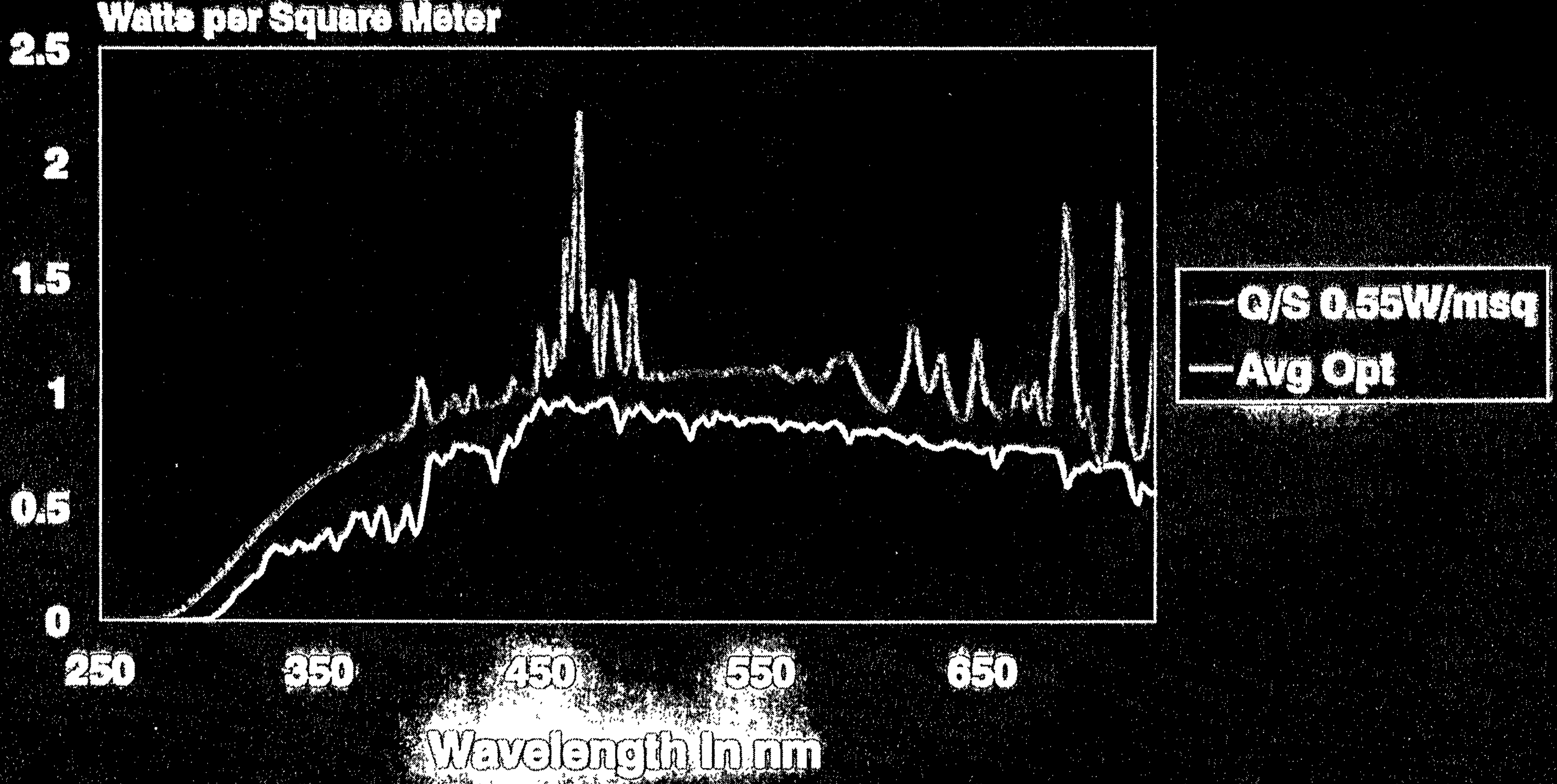
Cycle
40 Minutes light followed by
20 minutes light with front spray followed by
60 mintes light followed by
60 minutes dark with back rack spray

Solar Radiation ¢ 340nm
April 19th 1990



South Florida Test Service

Comparison of SAE J1960 (XQS) and Miami Average Optimum Daylight



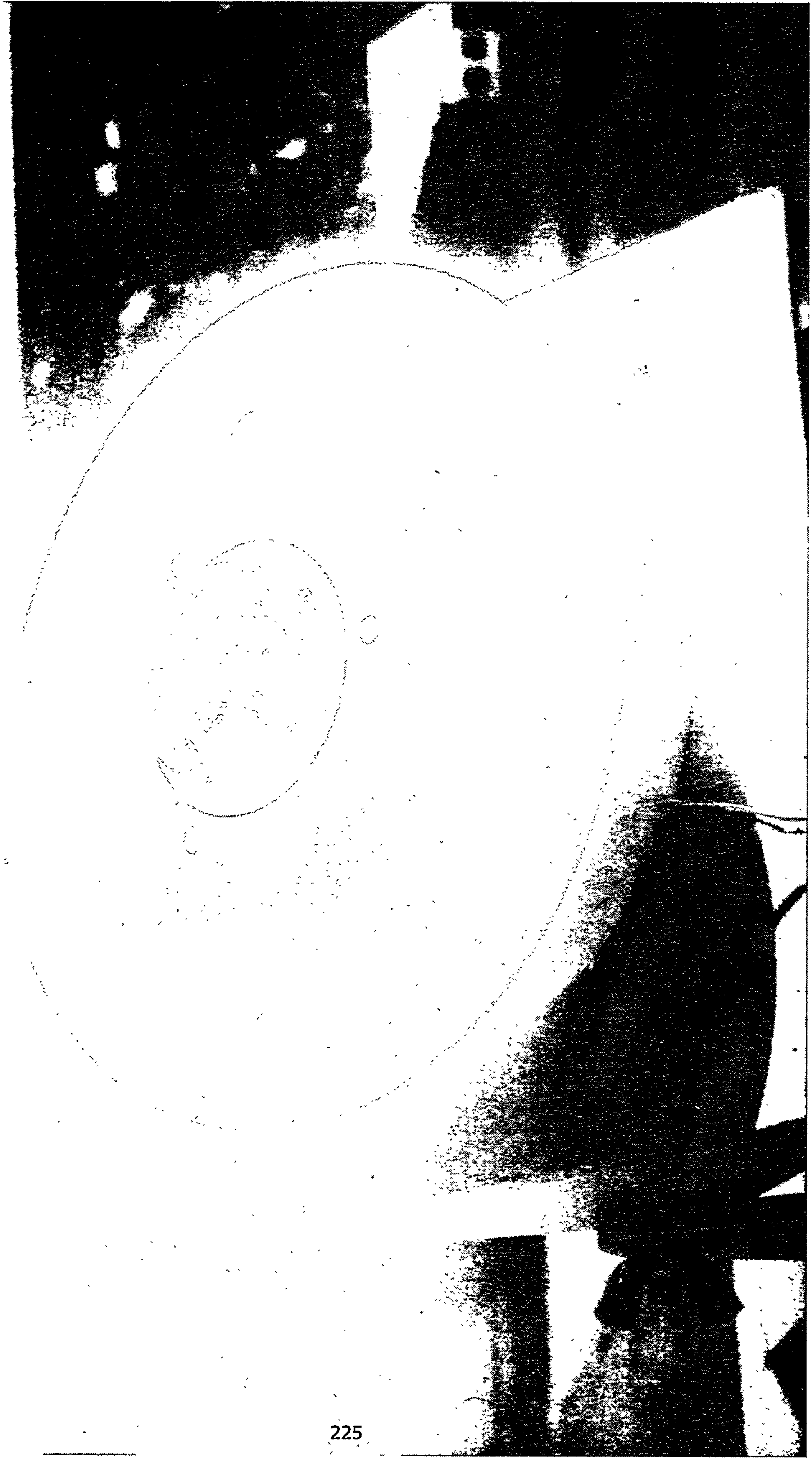
Quartz inner and type 'S' outer filters

Comparison of accelerated exposure with Florida Black Box Exposures Pearsons Correlation Coefficients

Scale	Fresnel Reflector SAE J1961	Fluorescent SAE J2020	Xenon Q/S SAE J1960	Xenon S/S Experimental
L*	0.81	0.25	0.49	0.92
a*	0.90	0.81	0.87	0.97
b*	0.91	0.87	0.85	0.97

Coated Panels, Sample Size (N) = 70

Verma M. and Crewdson L.F.E., SAE Congress Feb 1994



SIEMENS SOLAR INDUSTRIES

Don Aldrich

September 7, 1995

"Encapsulation and Service Lifetime: Designing Success or Failures?"

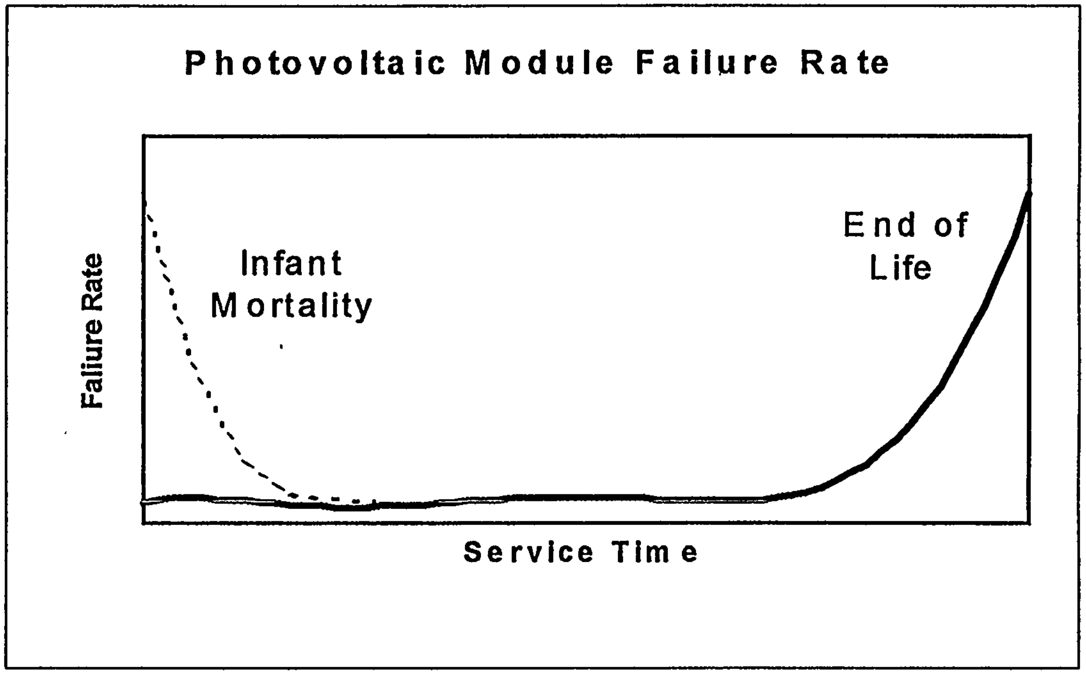
Some Thoughts

REVIEW OF MODULE RELIABILITY

THE GOOD

- Existing qualification tests have been successful in eliminating problems of infant mortality in photovoltaic modules.

- The Industry has yet to enter the end of life phase for our photovoltaic modules.



THE BAD

- The Industry has yet to identify the degradation mechanisms that lead to catastrophic failure of a photovoltaic module.

THE UGLY

- The Industry does not presently know when module end of life will occur.

THE CHALLENGE TO THE PHOTOVOLTAIC COMMUNITY

MANUFACTURERS
- Work on manufacturing quality systems with a goal of consistently producing the highest quality modules.

SUPPLIERS
- Work on developing the next generation of materials that will help manufacturers produce modules with a longer service life.

CUSTOMERS
- Identify module performance requirements that industry will need to meet in order for you to buy our systems.

NATIONAL LABORATORIES
- Work on developing the accelerated life tests and the reliability science that the rest of us can use to do our jobs.

EVA-Based Encapsulant Evolution

1st. Generation - "Standard-Cure" Technology

- Focus of All Concerns - 16 Year Old Technology
- Based on Lupersol 101 Crosslinking Agent
- Prone to discoloration (Browning), i.e. Carrisa Plains, Sede Boqer, SWRES, etc.
  - Solar Insolation/Temperature Induced
- Balance of Encapsulant's Functions Remain Viable
  - Elasticity, Adhesion, Electrical Isolation, Mechanical Integrity

Springborn Laboratories

EVA-Based Encapsulant Evolution Con't.

2nd. Generation - "Fast-Cure" Technology

- 10 Year Old Technology
- Rapid Processing Time
- Recently Proven More Photo/Thermally Stable Than "Standard-Cure" Technology
- Still Limited in Use, <50% of all Modules Produced Annually Worldwide
- Several MW In Service for Up To 9 Years, No Failures Noted to Date

Springborn

EVA-Based Encapsulant Evolution Con't.

Superstrate Glass Reformulation

- Early 1990's Incorporation of UV Screening Agent, AFG & PPG
  - Now Blocks Harmful Short Wavelength UV Light.
- Dramatically Reduces Rate of Discoloration
  - "Standard-Cure" & "Fast Cure" Encapsulants

Springborn Laboratories

EVA-Based Encapsulant Evolution Con't.

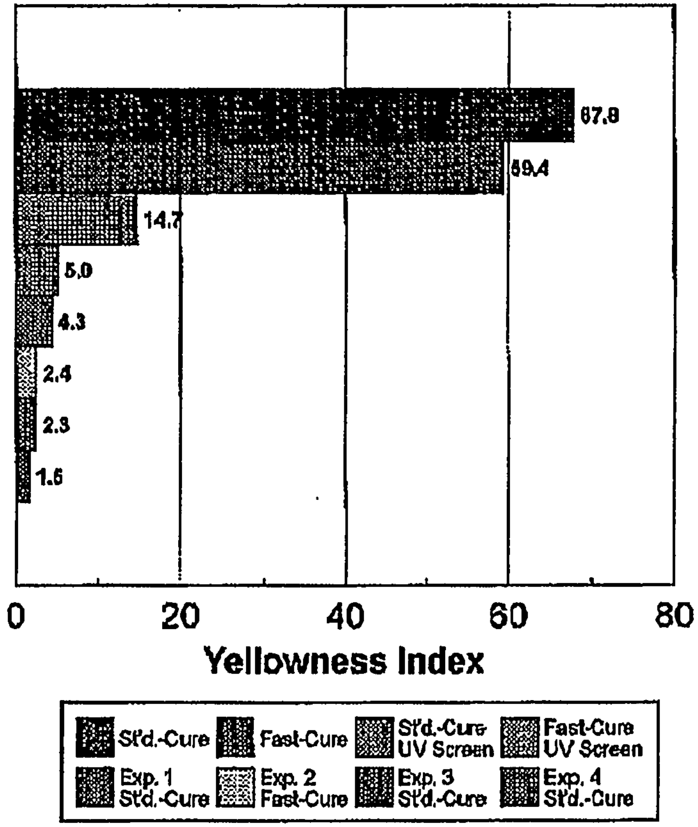
3rd. Generation - Enhanced Photo/Thermal Stabilization Technologies

- Advanced Cure & Stabilization Strategies
  - Does not require Low Wavelength UV Screening Superstrate Protection
- Presently Undergoing Qualification/Reliability Testing
  - Springborn Labs., DSET Labs., Arizona State University
- Planned Commercial Introduction in Early 1996
- "Standard-Cure" and "Fast-Cure" Processing Parameters
- Based on Same EVA Resin
- Comparable in Cost to Current Technologies

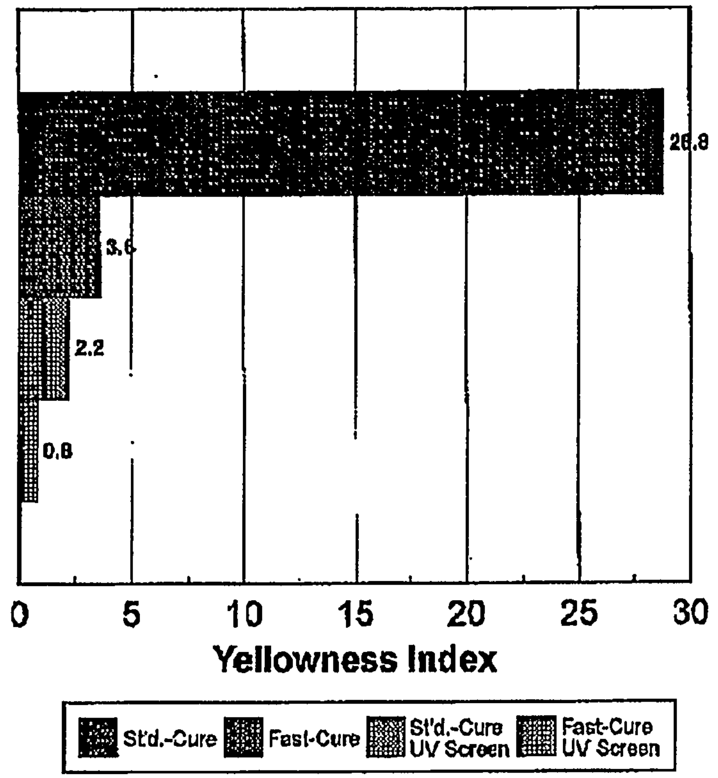
Springborn

Relative Encapsulant Discoloration on Accelerated Aging

28 Weeks Exposure Xenon-Arc Exposure



44 Weeks EMMA Exposure (DSET)



Visible Discoloration at Y.I. Value of 10

Springborn

What Needs to Be Done?

Insure the PV Module's Package Integrity

- Proper Choice of Encapsulant
  - Cost, Processing, Performance
- Proper Selection of Substrate
  - Should Interact with the Flexible Packaging Industry Low Cost For High Moisture Barrier Laminates
- Proper Module Edge Seal Protection
  - Mechanical Edge Seal or Frame
  - Hydrophobic Sealants or Caulks
  - Tapes
  - Combination of the Above

Springborn

Encapsulant Suppliers Role

Provide State-of-the-Art Encapsulants

- Cure Chemistry, Stabilization, Surface Texture, Primers, Various Thickness'

Qualified to Provide Technical Service

- Lamination Processes, Other Primer Systems for Non-Conventional Interfaces, Surface Treatments, etc.

Qualified to Assist in Module Packaging Design

- Materials Selection, Adhesion Characterization, Accelerated Aging, Moisture Resistance

Springborn

FIELD EXPERIENCE SESSION

Chair: Dick DeBlasio

Evaluation of Hybrid Inverters
for
Strategic Environmental Research and Development Program Applications

Jerry W. Ginn

PV System Components Department
Sandia National Laboratories
Albuquerque, NM 87185-0752

The photovoltaic systems test facility at Sandia National Laboratories is evaluating the performance of large hybrid power-processing centers (PPC's). The primary customer for this work has been the Strategic Environmental Research and Development Program (SERDP) of the Department of Defense. One of the goals of SERDP is to develop power-processing hardware to be used in photovoltaic-hybrid power systems at remote military installations. Power for these installations is presently provided by engine-generators. Currently, hardware for twelve such sites is in various stages of procurement. The subject of this talk is testing of the PPC for the first SERDP system, a 300-kW unit for Superior Valley, a US Navy site at China Lake, California.

Sandia's involvement in SERDP has three objectives. The first is to assist in the development of a significant PV market, namely, large hybrid systems. A second goal is to improve the field reliability of BOS components by rigorously testing them in order to provide a variety of stresses, establish load compatibility, and quantify performance. A final goal is to assist BOS vendors in their development of hybrid components by providing both technical assistance and laboratory facilities which may not otherwise be accessible to a private company.

Prior to being installed at their permanent sites, BOS components should be exercised as part of a complete system. The Sandia test environment furnishes the additional components such as a large battery bank, switchgear, diesel generator, and loads which provide a complete system. Thus the developmental testing continues after the inverter is installed as a system component at SNL. After rigorous testing as a system and resolution of any system-level problems, SNL conducts acceptance tests for the DoD. Finally, the system is installed at the DoD location and final acceptance tests are conducted. Problems are resolved during each step of the testing. It is intended that SNL testing provide a large and varied number of system stresses so that problems which might have gone undetected for months or years will be identified early and system field reliability will be increased.

Reliability tests at SNL have addressed issues which fall into four categories. These include: 1) stressing the equipment to search for hardware "weak links"; 2) thoroughly exercising the control system looking for problems related to electromagnetic noise or control logic; 3) verifying compatibility with loads that are anticipated at the site, including motors and nonlinear loads; and 4) quantifying performance in areas such as efficiency and distortion. Examples of each of these four test types are described.

Balance-of-systems hardware for large PV-hybrid systems is largely unproved due to a lack of test capability. Reliability of large inverters depends on a variety of factors, including planning, testing, hardware design, system controller hardware and software design, and field experience. Sandia provides a test bed to increase reliability by early identification of problems.

Testing of Inverters for the

Strategic
Environmental
Research &
Development
Program

Jerry W. Ginn
Photovoltaic Systems Evaluation Laboratory
Sandia National Laboratories

SERDP

- **Department of Defense** Research Program
- PV at Remote Military Installations
- $15M Program FY91-FY96
- SERDP supports Power Processing Center (PPC) development for *ECIP* projects:
  - ECIP is ongoing
  - Presently 12 Sites totalling 2 MW

> *Subject of this talk*:

Acceptance/development testing of First SERDP hardware:
Superior Valley, China Lake, **US Navy**

Sandia's Goals in SERDP

1. Assist development of significant PV market:

   Hybrid Systems

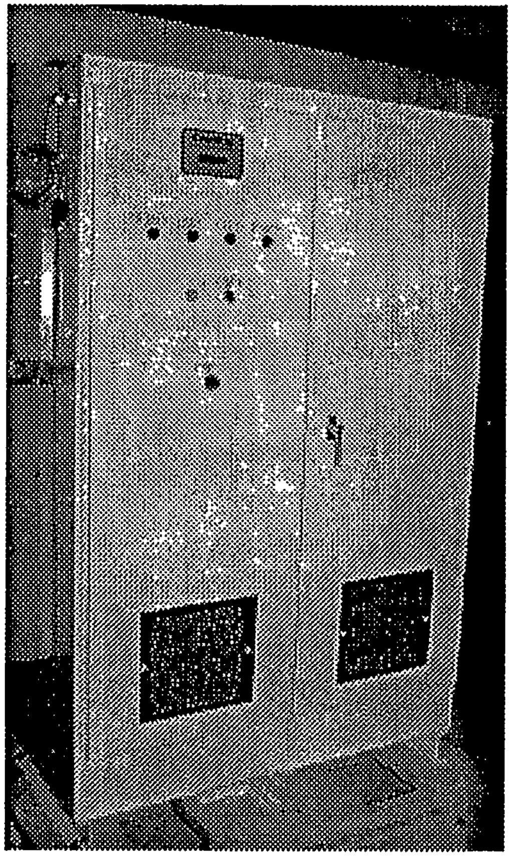
2. Improve field ***Reliability*** of BOS components by testing
   - provide many stresses
   - establish compatibility
   - quantify performance

3. Assist BOS vendors in hybrid *component development*
   - provide equipment and test facilities
   - provide technical assistance

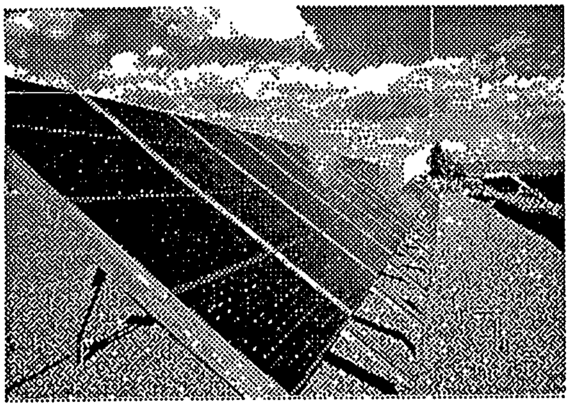
SNL Hybrid Test Program

- Developmental Units (30 kW)
  - Abacus: Complete
  - Omnion: Complete
  - AES: October, 95

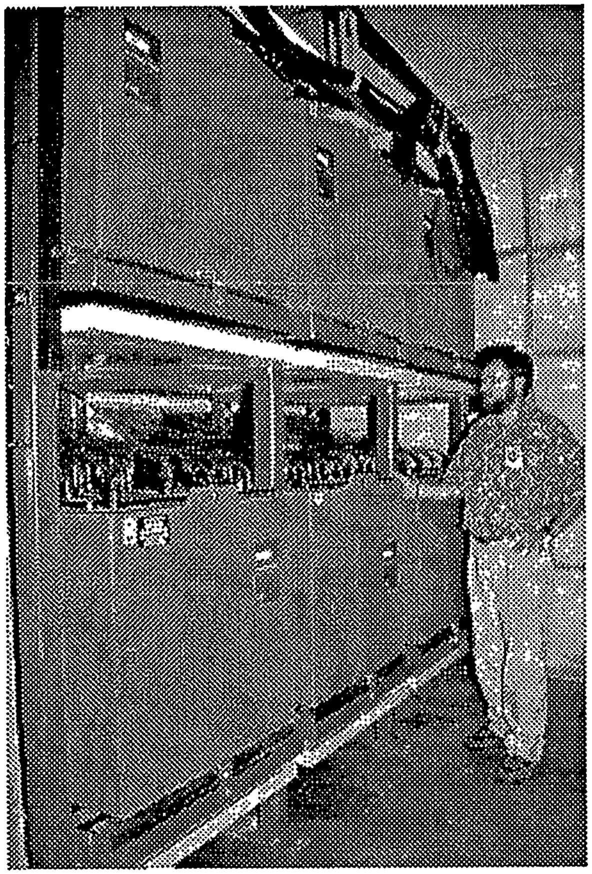
- Large Systems (to 450 kW)
  - Superior Valley: Complete
  - Five More SERDP/ECIP
  - Dangling Rope: January, 95



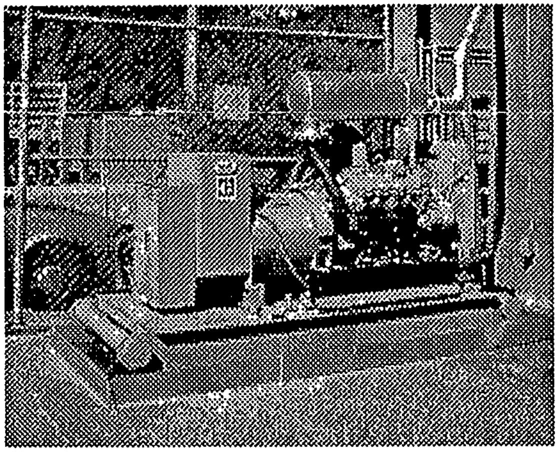
Configurable SNL Hybrid Test Components



30kW Array

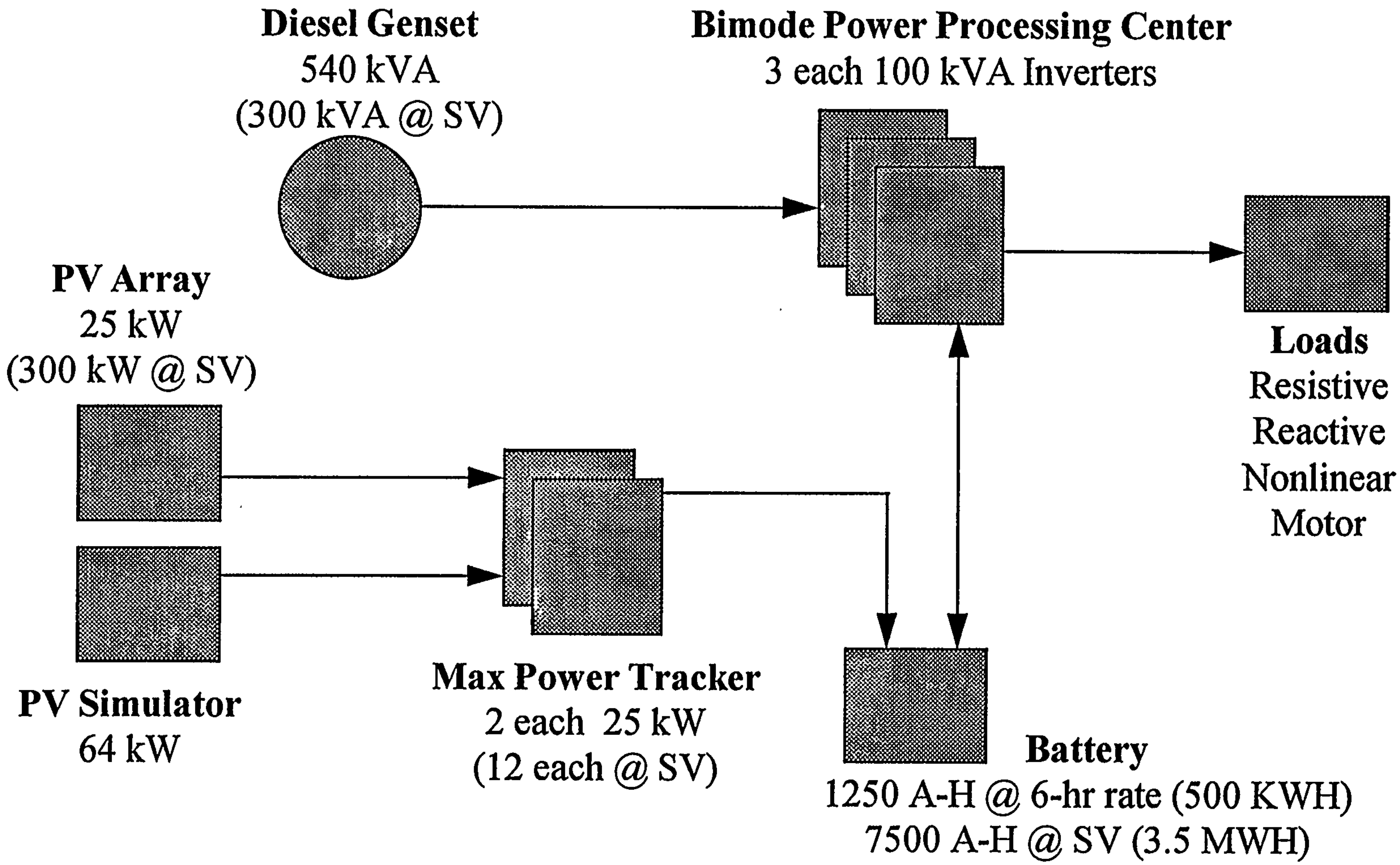


720 kWH Battery



92.5kVA Generator

Test Configuration
for
Superior Valley Hybrid System



Diesel Genset
540 kVA
(300 kVA @ SV)

Bimode Power Processing Center
3 each 100 kVA Inverters

PV Array
25 kW
(300 kW @ SV)

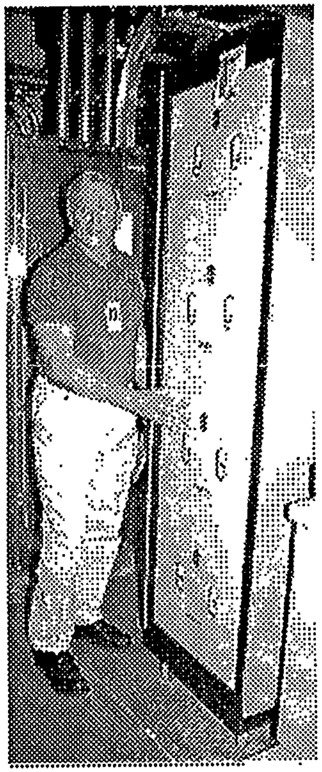
Loads
Resistive
Reactive
Nonlinear
Motor

PV Simulator
64 kW

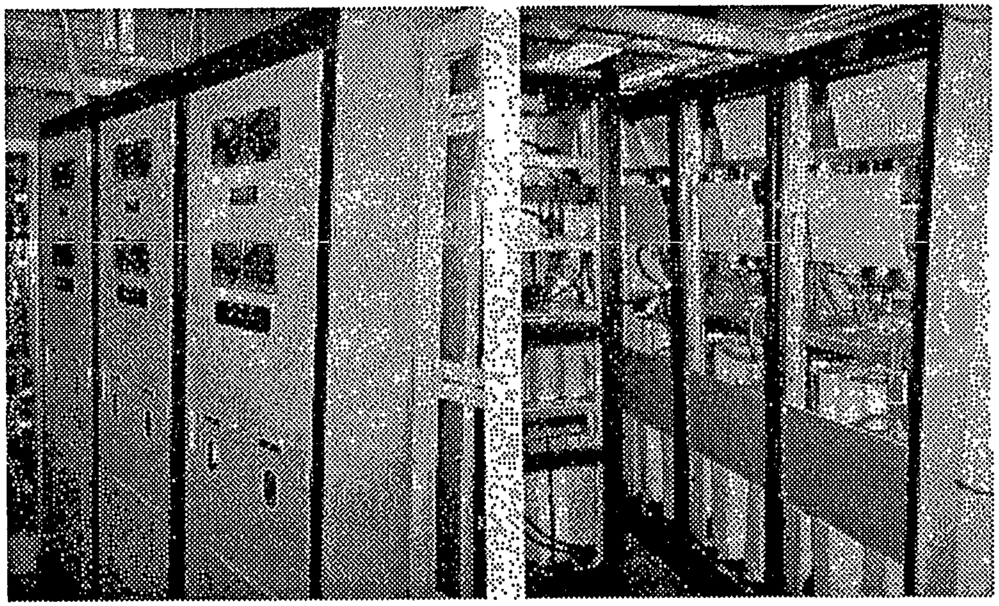
Max Power Tracker
2 each 25 kW
(12 each @ SV)

Battery
1250 A-H @ 6-hr rate (500 KWH)
7500 A-H @ SV (3.5 MWH)

Superior Valley Power Processing Hardware



Four 25kW
Max Power Trackers

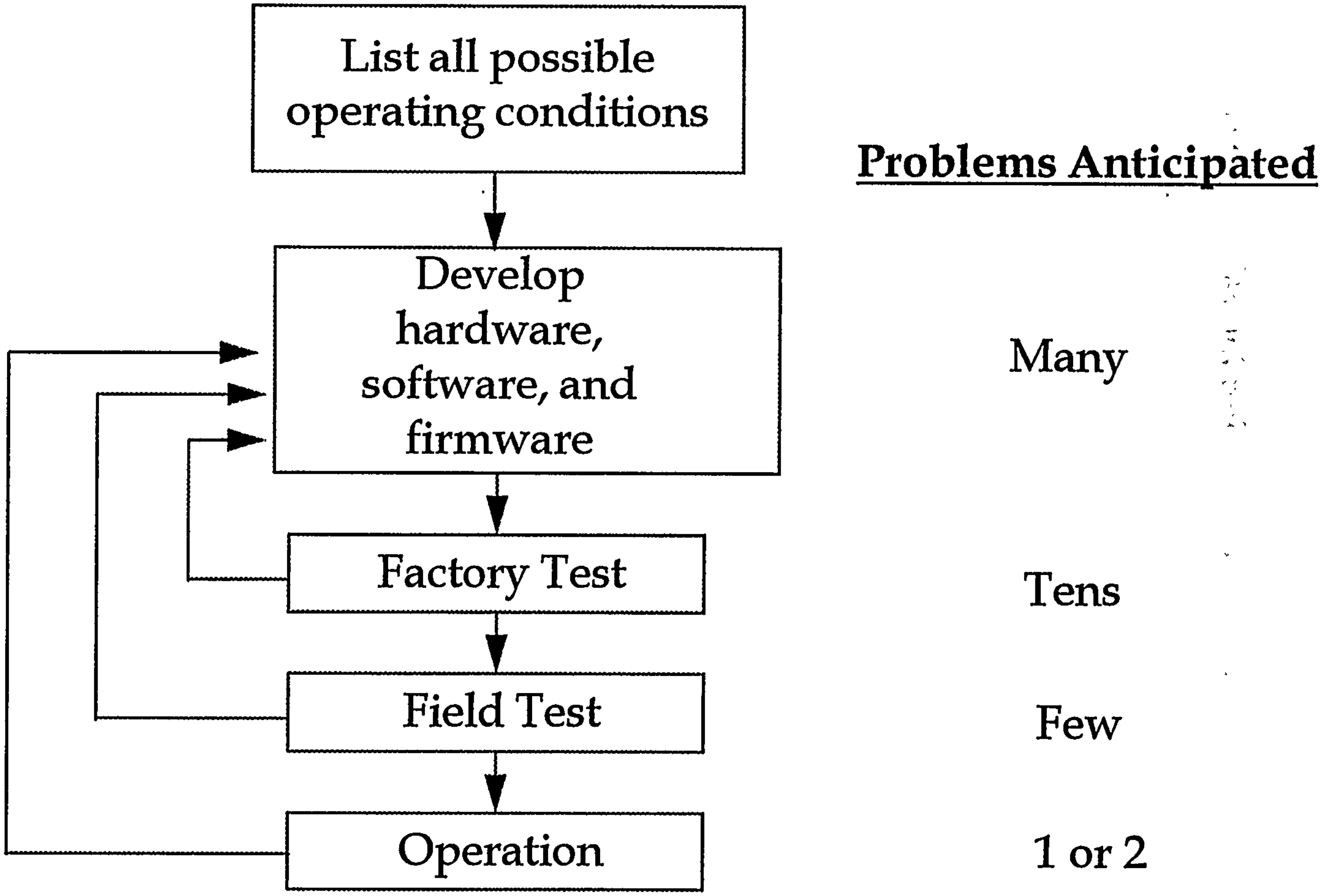


Three 50kW cabinets

Center Assembly

300kW Bimode Inverter

Development Process to Minimize Downtime



List all possible operating conditions

Develop hardware, software, and firmware

Factory Test

Field Test

Operation

Problems Anticipated

Many

Tens

Few

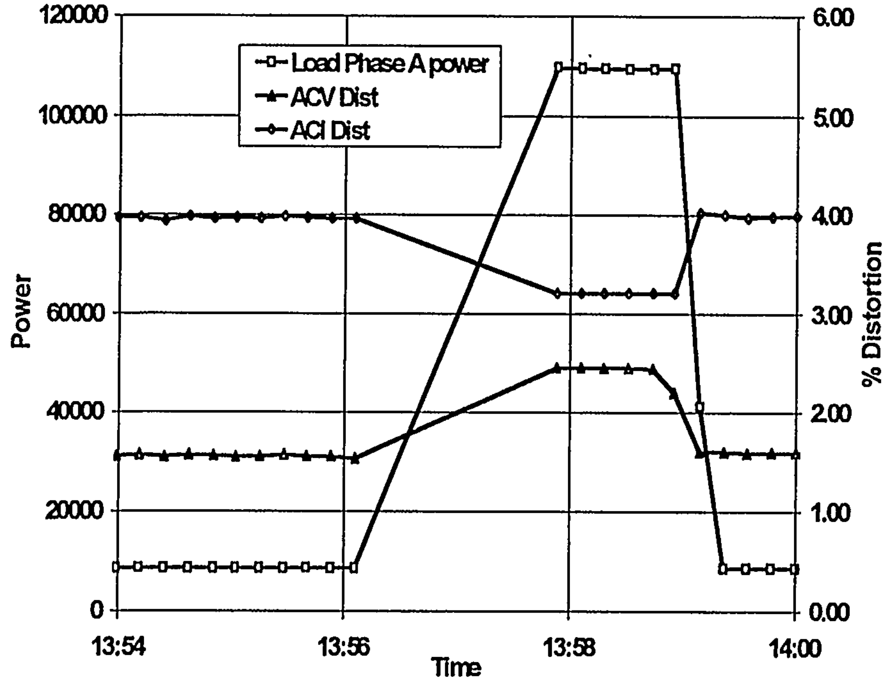
1 or 2

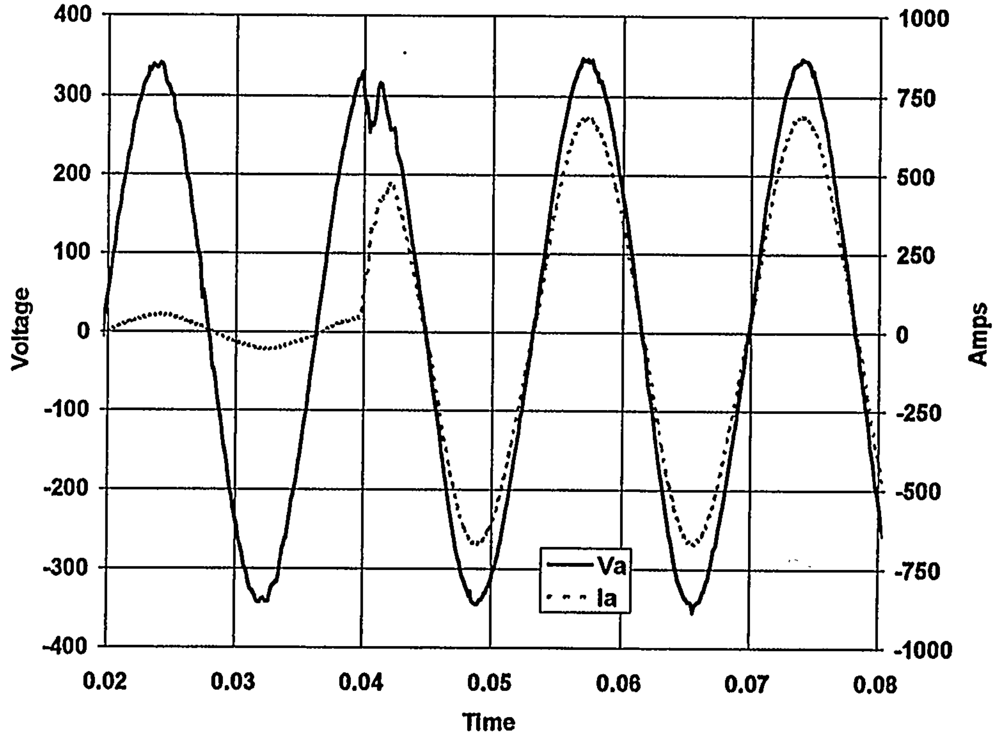
Reliability Issues

- Hardware "weak links"
- System Control
- Compatibility with Loads
- Quantify Performance

Hardware "weak-link" Testing Examples

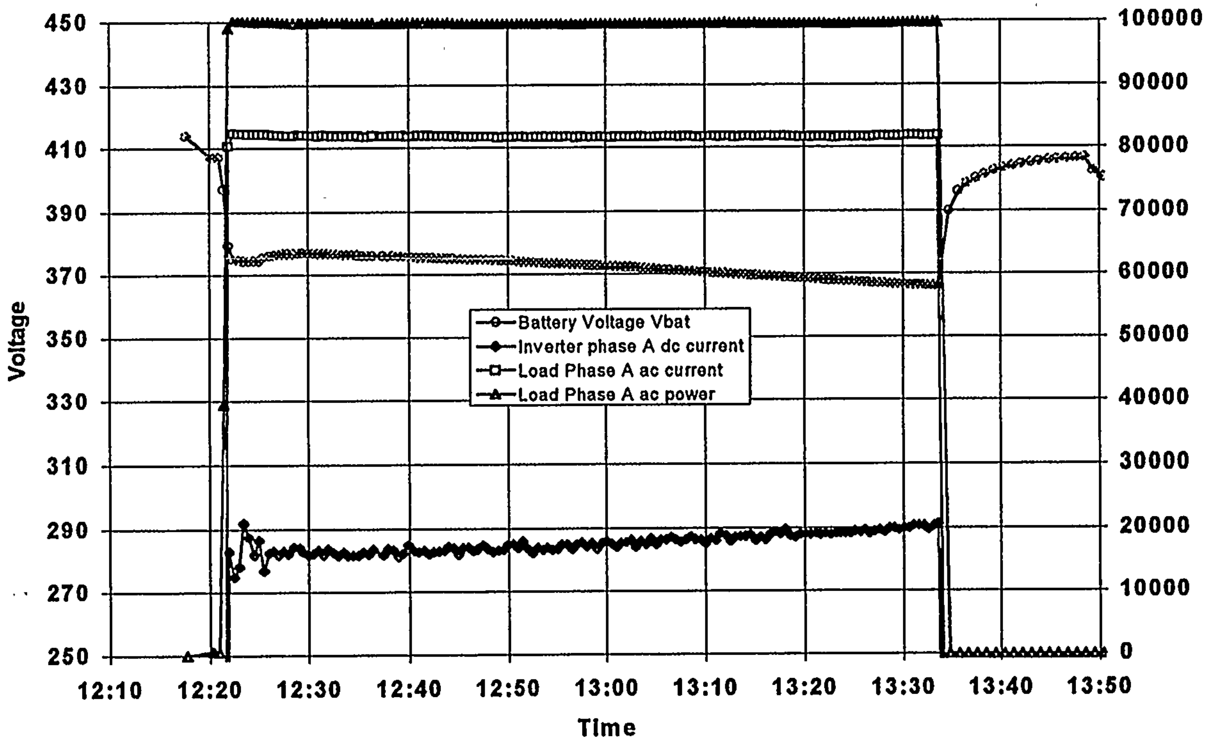
- 10-to-110 kW Load Transition





Hardware "weak-link" Testing Examples

- Extended Time at Full Rated Power



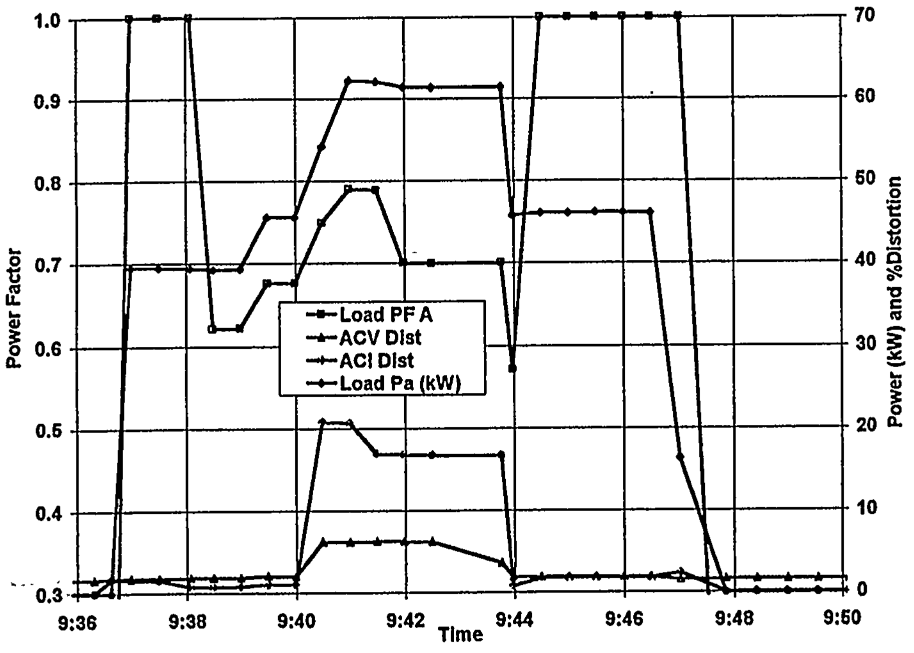
System Control Testing Examples

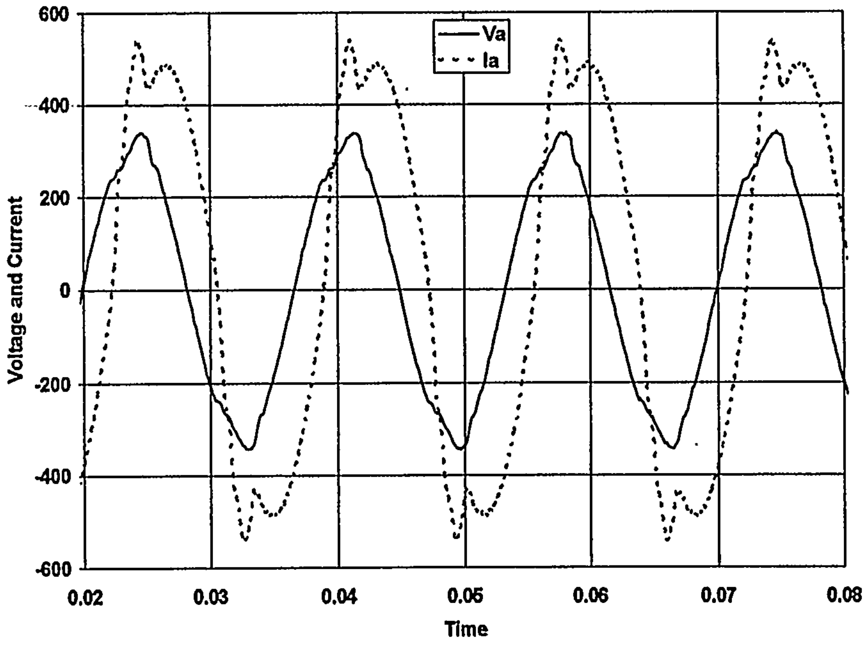
#	Event	Corrective Action
1	Generator frequency deviation > expected	Reprogram ASIC
2	Generator start inhibited	Software rewritten
3	Control card failure due to noise	Redesigned control card

Lab Impact: Days
Field Impact: *Loss of System* (days/weeks?)

Load Compatibility Testing Examples

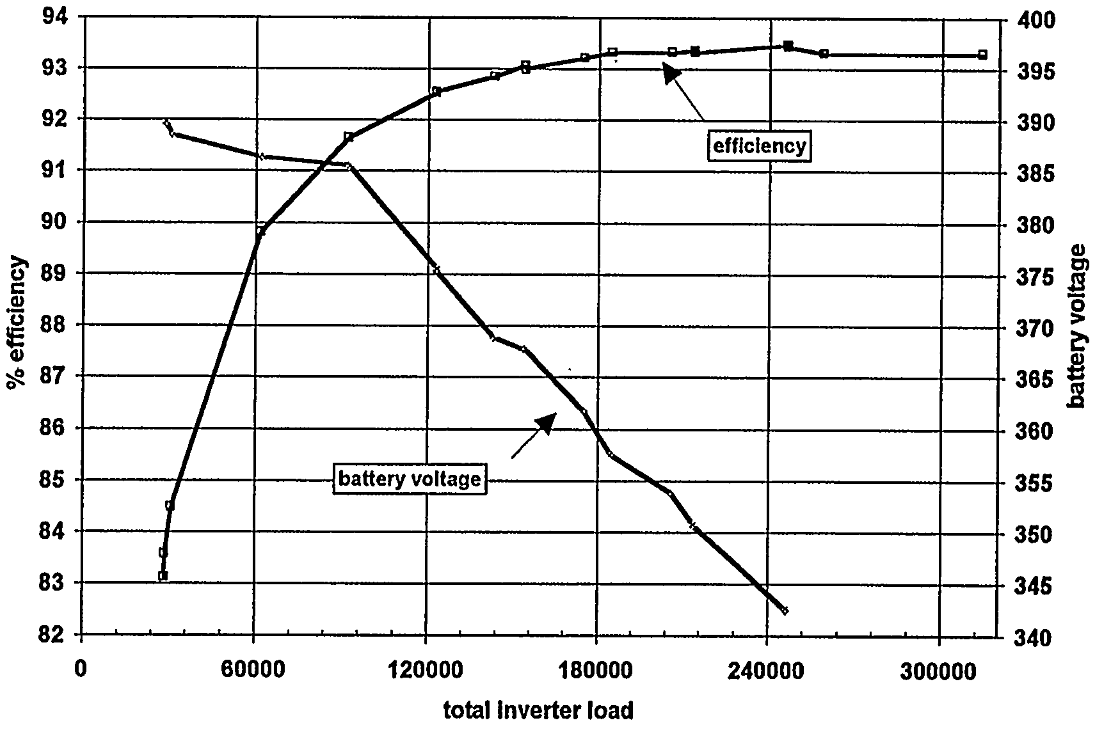
- Nonlinear Loads





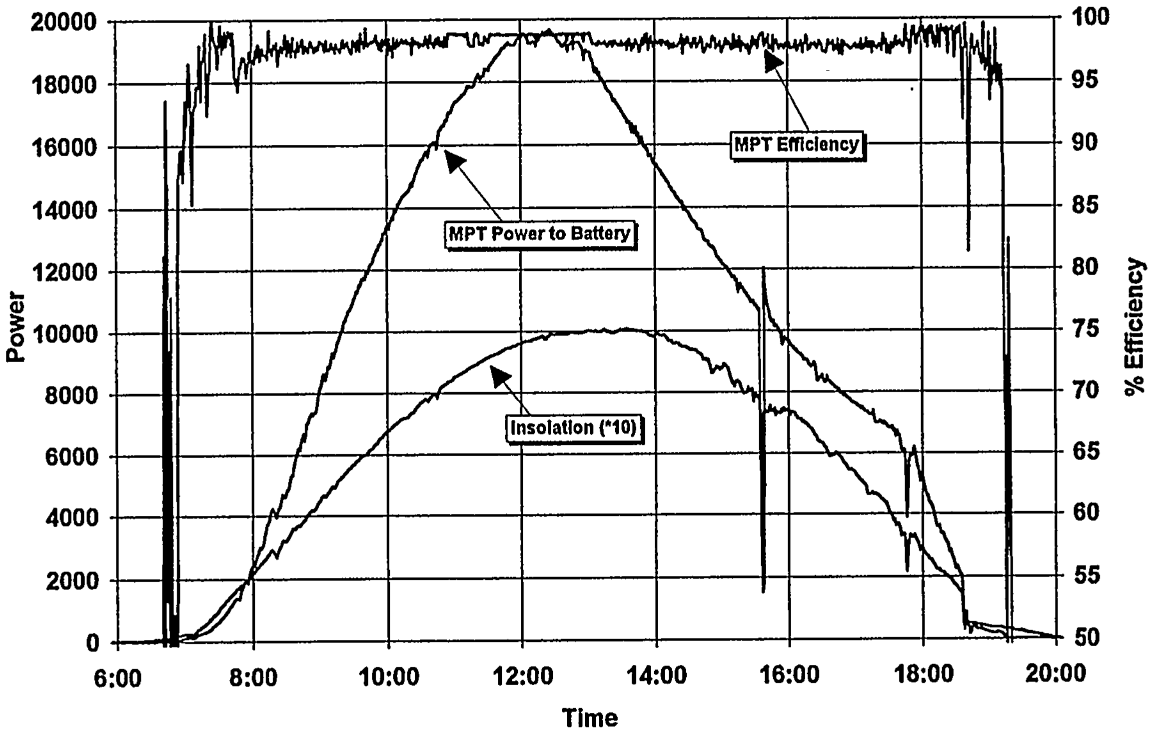
Quantify Performance Testing Examples

- **Inverter Efficiency**



Quantify Performance Testing Examples

- **Max Power Tracker Efficiency**



Summary

- Most BOS hardware for large hybrids is unproven
- Reliability of large inverters depends on:
  - Planning
  - Testing
  - Hardware design
  - System controller design
  - Field experience
- *Sandia provides a test bed to increase reliability by early identification of problems*

PV Water Pumping

NEOS Corporations recent PV water pumping activities

Cary Lane
NEOS Corporation

NEOS Corporation has been very active in PV-powered water pumping, particularly with respect to electric utilities. Most of the recent activity has been through the Photovoltaic Services Network (PSN). The PSN is an independent, not-for-profit organization comprised of all types of electric utilities: rural electric coops, public power districts, investor-owned utilities, and power marketing agencies. The PSN's mission is to work pro-actively to promote utility involvement in PV through education and training. PV information is distributed by the PSN in three primary forms: 1) consultation with PSN technical service representatives; 2) literature generated by the PSN; and 3) literature published by other organizations. The PSN can also provide assistance to members in developing PV customer service programs. The PSN's product support activities include consolidation of information on existing packaged PV systems and facilitation of the development of new PV product packages that meet utility-defined specifications for cost, performance, and reliability. The PSN's initial product support efforts will be focused on commercially available packaged PV systems for a variety of off-grid applications. In parallel with this effort, if no products exist that meet the PSN's functional specifications, the PSN will initiate the second phase of product development support process by encouraging the development of new packaged systems. Through these services and product support activities, the PSN anticipates engaging all segments of the PV industry, thus providing benefits to PV systems suppliers as well as local PV service contractors.

PV powered water pumping is the first application the PSN is focusing on. A PV pumping system product list is being developed which will list available PV pumping systems. The product list will include comparisons of the performance of each system for selected applications. The "Consumer Reports" type format will make it easier for utilities to select and purchase PV pumping systems that meet their needs.

Along with compiling data from the system suppliers, field testing is also being done. Evaluation projects are currently underway as described below. In addition to these projects, several utilities have purchased or been given prototype pumping systems and are currently testing them and sharing the results with the PSN.

The National Rural Electric Coop Association/ Rural Electric Research (NRECA/RER) is sponsoring a project to test the performance and reliability of a recently developed PV power system to operate "off-the-shelf" AC submersible pumps. A total of 13 Golden Photon systems have been installed at rural electric cooperatives across the western United States and American Samoa. These systems will be monitored and tested once a month through one pumping season ending in late fall of 1995. The objectives of this project are to compare the performance and reliability of Golden Photon systems to that of existing PV pumping systems, to examine and describe opportunities, limitations and requirements for these systems when used in co-op PV service programs and to directly document co-op experience with PV-powered AC pumping systems.

Another PV pumping test project is taking place near Colorado Springs, Colorado on the Fort Carson Army Base. The base is served by several of the PSN member utilities. The Directorate of Environmental Compliance and Management (DECAM) at Fort Carson agreed to purchase one each of seven different PV pumping systems that are presently being investigated as part of the PSN's water pumping initiative. Each system will be outfitted with a data acquisition system and these data will be incorporated into the PSN's PV pumping system comparative assessment activities.

The initial PV Pumping System Product List is being compiled with data provided by the systems suppliers. These data are difficult to compare since each supplier has their own way of testing and presenting their system performance. A much better method would be to have an independent testing lab do the same test on all of the listed systems. A "Consumer Report" type product list could then be compiled. The PSN is currently trying to encourage the development of such a facility.

The interest and support from both the PV industry and the utilities has been encouraging. The product testing and evaluation will continue with a focus on the prototype and recently commercialized systems. The coordinated utility purchases will undoubtedly continue to grow with a focus on the systems that are commercially available. While the current efforts have been with water pumping systems, the initial steps to repeat this commercialization process have begun for both residential and lighting PV systems.

PV Water Pumping

NREL PV Performance & Reliability Workshop

September 8, 1995

Cary Lane

NEOS Corp.

PV Pumping Systems

- PSN - a utility PV organization
- Commonly used systems
- Emerging products
- Commercialization projects
- Performance standards

NEOS Corp.

Photovoltaic Services Network

- Independent non-profit utility organization
- Governed by a 9 member board
- Focus on utility PV off-grid services
  - water pumping
  - residential
  - lighting
- 30 Utility members in 12 states

NEOS Corp.

PSN - Objectives

- Education & training
- Forum for information exchange
- Utility grade packaged PV systems
- Coordination of PV product purchases
- Alliances with other organizations
  - support PSN service
  - product development
  - product testing

NEOS Corp.

PSN - Current Activities

- Service support & training
  - utilities
  - local PV contractors
- Product testing & evaluation
- Coordinated utility purchases

NEOS Corp.

PSN - PV Pumping Initiative

- **Product list of available systems**
  - "packaged" system standards
  - "Consumer Report" type product reviews
  - Enough product information for educated purchasing decisions
  - Pre-negotiated prices with suppliers
  - PV industry review of process & requirements

NEOS Corp.

PSN's PV Pumping System Product List

- Includes system supplier provided information
- Systems must meet minimum requirements
- Evaluation criteria will be provided
- Systems compared at specific operating parameters
  - i.e.: 100' head, 3000 GPD, 6 sun hrs

NEOS Corp.

Systems Commonly Used By Utilities

- Diaphragms
  - Solarjack
  - Shurflo
  - Robison
- Large centrifugals
  - AY McDonald
  - Grundfos
- Pumpjacks
  - Jensen

NEOS Corp.

Emerging PV Pumping Systems

- Small centrifugals
  - Solarjack
  - AY McDonald
  - Grundfos
- "Standard" AC
  - Golden Photon
  - Franklin Electric
  - EPV

NEOS Corp.

Testing of Emerging Systems

- PSN member pilot projects
- Fort Carson Army Base / DECAM
  - Directorate of Environmental Compliance and Management
  - Customer of 2 PSN members
- NRECA/RER
  - National Rural Electric Coop Assn.
  - Rural Electric Research Division

NEOS Corp.

Fort Carson Army Base

- Systems installed
    - Solarjack centrifugal
    - AY McDonald, 1/2 size
    - Shurflo, diaphragm
    - Robison, diaphragm
    - EPV, AC centrifugal, 3 phase
    - Golden Photon, AC centrifugal, 1 phase
    - Grundfos, 1/2 size - pending

NEOS Corp.

PV Pump Testing Facility

- Develop test parameters
    - Industry agreement
- Verify performance of all systems
    - "Consumer Report" type testing
- Feedback for manufacturers

NEOS Corp.

Conclusion

- Product testing & evaluation
  - Focus on emerging systems
- Coordinated utility purchases
  - Focus on commercial systems
- Repeat commercialization process for other off-grid applications
  - residential
  - lighting

NEOS Corp.

Polycrystalline Thin-Film Module and System Performance

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INTRODUCTION

The Module and System Performance and Engineering Project at the National Renewable Energy Laboratory (NREL) conducts in-situ technical evaluations of photovoltaic (PV) modules and systems (arrays). These evaluations on module/array performance and stability are conducted at the NREL Photovoltaic Outdoor Test Facility (OTF) in Golden, CO (See Figure 1). The modules and arrays are located at 39.7°N latitude, 105.2°W longitude, and at 1,782 meters elevation.

Currently, two polycrystalline thin-film technologies are the focus of the research presented here. The module structures are copper indium diselenide (CIS) from Siemens Solar Industries and cadmium telluride (CdTe) from Solar Cells, Inc. The research team is attempting to correlate individual module performance with array performance for these two polycrystalline thin-film technologies. This is done by looking at module and array performance over time. Also, temperature coefficients are determined at both the module and array level.

EXPERIMENTAL PROCEDURE

Long-term performance data is acquired on individual modules using a Raydec RD-1200* multi-tracer and on arrays using a Daystar* current-versus-voltage (I-V) curve tracer as well as Campbell Scientific* dataloggers. Individual module and system data is then compared for correlation. It should be noted that, because these are research modules, they do not all come from a common process or production stream and this fact may be the source of some variation in the data. Therefore, the temperature coefficients presented in this paper are preliminary for these technologies.

Individual Module Data Acquisition

Individual module performance is monitored with a RD-1200 multi-tracer. The multi-tracer is capable of testing up to 15 individual modules. For this experiment, the modules are loaded at their maximum power (max-power) point except when I-V curves are taken. I-V curves are swept from I_{sc} to V_{oc} and are acquired every half hour at irradiances of 950-1050 W/m^2. Data were collected over a period of approximately 1 year for this test.

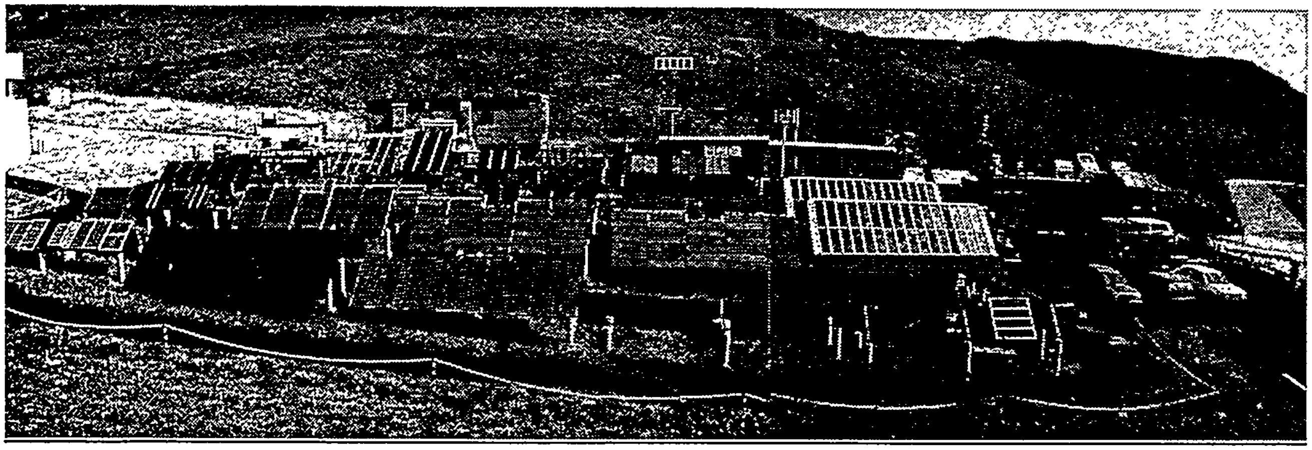

Figure 1. NREL Photovoltaic Outdoor Test Facility

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* Reference to a specific manufacturer's product does not constitute an endorsement by the Department of Energy or NREL, but refers to products that are representative of instruments used for the purposes described in this text.

Array/System Data Acquisition

To monitor and evaluate system performance, two sets of data are collected. The two data sets include instantaneous measurements and long-term data acquisition.

The instantaneous array performance is monitored via a portable I-V curve tracer. These I-V traces are acquired once a month (weather permitting) at plane-of-array (POA) irradiances between 900 and 1100 W/m^2.

Long term array/system performance is monitored via a Campbell Scientific CR10 datalogger. Data collected include array current and voltage, back-of-module and ambient temperatures, and POA irradiance. Data are sampled every 5 s and are stored as 15-min averages.

RESULTS AND DISCUSSION

Siemens Solar Industries CIS Modules

Siemens Solar CIS Module Performance

One Siemens Solar CIS module was used for the module data. This module is from a process or production stream similar to the system modules. All modules underwent the same thermal-cycling procedure prior to deployment. The module was installed at a 40° tilt and is loaded at maximum power during the day, except when I-V curves are taken. Data collection for this study started on July 11, 1994, and ended on June 1, 1995. Figure 2 shows that the CIS modules show a strong inverse correlation of P_{max} with back-of-module temperature. This effect can be attributed to the narrower band gap of the CIS material. Gaps in the data occur where the multi-tracer was unavailable while being used for other experiments.

To examine the long-term stability of this module, we corrected the data to a constant temperature. For comparative purposes, 25°C was chosen. To correct the performance data to 25°C, a temperature coefficient for the module was calculated. Using a linear regression of power (normalized to 1000 W/m^2) versus back-of-module temperature, a temperature coefficient can be calculated (Figure 3). The temperature coefficient of -0.672%/°C is consistent with previously reported results for the CIS material [1]. Based on this value, the module was calculated to have a P_{max} rating at 25°C of 29.7W. Figure 4 shows P_{max} corrected to 25°C versus time for the CIS module. From this figure, note that the module shows good stability over time.

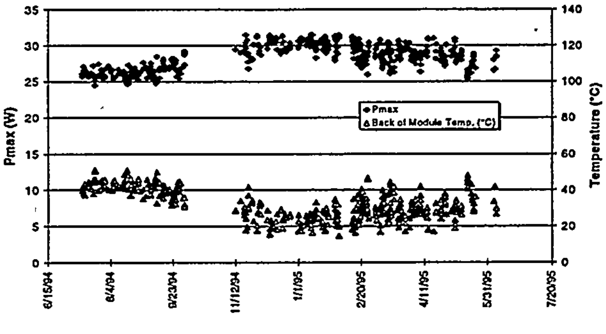

Figure 2. Normalized power and module temperature versus time

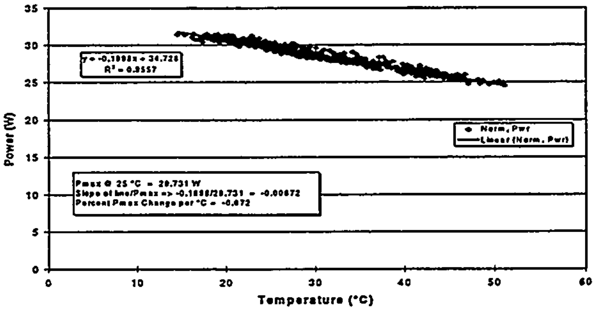

Figure 3. Normalized power versus module temperature

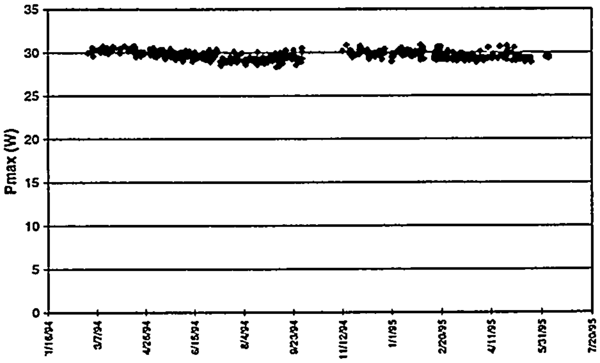

Figure 4. Normalized and temperature-corrected power versus time

Siemens Solar CIS System/Array Performance

The Siemens Solar CIS array is comprised of 34 modules. The array is located at NREL's PV Outdoor Test Facility. All modules were subjected to accelerated testing at Siemens prior to deployment at

NREL. Each module has an aperture area of 3946.3 cm^2 (127.3 by 31.0 cm). The average module from this group had the following electrical characteristics (measured at NREL prior to deployment): P_{max}=28.3 W, V_{max}=15.56 V, V_{oc}=22.38 V, I_{max}=1.832 A, and I_{sc}=2.264 A. Using the average max-power, the summation of module max-powers at standard test conditions (STC) is 962 W.

These modules are vintage CIS modules and do not represent the current state-of-the-art for Siemens Solar. The array is fixed at a 40° tilt and is aligned true south. The array is divided into three separate subarrays. Two of the subarrays are composed of six parallel strings of two modules in series, and the remaining subarray is composed of five parallel strings of two modules in series. Each subarray feeds dc power to a separate max-power tracker. The output of each max-power tracker is paralleled and tied to a 0.95ohm, 2-kW fixed resistive load.

Array installation was completed on September 15, 1993. From then until March 21, 1994, each module's output was shorted. Data acquisition then began on April 1, 1994. Data continues to be acquired without anomaly.

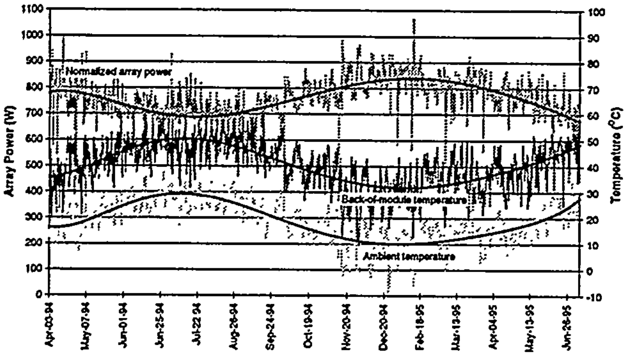

Figure 5. Normalized array power, back-of-module temperature, and ambient temperature versus time

Figure 5 shows array power, back-of-module temperature, and ambient temperature versus time. The data in this chart were restricted to POA irradiances greater than 850 W/m^2. Array power is normalized to 1000 W/m^2. To establish any visual trends, each data series was fit with a 6th order polynomial trend line. The figure shows a strong inverse correlation between array power and back-of-module temperature.

Siemens Solar CIS Array Temperature Coefficients

The array performance is monitored via a portable I-V curve tracer. I-V traces are acquired once a month (weather permitting) at POA irradiances between 900 and 1100 W/m^2. Based on this data set, a preliminary temperature coefficient for P_{max} was calculated. The data were not corrected for spectral effects. Thus, this preliminary coefficient may be influenced by spectrum. Figure 6 presents the temperature coefficient derivation for P_{max}. This was calculated by performing a first-order regression analysis of P_{max} (normalized to 1000 W/m^2) versus back-of-module temperature. The temperature coefficient for P_{max} was determined to be -0.845%/°C with a R^2 of 0.91. This R^2 indicates that P_{max} is well correlated with temperature.

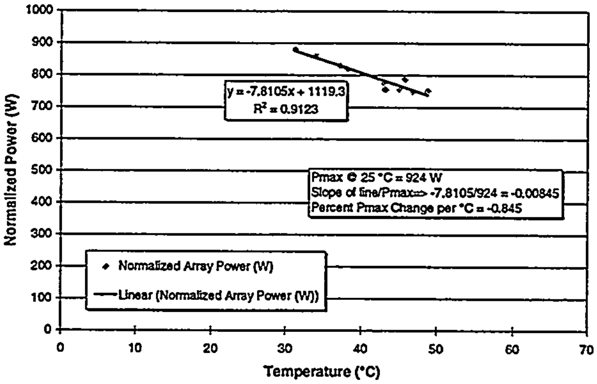

Figure 6. Array P_{max} temperature coefficient derivation

The array power presented in figure 5 was corrected for temperature based on the temperature coefficient of -0.845%/°C. The array performance, normalized to 1000 W/m^2 and corrected to 25°C back-of-module temperature, is shown in Figure 7. Figure 7 highlights two system performance anomalies.

From late August 1994 to late September 1994, a ground path between each max-power tracker was found. As these particular max-power trackers switch the negative input from the array, a loss in power was experienced. The increase in output seen from December 1994 to April 1995 is due to a failed max-power tracker. The failed max-power tracker was bypassed by tying the subarray directly to the resistive load. Therefore, at or near onesun, the subarray was well matched to the fixed resistive load. Conversely, at lower irradiance levels, the array output would not be well matched to the load and a loss in power would be seen. Neglecting the aforementioned max-power tracker anomalies, the temperature-corrected array power is relatively stable with only slight fluctuations that still inversely trend temperature.

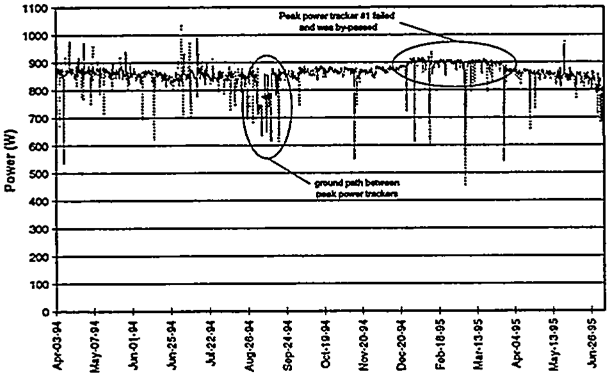

Figure 7. Normalized and temperature-corrected array power versus time

Solar Cells, Inc. CdTe Modules

Solar Cells, Inc. CdTe Module Performance

One CdTe module from Solar Cells, Inc., was used for the module performance analysis. This module is from a similar process or production stream as the system modules. The module was installed at a 40° tilt and is loaded at maximum power during the day, except when I-V curves are taken. Data collection for this experiment started June 1, 1994, and ended June 1, 1995. Figure 8 shows that the CdTe modules show a weak inverse correlation between P_{max} and the back-of-module temperature. This effect can be attributed to the wider band gap of the CdTe material as compared to CIS. Gaps in the data occur where the multi-tracer was being used for other experiments.

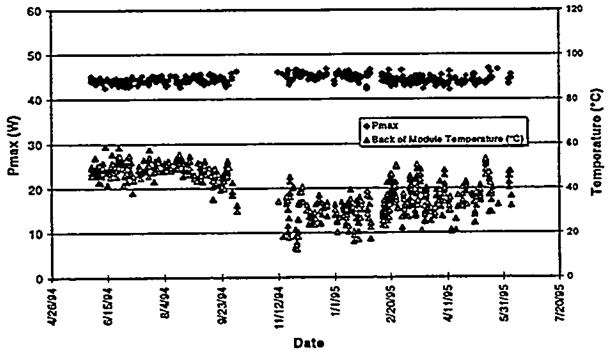

Figure 8. Normalized power and module temperature versus time

To correct the performance data to 25°C, a temperature coefficient for the module was calculated. Using a linear regression of power (normalized to 1000 W/m^2) versus back-of-module temperature, a temperature coefficient was calculated (Figure 9). The temperature coefficient was calculated to be -0.217 %/°C. This temperature coefficient had an R^2 of 0.4, which means that the data contain considerable scatter. This module was calculated to have a P_{max} rating at 25°C of 46.6W.

Figure 10 shows the P_{max} data of Figure 9 corrected to 25°C. The figure shows that this module had good stability over the test period.

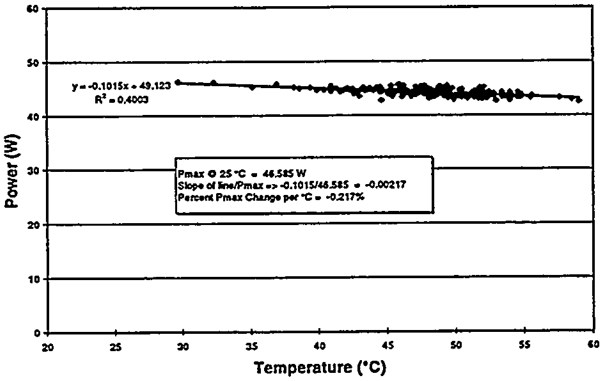

Figure 9. Normalized power versus module temperature

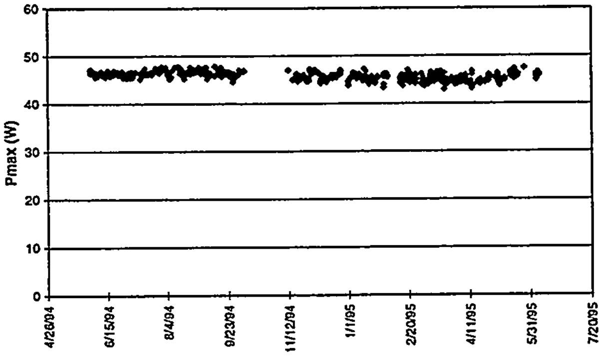

Figure 10. Normalized and temperature-corrected power versus time

Solar Cells, Inc. CdTe System/Array Performance

On June 21, 1994, eight SCI CdTe PV modules were integrated into a utility-interconnect PV system at NREL for test and evaluation. The PV array comprises two monopoles. Each monopole employs four series-connected SCI PV modules. The average module from this group had the following electrical characteristics (measured at NREL prior to deployment): 51 W_{max}, 89 V_{oc}, 0.93 A_{sc}, 65 V_{max}, and 0.79 A_{max}. The module's aperture area is 0.68 m^2 (57.7 by 117.7 cm). The array is fixed at a 30^0 tilt angle. The summation of module max-powers (as measured by NREL) was approximately 400 W_{dc}. Thus, the system was labeled the SCI 400 W_{dc} PV array. The array was operated at its max-power point by an Omnion series 2200 inverter. The output of the Omnion inverter was fed to the local utility's power distribution grid. The modules were deployed in intervals beginning in February 1994 and ending in May 1994. System operation began June 21, 1994. Data acquisition commenced on July 7, 1994.

The 400 W_{dc} array was decommissioned on June 19, 1995, and was replaced with 24 newer modules that incorporate SCI's frameless mount and a wire pigtail in place of the terminal block and junction box. This paper discusses only the performance of the 400 W_{dc} array over the 1-year test period.

Figure 11 shows dc power, ac power, back-of-module temperature, and ambient temperature versus time for the 400 W_{dc} array. The data are fit with 6th order polynomial trend lines to aid visually in establishing any trends. The data used in the figure were restricted to POA irradiance greater than 850 W/m^2. Dc and ac power were normalized to 1000 W/m^2 for the figure. The back-of-module temperature ran at an average of 26°C above the ambient. This figure shows that temperature had little effect on ac power output at or near one-sun. However, dc power shows a weak inverse correlation with temperature. This discrepancy is possibly due to the low input level at which the 400 W_{dc} array operated the 2 kW_{ac} Omnion inverter. The figure further shows that array/system performance were relatively stable over this test period.

Based on the monthly CdTe I-V curve trace results, a preliminary temperature coefficient for P_{max} was calculated. The coefficient was obtained through a first order regression analysis and was calculated to be -0.265%/°C and -0.236%/°C for the positive and negative monopoles, respectively. The corresponding R^2 values for these coefficients are 0.64 and 0.79. These R^2 values indicate that the P_{max} temperature coefficients explain about 70% of the variation in P_{max} due to temperature. To simplify this analysis, the two temperature coefficients were averaged, that is, ((-0.265 + -0.236)/2 = -0.25 %/°C).

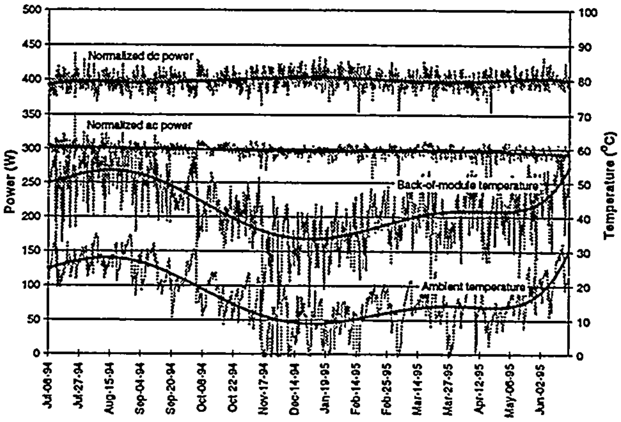

Figure 11. Normalized ac and dc power versus time

Figure 12 shows dc power corrected for temperature and normalized to 1000 W/m^2 versus time for the 400 W_{dc} array. For comparison, the normalized dc power (not corrected for temperature) is also included in the chart. The temperature coefficient used was -0.25%/°C, the average between the positive and negative monopoles. The data used in the figure were restricted to POA irradiance greater than 850 W/m^2. Note that the temperature coefficient used slightly reduces the variation in P_{max} caused by temperature.

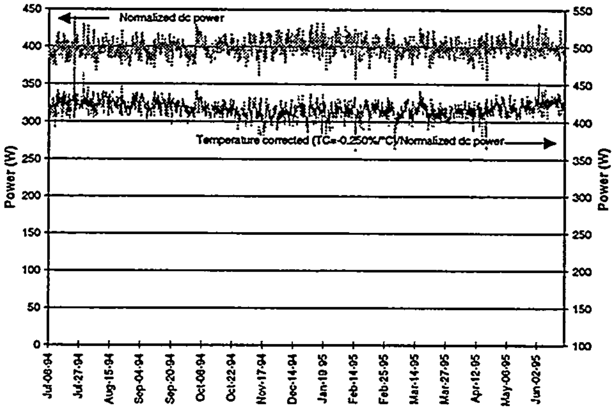

Figure 12. Normalized and temperature-corrected dc power compared to the normalized dc power

CONCLUSIONS

Preliminary temperature coefficients for P_{max} for both polycrystalline technologies at the module and array level were calculated. Table 1 summarizes these results. The data were not corrected for spectral effects, thus, these preliminary coefficients may be influenced by spectrum.

Correlation of CIS Module and System Data

A strong inverse correlation between array power and back-of-module temperature was shown to exist at both the module and array levels. This is mainly due to the narrow band gap of the CIS material, which results in a strong inverse correlation between voltage and temperature. The temperature-corrected module and array powers were shown to be relatively stable over the one year test period.

Preliminary temperature coefficients for P_{max} at the module and array level were calculated. The temperature coefficient obtained at the array level is greater than that for the module. This is attributable to several factors, e.g., temperature sensor location, module (elevated) versus array (ground level) location, and variations in the process or production stream.

Correlation of CdTe Module and System Data

Temperature was shown to have little effect on max-power at both the module and array level. Both module and array/system performance were relatively stable over the test period.

Preliminary temperature coefficients for P_{max} at the module and array level were calculated. Given the low R^2 obtained for the module's P_{max} temperature coefficient, the corresponding temperature coefficients are considerably more uncertain. The temperature coefficient obtained at the array level was found to be marginally acceptable.

Table 1. Preliminary peak power temperature coefficients

Structure	Device	Max-Power Temp. Coeff	R^2
CIS	Module	-0.672 %/°C	0.9
CIS	Array	-0.845 %/°C	0.91
CdTe	Module	-0.217 %/°C	0.4
CdTe	Array	-0.25 %/°C	0.64/0.79

FUTURE WORK

The Photovoltaic Module and Systems Performance and Engineering Project at NREL will continue to investigate the issues affecting polycrystalline thin-film module and array performance and stability. This will include in-depth performance versus temperature studies and module versus array/system performance.

ACKNOWLEDGMENTS

The authors thank Richard DeBlasio for his support of this work. The authors also thank Yehoshua Caiyam, Larry Ottoson, Steve Rummel, and Keith Emery for their help with module measurements and characterization and Joe Burdick for his technical support. Finally the authors would like to thank Siemens Solar Industries and Solar Cells, Inc., for samples and support of this work. This work was supported by the U.S. Department of Energy under contract No. DE-AC36-83CH10093.

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NREL Photovoltaic Performance and Reliability Workshop ☼ September 1995

THE DEVELOPMENT AND PERFORMANCE OF SMUD GRID-CONNECTED PHOTOVOLTAIC PROJECTS

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ABSTRACT

The utility grid-connected market has been identified as a key market to be developed to accelerate the commercialization of photovoltaics. The Sacramento Municipal Utility District (SMUD) has completed the first two years of a continuing commercialization effort based on the sustained, orderly development of the grid-connected, utility PV market. This program is aimed at developing the experience needed to successfully integrate PV as distributed generation into the utility system and to stimulate the collaborative processes needed to accelerate the cost-reductions necessary for PV to be cost-effective in these applications by the year 2000. In the first two years, SMUD has installed over 240 residential and commercial building, grid-connected, rooftop, "PV Pioneer" systems totaling over 1MW of capacity and four substation sited, grid-support PV systems totaling 600 kW bringing the SMUD distributed PV power system to over 3.7 MW. The 1995 SMUD PV Program will add another approximately 800 kW of PV systems to the District's distributed PV power system. SMUD also established a partnership with its customers through the PV Pioneer "green pricing" program to advance PV commercialization.

1. INTRODUCTION

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. SMUD is "constructing" a 600 Megawatt (MW) "Conservation Power Plant" and plans to add nearly 400 MW of renewable and advanced energy projects by about the year 2002. Solar energy will provide an important part of both the "Conservation Power Plant" and renewable resource technologies. Investments made in solar power today are expected to provide the customer-owners of SMUD with substantial long-term energy and community benefits.

The SMUD Solar Program has three elements designed to increase Sacramento's use of solar energy. The Solar Domestic Hot Water Program uses attractive performance based rebates and financing and strict quality assurance requirements to encourage the electric water heat customer to switch to solar water heating. Since May 1992, over 3000 SMUD customers have used this program and reduced their electric water heating energy consumption by an average of 60% and provided the District with needed peak capacity and energy benefits. The Solar Buildings Program provides design assistance and incentives to encourage the incorporation of cost-effective passive and other solar features in the design and construction of both new buildings and the retrofit of existing buildings. The Solar Buildings Program is also responsible for collaborative solar cooling development and demonstration projects.

The Solar Electric Program includes solar thermal electric systems, such as the Solar Two Central Receiver Project and the Utility-scale Solar Dish/Stirling Engine Joint Venture, and a wide variety of photovoltaics applications aimed at the accelerated commercialization of grid-connected PV systems.

2. SMUD PV PROGRAM

SMUD has embarked on an ambitious commercialization effort based on the sustained, orderly development of the grid-connected, utility PV market. This program is aimed at developing the experiential base needed to successfully integrate PV as distributed generation into the utility system and to stimulate the collaborative processes needed to accelerate the cost-reductions necessary for PV applications to be cost-effective in these applications.

SMUD is playing a leadership role in the commercialization of grid-connected PV through its own PV programs as well as helping to developing the collaborative State and national utility PV commercialization efforts underway including the Utility Photovoltaic Group (UPVG) and Photovoltaic for Utilities (PV4U) programs.

SMUD is a leader in utility grid-connected applications of

PVs with the world's largest distributed PV power system. The SMUD PV system, currently over 3.7 MW, includes SMUD PV1/PV2 (2 MW operating since 1984, figure 1), the first public PV electric vehicle recharge station in the West, residential grid-connected PV installations, and numerous remote power and sensor applications including a number of PV powered street lights and PV powered, emergency phones. In 1993 SMUD adopted a long-term PV commercialization strategy aimed at accelerating the cost-reduction of grid-connected utility PV applications. As part of this effort SMUD installed in 1993 723 kW of grid-connected PV systems. These systems include 109 4 kW (400 kW total) residential, roof-mounted PV systems; a 50 kW commercial building sited, concentrating PV system; a 3 kW demonstration building integrated, PV roofing system (figure 2) and a 258 kW substation sited, distribution support PV system (figure 3).

The 1994 SMUD PV Program included 958 kW of grid-connected PV systems. These included 472 kW of residential rooftop, 144 kW of commercial rooftop and 3 substation projects totaling 342 kW. The 1995 SMUD PV Program is expected to field in late 1995 and early 1996 about another approximately 800 kW. Both the 1994 and the 1995 PV Projects include USDOE/UPVG TEAM-UP cost-share funding. The 1995 additions will bring the SMUD Distributed PV System to about 4.5 MW.

2.1 Rating of PV Systems

SMUD has adopted a convention of rating the effective kW output of grid-connected PV systems based on national utility standards. All PV systems, unless otherwise noted, are rated based on the AC output of the system at PVUSA test conditions (kW, AC, PTC). PVUSA Test Conditions (PTC) are used by the utility industry and specified by UPVG. PTC ratings are typically 10% more conservative than the Standard Test Conditions (STC) ratings used by the PV industry.

To account for the differences in energy production between fixed and tracking PV systems, the Energy Production Factor, EPF, has been adopted. Established by the Utility Photovoltaic Group (UPVG), the EPF factor permits a more appropriate comparison between fixed and tracking systems. This permits the conventional comparison of $/W to attach value to the additional energy production value of tracking as well as accounting for the added cost. SMUD rates tracking PV systems based on the AC output of the system at PVUSA test conditions with the Energy Production Factor adjusting the nominal output of the system (kW, AC, PTC, EPF).

2.2 Residential PV Pioneer Project

The 1993 SMUD PV Pioneer Project established a partnership with customers willing to assist in the early adoption of photovoltaic (PV) technology. Under the 1993/1994 projects, SMUD purchased, installed, owns and operates about 240 residential rooftop PV systems, each about 4 kW. SMUD plans to continue adding 100+ PV Pioneer systems each year for 5 years. Customers (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. The PV Pioneer pays a $4 to 6 per month premium (about 15% of the average electric bill) on their utility bill to participate. In doing so, the PV Pioneers have the satisfaction of generating clean, renewable energy on their own rooftops. SMUD gains experience in the installation, operation, maintenance, pricing strategies and other aspects of residential PV systems. This joint effort also helps accelerate the commercialization of PV as part of a process of sustained, orderly development.

The 1993 PV Pioneer systems were supplied as turn-key, installed systems by Siemens Solar Industries (SSI) for $7.70/W AC, PTC. The 4 kW system make up a standard 400 square foot array. A few systems were down-sized to accommodate homes with smaller roof area. Innovative roofjacks permitted quick installation of the PV array. The complete PV system installation requires only half of a day. The PV system parallels on the utility side of residential service meters and enters the utility grid through a separate utility meter mounted next to the house utility meter.

The 1994 PV Pioneer systems were supplied by two contractor teams for a total of 134 systems and 472 kW. Solec International, Inc supplied 109 3.7 kW systems with Omnion invertors at a turn-key cost of $6.23/W (figure 4). Resource Management International and Solarex is supplying 25 3.5 kW systems with Pacific invertors at a turn-key cost of $6.98/W. The RMI/Solarex systems contracted for in 1994 are being supplied and installed in mid-1995.

The 1995 PV Pioneer Program also will include an additional 80 4.1 kW systems (329 kW) from Placer/RMI/Solarex using Trace invertors at a turn-key cost of $5.98/W. These systems are to be installed on residential and commercial rooftops in late 1995 and early 1996.

2.3 Customer Attitudes and Response to PV Green Pricing

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. A March 1993 scientific market research survey showed that the people of Sacramento are interested in helping to lead the way to a cleaner, sustainable future. The survey determined the potential participation levels for the general public and "green" consumer (members of Sacramento area environmental groups). The market research showed that:

1) 26% of the general population, and
57% of the "green" population
would be willing to pay a premium price (15%) for PV generated electricity from their rooftops.

2) 49% of the general population, and
77% of the "green" population
would be willing to pay a premium (15%) with rate stabilization of the PV portion.

3) 70% of the general population, and
88% of the "green" population
would be willing to participate in a general "green pricing" program of 1 to 10% of the utility bill to for a "Clean Energy" program District wide (not necessarily on their own roof).

The response of a limited, media effort greatly exceeded expectations with almost 2000 customers volunteering for the first 100 slots with over 600 passing the pre-qualifying screen and agreeing to pay the 15% premium. From this pool, the 100+ PV Pioneers for 1993 were selected. With the restrictive roof requirements, qualifying rooftops have been a much greater constraint to volunteers than the "green fee". SMUD continues to get more volunteers than can be accommodated by the program although on going recruitment is necessary to maintain the needed numbers of qualified sites with appropriate shade-free roofs.

2.4 Commercial Building Sited PV Systems

This project provides for the installation of PV Pioneer systems on commercial rooftops. The first system, started in 1993 and completed in 1995, is a nominal 40 kW, single axis tracking, concentrating PV system uniquely adaptable to roof-top applications installed on the SMUD 59th Street Warehouse. This tracking system has an effective rating of 50 kW, EPF. The system by Solar Energy Applications Corp. (SEA), is a roof mounted single axis tracking, concentrating PV system with a south orientation at a 38 degree pitch. The system uses 10X concentration fresnel lenses focused the PV cells covers 4000 square feet of roof area. The system price of this demonstration project is $7.41/watt, EPF.

The 1994 SMUD PV Program installed flat plate PV Pioneer systems on commercial building roof-tops totaling 144 kW by Solec for $6.25/W. These Commercial PV Pioneers include a 24 kW system on a VFW Hall and a 30 kW system on the Wilton Bible Church (figure 5) and a 18 kW system on the Northridge Church of God. Each requires about 100 square feet of roof area for each kW.

2.5 Building Integrated and Parking Lot Sited PV Systems

The 1994 PV Program installed a 3 kW building integrated PV demonstration system in partnership with the Western Area Power Administration (WAPA). The PV systems is integrated in the reroofing structure installed on a WAPA office building. The PV roofing tile system is part of the roofing system installed to insulate and protect the roof membrane. The "Powerguard" PV system in being designed and installed by Powerlight Corporation and Western Single Ply, a commercial roofing contractor.

In 1994, the lowest bid received by SMUD for a parking lot sited PV system was for nearly $10/W. While the development of parking lot air space for PV energy production is of very high priority to SMUD (and especially important in urban/suburban areas) the price was too high. In 1995 Utility Power Group will supply and install a 158 kW, EPF parking lot sited PV system. This system is a single axis tracking system and costs $6.36/W, EPF.

2.6 Substation Sited, T&D PV Systems

The 1993 project installed a 258 kW, EPF (210 kW nominal) ground mount, single axis tracking PV system at the SMUD Hedge Substation. The installation of this PV system demonstrated the ability and versatility of placing medium size PV systems for District distributed generation benefits. The system is located at the Hedge Transmission and Distribution training yard and connected to the 12kV distribution system. The system was designed and installed by Utility Power Group (UPG) and is a single axis tracking 258 kW, EPF PV generation plant. SMUD provided the site preparation and utility grid interconnection. The turn-key system price was $7.70/watt (nominal) compared to $8.90/watt for the PG&E 500kW Kermin PV plant completed in Spring 1993. The system (figure 3) is a ground mount, flat plate, single axis tracking system utilizing Siemens solar modules. A 250 kW Omnion inverter/transformer converts 720 VDC to 12.47 kVAC for grid interconnection. Accounting for the increased production due to tracking (using the Energy Production Factor, EPF) the effective price was $6.26/W AC,EPF. The system was completed in early 1994.

Three additional PV power stations at the Hedge site totaling an additional 317 kW were installed under the 1994 program and completed in 1995. Bell Products, Inc and Advanced Photovoltaic Systems, Inc. supplied a fixed, 108 kW system using the APS thin-film module and a Kenetech invertor at a cost of $6.68/W. Resource Management International and Solarex supplied a fixed, 102 kW system using Solarex modules and a Kenetech invertor at a cost of $7.35/W. Utility Power Group and Siemens Solar supplied a 132 kW, EPF (107 kW nominal) single axis tracking system using Siemens modules and multiple UPG invertors at a cost of $7.50/W, nominal or $6.10/W EPF.

The 1995 substation PV project will be a 263 kW, EPF (214 kW nominal) single axis tracking system by Utility Power Group. This system has a turn-key price of $5.71/W, EPF ($7/W nominal).

2.7 1993 - 1995 SMUD PV Program Cost Improvements

The 1994 SMUD PV Program systems showed substantial cost improvements over the 1993 projects. This improvement has continued into 1995. This is true both for the turn-key contract costs as well as for the costs incurred by the utility to develop, procure, administer, and preform the Utility side of the systems installation and integration into the grid, as can be seen in the following table for the residential (RES) and substation (SUB) systems.

1993 - 1995 SMUD PV COST IMPROVEMENT

PROJECT-YR	TURN-KEY COST[1]	SMUD[4] ADD COST	TOTAL COST	30 yr ¢/kWk[5,6]
SUB - 1993[2]	$6.26/W	$3.89/W	$10.15/W	32¢
SUB - 1994[3]	$6.68/W	$1.07/W	$ 7.75/W	21¢
SUB - 1994[2]	$6.10/W	$0.87/W	$ 6.97/W	19¢
SUB - 1995[2]	$5.71/W	$0.91/W	$ 6.62/W	18¢
RES - 1993[3]	$7.70/W	$1.08/W	$ 8.78/W	23¢
RES - 1994[3]	$6.23/W	$0.90/W	$ 7.13/W	20¢
RES - 1995[3]	$5.98/W	$0.89/W	$ 6.87/W	18¢

[1] Turn-key contract cost up to utility interconnection without tax, bonding or utility add-on costs.
[2] Single axis tracking system. Includes credit for Energy Production Factor (EPF) [for single-axis tracking, EPF = 1.23 compared to fixed tilt].
[3] Fixed, non-tracking system, EPF = 1.00
[4] Includes: interconnections, metering, site preparation, District labor, administration, overheads, tax, bonding, AFUDC, and other costs.
[5] Includes: O&M, does not include DOE cost-share.
[6] Preliminary estimate.

2.8 The Roof-top Resource

In metropolitan areas, hundreds of thousands of square acres of residential and commercial roof area, parking lots and transmission corridors are setting unused in the sun. As Skip Fralick of San Diego Gas & Electric Company pointed out, "This rooftop area is the equivalent of "free land" for photovoltaic generation: it needs no development, environmental impact statements, or extensions of transmission lines." In Sacramento alone, these south to west oriented roofs, parking lots and transmission corridors represents the potential of hundreds of megawatts of photovoltaic resource.

Power plant siting is normally a troublesome, time consuming and expensive exercise, especially in a suburban or urban area. However, over the past two years, SMUD has sited about 250 PV power plants all across Sacramento with little trouble or expense. Indeed, hundreds of customers have paid extra on their utility bill to host a SMUD PV power plant on their roof. This ease of siting combined with the environmental, modular and distributed benefits of PV add substantially to the value PV brings to the utility's energy mix.

3. A UTILITY PERSPECTIVE ON PV COMMERCIALIZATION

There is a critical need to accelerate and complete commercialization of PVs to meet our needs for grid-connected, utility applications for year 2000 and beyond. Without a concerted and collaborative effort we can not assume that PVs will be ready to serve the utility market when we will need it. Our actions today are our investments for tomorrow.

The off-grid, "currently cost-effective" PV applications are not sufficient to commercialize and make cost-effective the grid-connected, utility PV applications. We must continue the process of the grid-connected market development directly. These grid-connected applications have value beyond energy and capacity and include residential and commercial customer sited PV for distributed generation and DSM applications and substation/T&D sited PV for grid-support value.

There are three central concepts necessary to achieve the production levels and cost reductions required for the accelerated commercialization of photovoltaics for utility systems:

- ☼ Sustained Orderly Development (SOD)
- ☼ Commercialization path life-cycle costing
- ☼ Proactive leadership to stimulate early adoption

3.1 Sustained Orderly Development (SOD)

The solar industry needs a reliable and long-term market volume to develop and achieve long-term cost reductions required for full commercialization. Current "cost-effective" utility markets have not provided sufficient market volume to accelerate commercialization. Demonstration and R&D projects alone do not accelerate the commercialization of new technologies. In fact, large, one-time purchases tend to dry up supply (and thereby increase price) without stimulating the increase in production capacity necessary for manufacturing cost reductions. Furthermore, manufacturers do not rely upon short term subsidies, mandated purchases, or set-asides in making investment decisions because these programs create "false markets." A combination of aggressive price reductions and commitments for substantial and sustained capacity acquisition is required for full commercialization of these technologies. Sustained orderly development and economies of scale for solar electric systems will result in the rapid development of a mature, cost-effective solar industry.

3.2 Commercialization Path Life-Cycle Costing

Technology development (or commercialization path) life-cycle costing, and not just "project" life-cycling costing, needs to be used. It is important to analyze total expenditures and total acquired capacity over the entire commercialization path. Higher costs for early applications can be a good investment if they contribute to accelerating the trend towards lower costs and higher performance (figure 6). When solar investments are selected carefully and in collaboration with other stakeholders in renewable energy development, they can be among the wisest and, ultimately, the lowest risk investment that can be made, despite their higher initial capital costs.

3.3 Proactive Leadership to Stimulate Early Adoption

Sustained orderly development and accelerated commercialization will not occur early relying just on natural market forces. Accelerated commercialization won't occur just by demonstration projects and watching the cost curve. Utilities and other potential bulk purchasers must commit to an early and sustained series of substantial buys to permit the industry to invest in expanded production and automation. The "diffusion model" of PV commercialization where high value applications are identified and filled, then the next value level developed is an important starting point. It does not, however, result in a sufficient aggregation of order commitments to allow the needed expansion of production. Instead, utilities play their role in commercialization of grid-connected applications. Utilities need to make multi-year commitments for substantial and continuing, multi-megawatt per year purchases.

While these first increments of PV may not be cost effective on their own, they represent a beginning of a cost effective process. Support by the other stakeholders in the process, especially by other utilities, the regulators and a reliable DOE shared risk is required on a sustained, multi-year basis to close the early cost-value gap and make the process work. The utility community has taken the responsibility to get this process underway now and to work with regulators, customers and other stakeholders to make it successful. The national Utility PV Group (UPVG, now up to 90 utility members) has announced the first awards under TEAM-UP. Project TEAM-UP, provides the initial part of a sustained, orderly development process with a target of 50 MW of utility PV purchases over a four year period. Under this proposal the USDOE would provide only about 30% of the estimated $513 million program. As Andrew Vesey, Chairman of the UPVG Board of Directors and Vice President of Niagara Mohawk Power Corporation stated:

> *While TEAM-UP's partners may greatly help to underwrite today's "cost gap", only the federal government can close it. Critically, this federal support must also be* <u>*sustained*</u>*. Funding assurance is essential for gaining market and supplier commitments, gearing up and implementing the program, verifying the march down the cost curve, and establishing the federal government as a reliable partner throughout the entire commercialization process.*

The successful, accelerated commercialization of utility PV applications will need to be a collaborative effort of many participants. Utilities, State and Federal agencies and other stakeholders must join together. If manufacturers do not continue to respond with aggressive forward pricing, if utilities do not implement substantial, sustained purchases, if DOE does not provide a reliable and predictable multiyear costshare absorbing a part of the early risk and if other stakeholders do not proactively support the commercialization process, this process won't succeed.

4. PV COMMERCIALIZATION COST CURVE

Photovoltaics (PV) offer many advantages as distributed generation systems, both as a supply side option and as a demand-side management (DSM) option. PV's are the most modular and operationally simple of the clean, distributed power technologies. From 1972 to early 1992, PV module costs have been reduced 100-fold. The strategic, competitive advantages of PVs will continue to increase as this cost trend continues.

Despite tremendous price decreases, PV is still too costly for most grid-connected applications. In addition, cost-effective storage and the related problem of intermittency of the solar generated electricity continue to limit PV utility applications. Significant RD&D efforts are underway nationally to develop more efficient batteries and other electricity storage methods that will help to resolve the storage and intermittency problems. The problem of cost is being attacked on several fronts. New PV materials and designs are being developed to improve efficiency and reduce manufacturing costs and niche markets are being developed and exploited to continue the initial phases of commercialization. Indeed, the current level of production capability is all but sold out for remote applications, consumer devices and third world applications.

To achieve the next series of price reductions, firm utility scale markets must be generated and sustained to encourage the investments needed in new technology and production. Utilities can play a leading role in accelerating the further commercialization of PVs through assisting the development of utility PV markets. This effort can reap benefits for our customers by the resulting improvements in PV systems, distributed generation support to our system and accelerated reductions in PV costs.

Residential "rooftop" systems in the 2 to 4 kW range were costing about $15/W installed in 1992. Substation applications were costing about $10/W. The SMUD 1993 PV projects cost about $7.70/W and for the 1994 PV projects averaged about $6.44/W with a low of $6.10/W. The 1995 projects, despite constrained PV module supplies, have continued tracking down the accelerated commercialization cost curve with prices as low as $5.71. With a sustained, widespread collaborative effort, one could expect prices to drop below $3/W by about the turn of the century. Figure 6 summarizes SMUD's analysis of the TEAM-UP commercialization plan. It shows the levels of purchase needed by utilities over this decade and the expected results of a sustained orderly development process on the utility PV market based on a number of market studies by the PV industry, analysis by SMUD, UPVG and others and from sources from DOE and the national labs.

In 1993 SMUD implemented its commitment to a sustained orderly development effort starting with the 640 kW of grid-connected utility PV systems and a 5 year program of yearly PV Pioneer and T&D buys. This 5 year program leads to a 5 year period starting in 1998 where SMUD will purchase about 10 MW per year of renewable energy resources including PV. It is expected that this multi-year effort would involve the establishment of a new PV manufacturing facility with part of it's production dedicated to the multiyear, multimegawatt utility commitment. This is especially important since it is generally agreed that "ramping up" to commercial scale PV production for utility applications cannot be at few kilowatts at a time, but rather in annual sales in the multimegawatt range. These orders need to have continuity and be steadily increasing. Early utility industry orders and PV production increases need to be in the range of 2-5 MW/year, and they must quickly (within 2-3 years) reach 10 MW/year and 50-100 MW/year nationwide by the end of this decade. While the efforts of a few utilities, such as SMUD, can achieve some initial reductions of price, the needed cost reductions for commercialization will require a much broader effort. The level of response to the 1995 TEAM-UP program is indicative that this level of commercialization can be maintained given only modest - but sustained - DOE shared-risk. These efforts, supported by all the stakeholders in the PV commercialization process, will be necessary if PVs are to achieve the cost reductions needed to meet our needs in a reasonable time-frame.

During 1995, the District will continue its efforts to accelerate the commercialization of grid-connected PV applications and to define and compare the relative costs and benefits of the various models of utility PV applications including the issues of systems ownership, shared risk and benefits, levels of T&D benefits and the general issue of the appropriate accounting for all the value of distributed generation. This information will be used to update the analysis of PV benefit/cost as part of the integrated planning process.

5. COLLABORATIVE PV COMMERCIALIZATION

To succeed in accelerating the commercialization of grid-connected utility PV applications, the commercialization process must truly be a collaborative effort. The PV industry needs to nurture the grid-connected, utility market. They need to aggressively forward price to foster this developing market and to enable utilities to field systems. They need to look at investing in this market development now to create a profitable market for the future. Utilities need to proactively assist in developing a substantial, growing and sustainable grid-connected utility PV market. They need to aggressively account for the non-traditional benefits of distributed PV generation and maximize what they can afford to invest in early systems to accelerated the cost reduction and commercialization of grid-connected PV. Regulators need to recognize that the long term best interests of the ratepayer will be served by permitting and encouraging modest early investments in higher cost PV today when these investments will lead to earlier and greater cost reductions of PV for the future. They need to account for societal and economic development benefits and the benefit of commercializing a source of "green and inflation-proof" energy. The Federal government needs to share the risk by helping to fill the cost-value gap, a gap declining as commercialization moves forward, between how high utilities and regulators can value PV benefits and how low the PV industry can forward price grid-connected PV systems. Each party needs to analyze their investment for a "commercialization-path" life cycle cost rather than a project-by-project basis. This process must be developed as a sustainable, orderly development of the market in a way that the PV industry can invest with confidence in new processes and manufacturing lines to lower costs and that utilities and their regulators can see accelerated and continuous progress to cost-effectiveness.

Efforts such as the Utility PhotoVoltaic Group's Project TEAM-UP with the USDOE and the PV4U collaborative state working groups offer the framework to make this collaborative commercialization of the grid-connected, utility PV market succeed.

As was stated in Time Magazine of October 18, 1993:
Some of the biggest boosters of solar power are bound to be utility companies, eager for a clean source of electricity that will enable them to produce more power without new billion-dollar plants.

Both as consumers of solar technology and as the promoters of home solar panels, utilities will drive much of the industry's growth into the next century. "Utilities are beginning to realize that they're going to have to get on the solar bandwagon, says S. David Freeman, (former) general manager of the Sacramento Municipal Utility District (SMUD). "If they don't and rates go up sharply, people are going to buy their own solar panels and pull the plug on the utilities." ... "Solar is competitive now if you take the long view. And it's going to be highly competitive by the end of the decade."

The use of solar energy has many benefits to utilities, the our local communities and the country in general. Solar technology reduces the use of non-renewable resources. It is a renewable and sustainable energy source and helps improve air quality. PV power generation systems are clean, quiet and environmentally beneficial. They use no fuel and have no emissions. Each MW of PV power generated by a plant with a 25% capacity factor, will eliminate the production of more than 20,000 tons of carbon dioxide and more than 25 tons of NOx during its life as compared to the cleanest fossil fuel plants available for purchase today. Solar electric systems stimulate economic development and employment opportunities to a much greater extent than conventional energy sources. They represent a source of diversified, inflation-proof energy. For all these reasons, PV represents an energy supply that utility customers are demanding. The question is, do we have the national will to make a modest but sustained commitment to the investment in our future that will make this a cost-effective and substantial part of our national energy mix in the timeframe that we need.

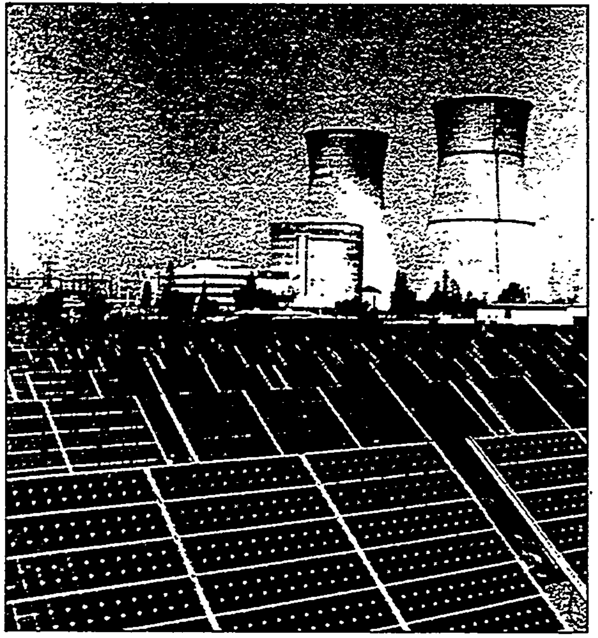


Figure 1. SMUD's 2 MW PV generating station at site of the closed Rancho Seco nuclear plant. Established 1984.

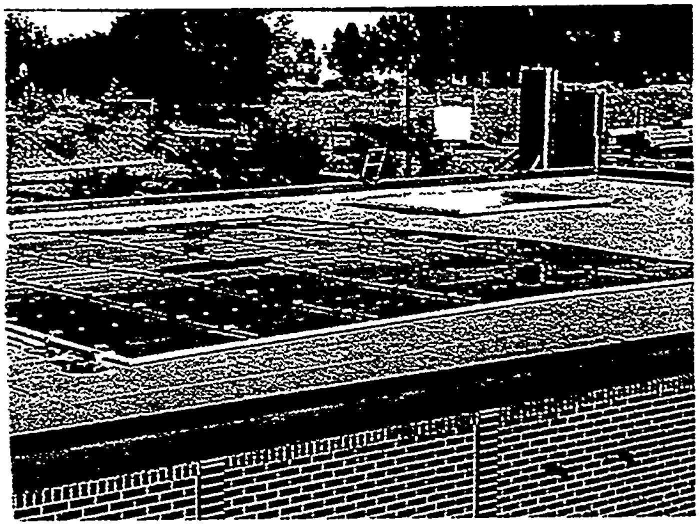


Figure 2. SMUD/WAPA Building Integrated 3 kW PV Roofing System

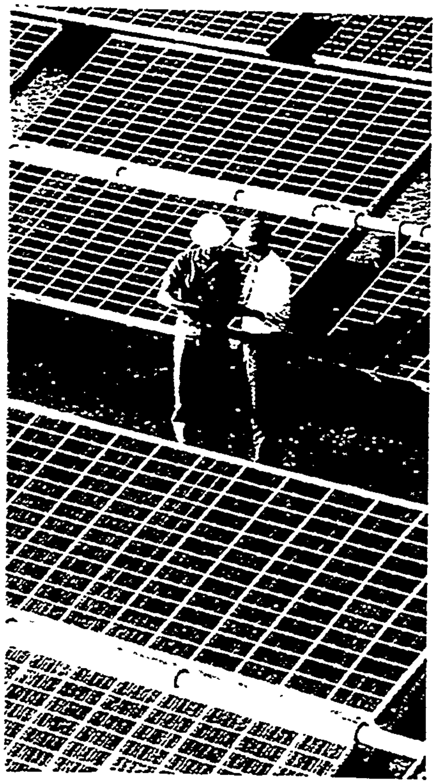


Figure 3. 200 kW SMUD Hedge Substation PV system.

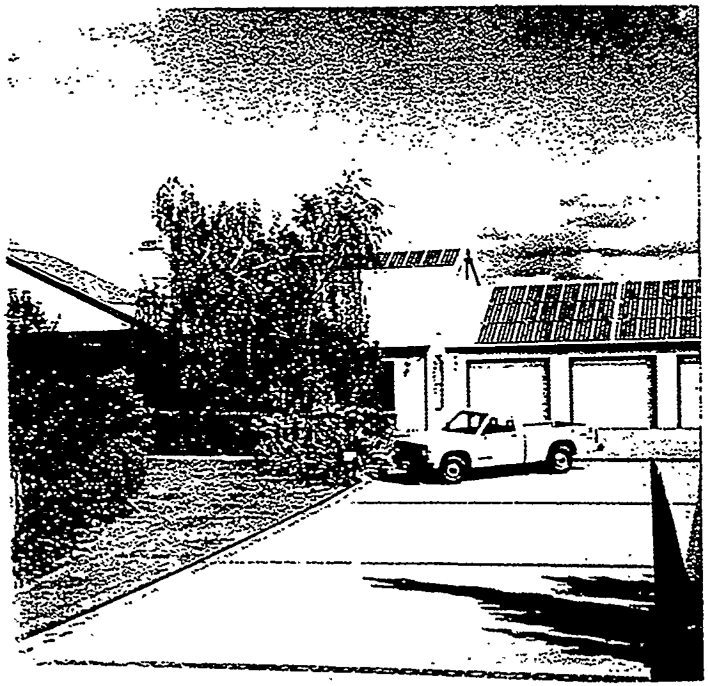


Figure 4. SMUD Residential PV Pioneer (2 Systems).

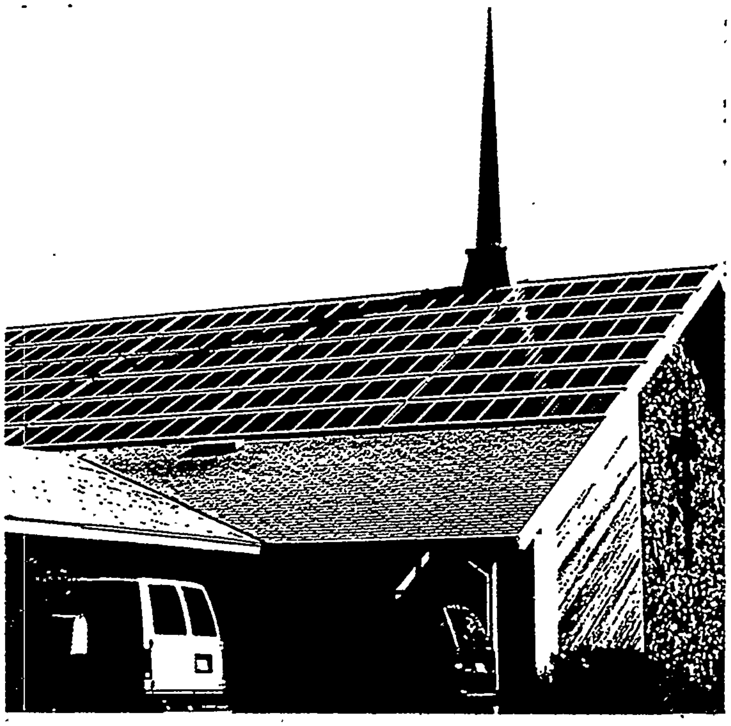
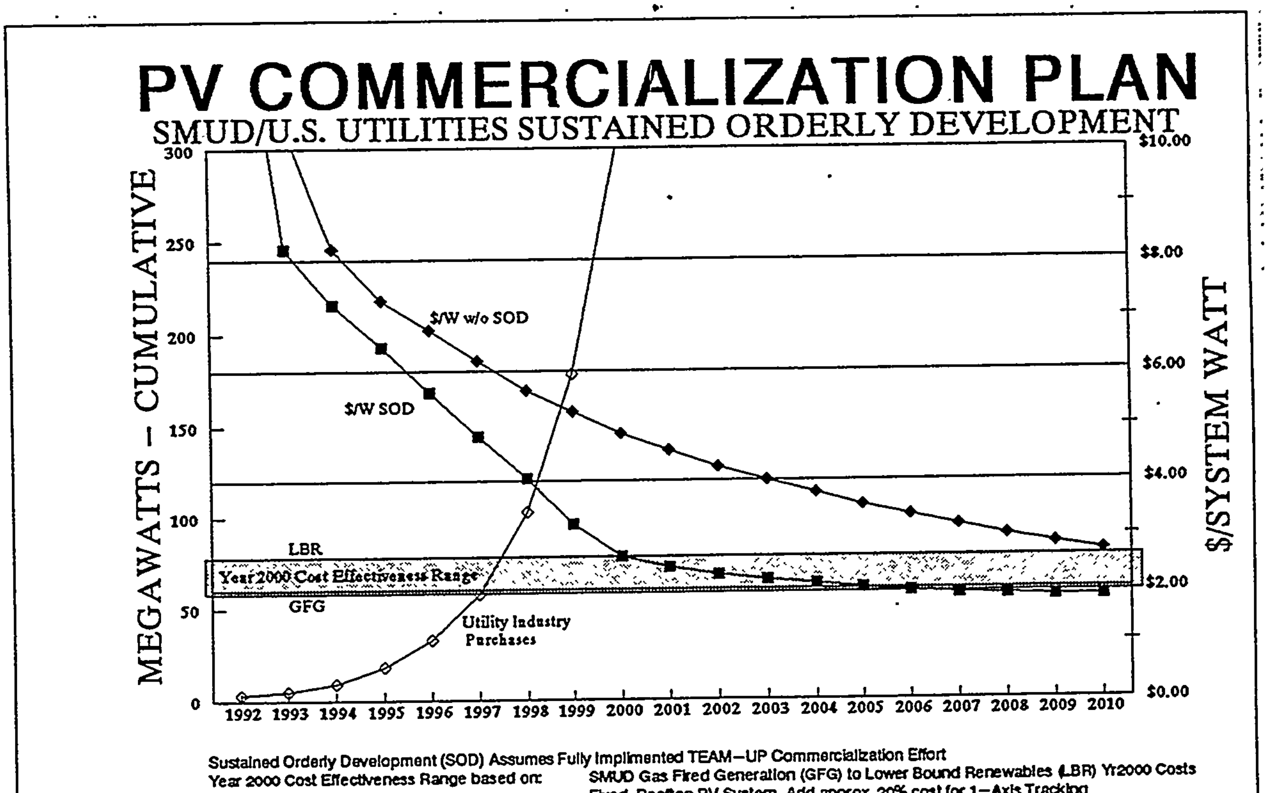


Figure 5. 30 kW Wilton Bible Church Commercial PV Pioneer System.



Sustained Orderly Development (SOD) Assumes Fully Implimented TEAM–UP Commercialization Effort

Year 2000 Cost Effectiveness Range based on: SMUD Gas Fired Generation (GFG) to Lower Bound Renewables (LBR) Yr2000 Costs
Fixed, Rooftop PV System. Add approx. 20% cost for 1–Axis Tracking
Turn–Key System Prices (Total Project Cost Less Utility Add–on Costs)
Does not include some non–traditional benefits such as Distributed Benefits

Prices ($/W) are Turn–Key System Prices Up To Meter, AC, PTC, 30 year life. Includes Installation and Tax. Does Not Include Utility Add–on Costs.
Real 1994 $

PVSOD5D.WK3

Figure 6. Utility PV Commercialization Cost Curve

Utility-Scale System Preventive and Failure-Related Maintenance

Christina Jennings
Pacific Gas & Electric

Paul Hutchinson
Endecon

NREL PV Performance and Reliability Workshop
September 7-8, 1995

Presentation Objectives

Provide design and performance background on PVUSA utility-scale systems at Davis and Kerman, California

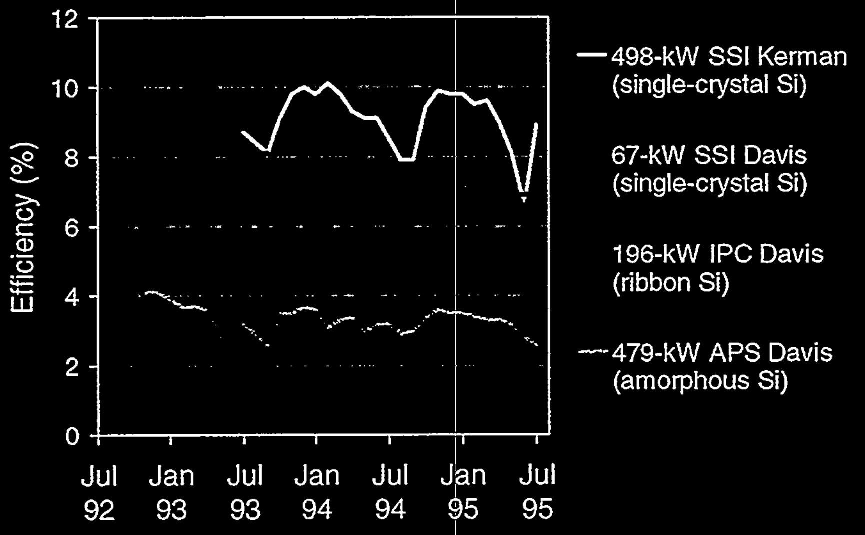
Report preventive and failure-related maintenance approach and costs

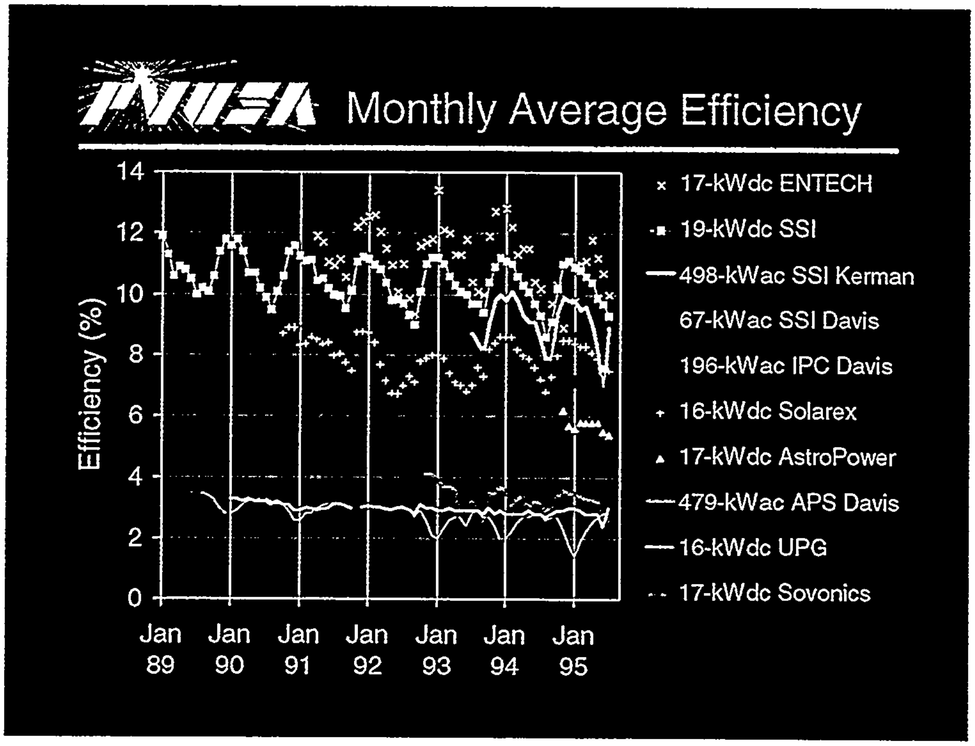
Davis and Kerman US Systems

PV System	**Technology**
479-kW$_{ac}$ APS Davis	9,600 APS amorphous Si modules, fixed 30° tilt, 4 APS PCUs
196-kW$_{ac}$ IPC Davis	1,100 Mobil Solar ribbon Si modules, 1-axis active tracking, 1 Omnion PCU
67-kW$_{ac}$ SSI Davis[a]	3,968 SSI single-crystal Si modules, 1-axis passive tracking, 2 BluePoint PCUs
498-kW$_{ac}$ SSI Kerman	12,240 SSI single-crystal Si modules, 1-axis passive tracking, 2 Omnion PCUs

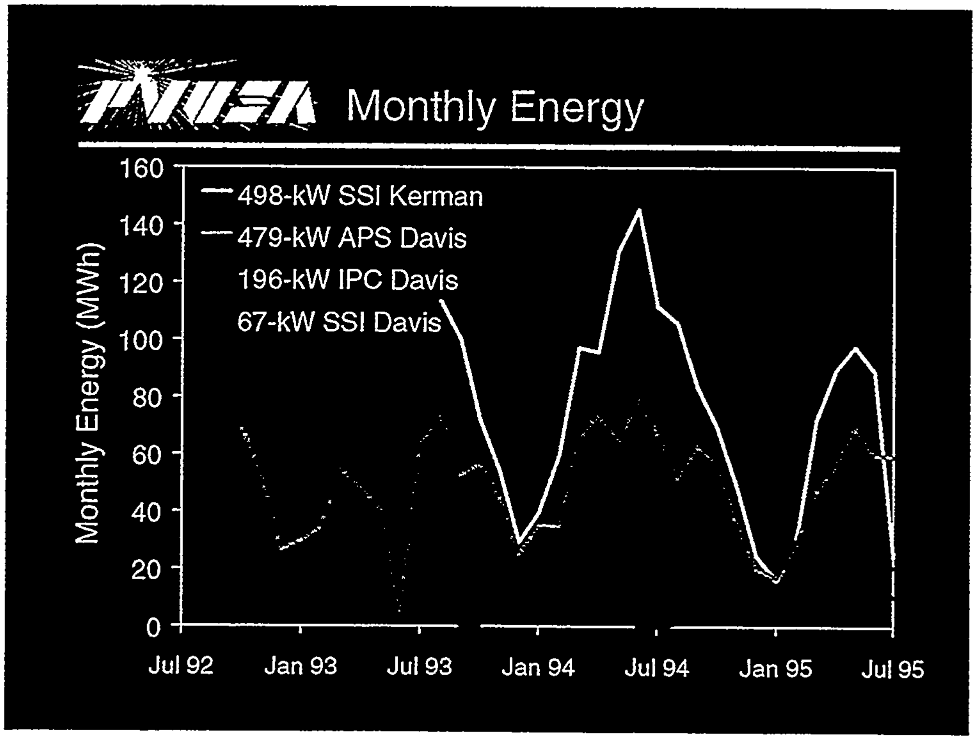
[a] *Based on 50% of the installed array; one PCU is not operational.*

Monthly Average Efficiency





Monthly Average Efficiency

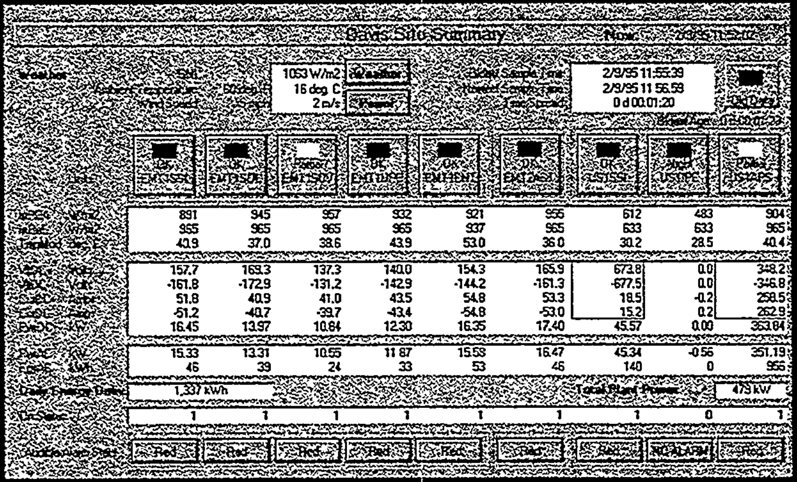


Monthly Energy

System Maintenance Approach

- Procedures detailed in PVUSA Davis and Kerman PV Plant O&M Manuals and summarized in 1993 IEEE PVSC paper
- PVUSA complies with system supplier recommendations for preventive maintenance (except for Kerman in 1995)
- Failure-related maintenance balances minimizing downtime, understanding cause
- System status monitored via data acquisition system and visual inspections...

Davis System Status Screen



Davis Site Summary

1053 W/m2
16 deg C
2 m/s

2/9/95 11:55:39
2/9/95 11 56.59
0 d 00:01:20

[illegible] W/m2	891	945	957	932	921	956	612	483	904
[illegible] W/m2	955	965	965	965	937	965	633	633	965
[illegible]	40.9	37.0	38.6	43.9	53.0	36.0	30.2	28.5	40.4
[illegible]	157.7	169.3	137.3	140.0	154.3	165.9	673.8	0.0	348.2
[illegible] Volt	-161.8	-172.9	-131.2	-142.9	-144.2	-161.3	-677.5	0.0	-346.8
[illegible]	51.8	40.9	41.0	43.5	54.8	53.3	18.5	-0.2	258.5
[illegible]	-51.2	-40.7	-39.7	-43.4	-54.8	-53.0	15.2	0.2	262.9
[illegible] kW	16.45	13.97	10.84	12.30	16.35	17.40	45.57	0.00	363.84
[illegible] kW	15.33	13.31	10.55	11.87	15.58	16.47	45.34	-0.56	351.19
[illegible] kWh	46	39	24	33	53	46	140	0	955

Daily Energy [illegible]: 1,337 kWh

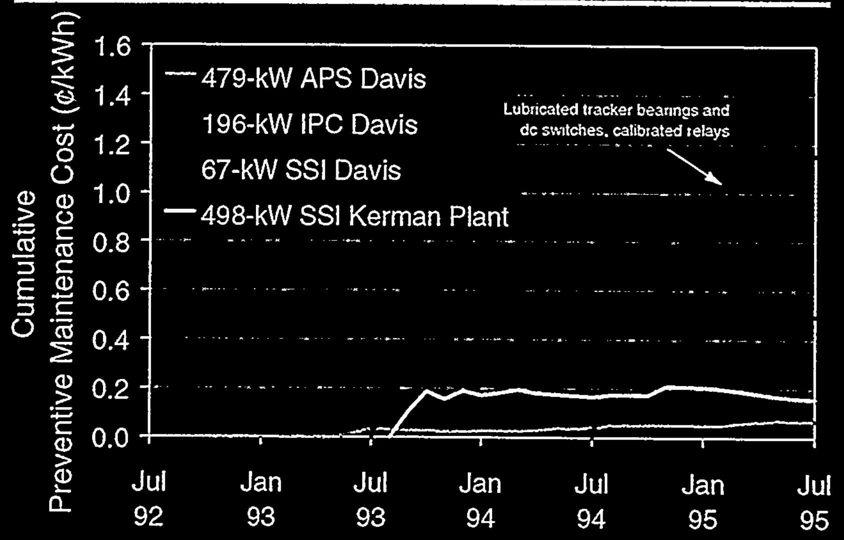
Total Plant Power: 479 kW

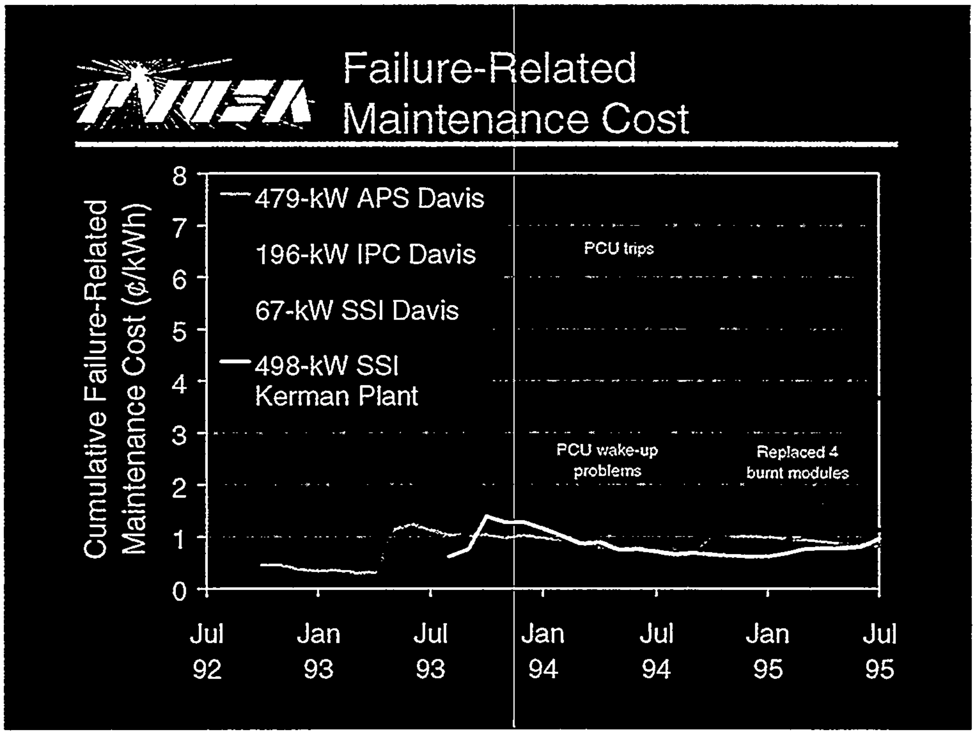
[illegible]	1	1	1	1	1	1	1	0	1
[illegible]	Red	Red	Red	Red	Red	Red	Red	NO ALARM	Red

PVUSA Maintenance Cost Analysis

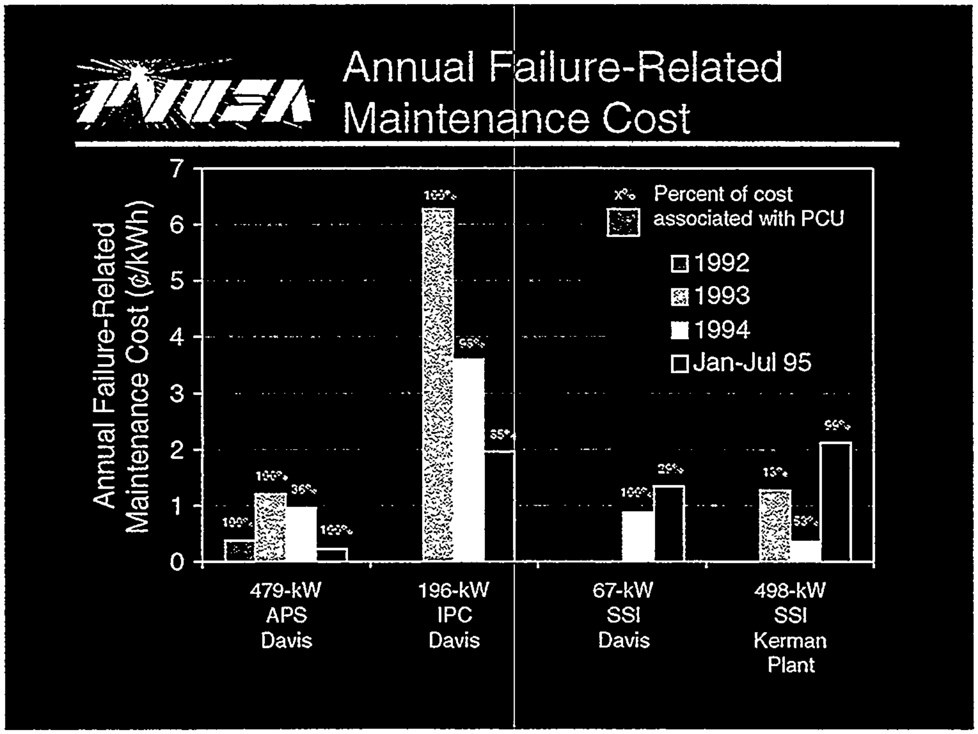
- $50/hour fully burdened labor cost assumed
- Excludes maintenance prior to system acceptance by PVUSA
- Excludes research-related maintenance (e.g., I-V curves, PQ tests, DAS upgrades)
- Excludes travel time and expenses
- Balance-of-plant maintenance costs excluded for Davis, included for Kerman

PVUSA Preventive Maintenance Cost

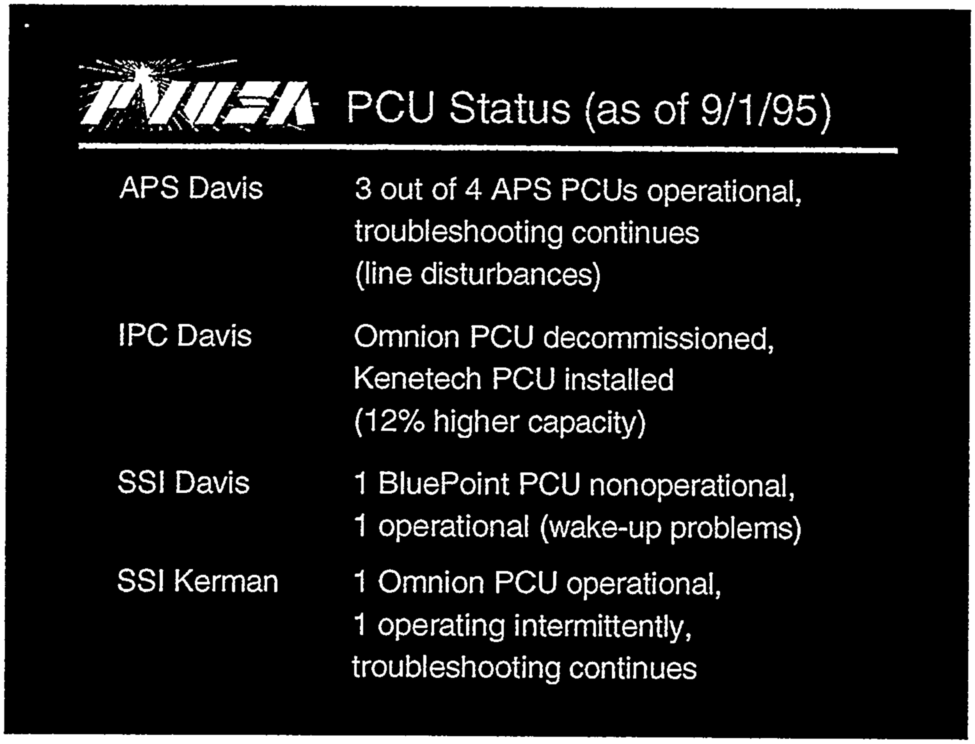




Failure-Related Maintenance Cost

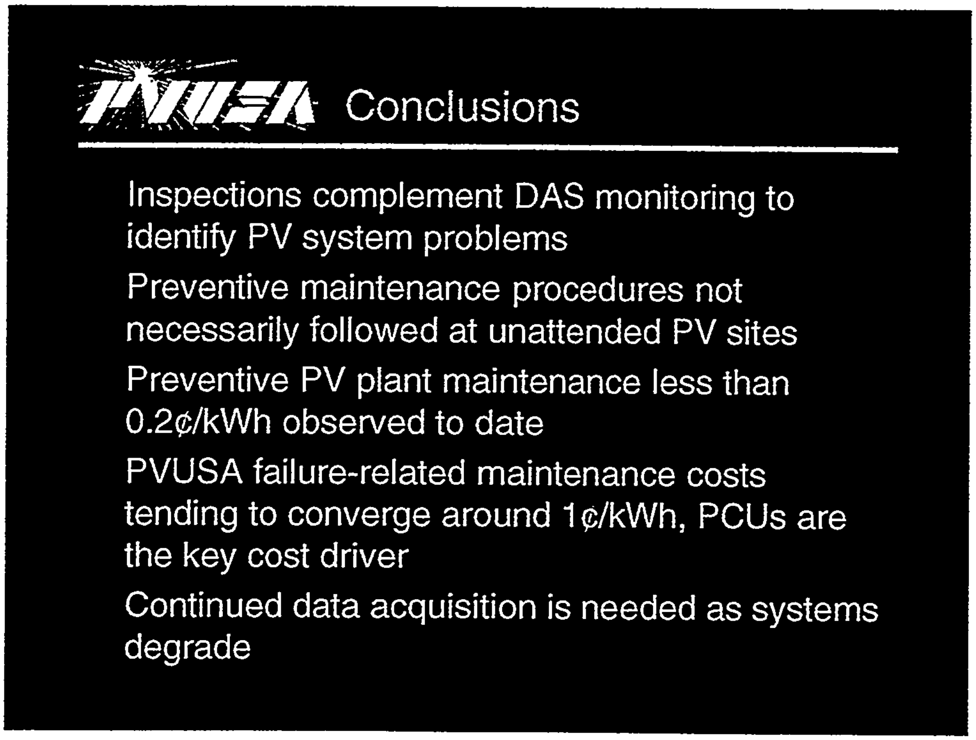


Annual Failure-Related Maintenance Cost



PCU Status (as of 9/1/95)

APS Davis	3 out of 4 APS PCUs operational, troubleshooting continues (line disturbances)
IPC Davis	Omnion PCU decommissioned, Kenetech PCU installed (12% higher capacity)
SSI Davis	1 BluePoint PCU nonoperational, 1 operational (wake-up problems)
SSI Kerman	1 Omnion PCU operational, 1 operating intermittently, troubleshooting continues



Conclusions

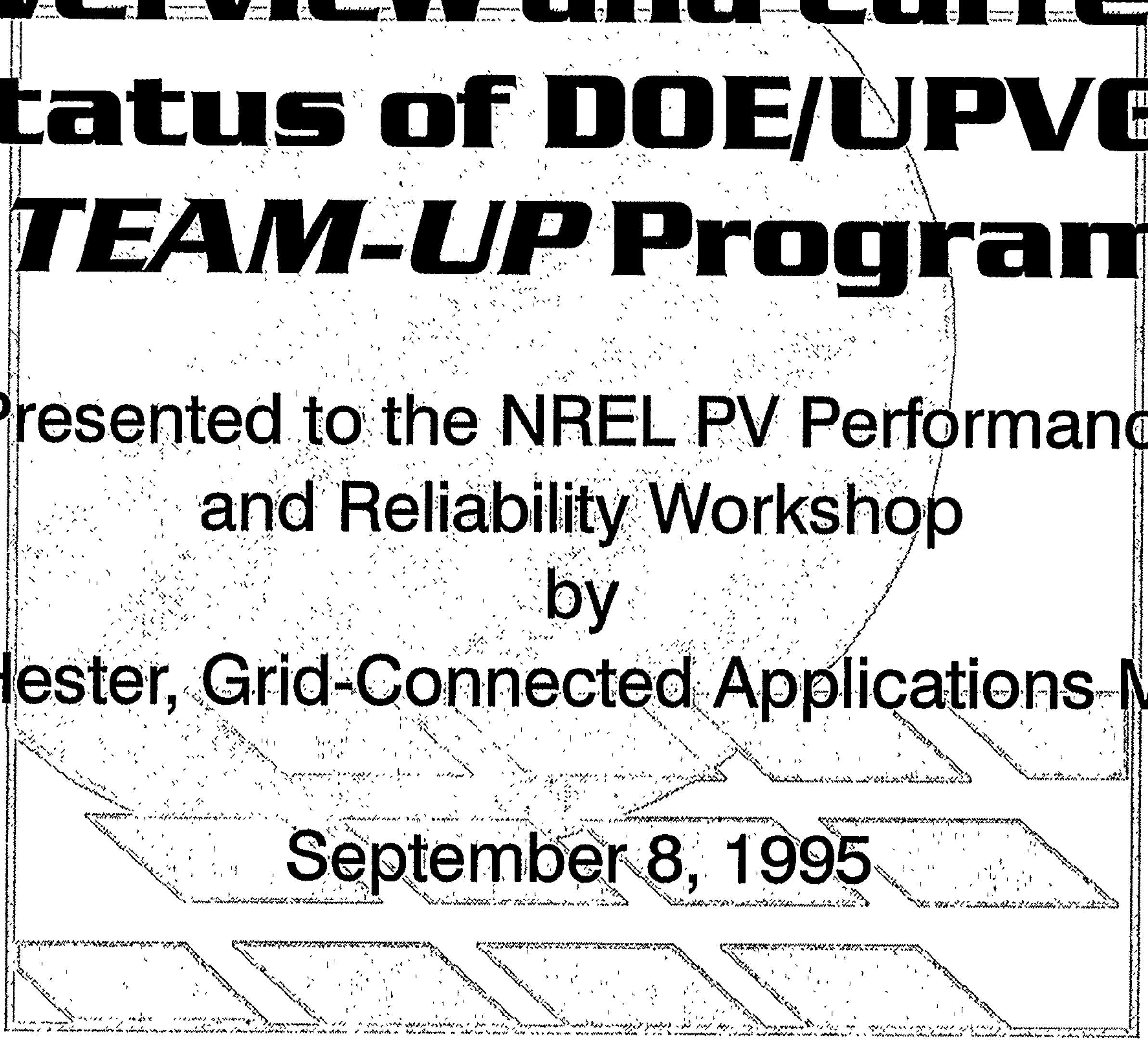
Inspections complement DAS monitoring to identify PV system problems

Preventive maintenance procedures not necessarily followed at unattended PV sites

Preventive PV plant maintenance less than 0.2¢/kWh observed to date

PVUSA failure-related maintenance costs tending to converge around 1¢/kWh, PCUs are the key cost driver

Continued data acquisition is needed as systems degrade



Overview and Current Status of DOE/UPVG's *TEAM-UP* Program

Presented to the NREL PV Performance
and Reliability Workshop
by
Steve Hester, Grid-Connected Applications Manager

September 8, 1995

Utility PhotoVoltaic Group

Mission

To accelerate the use of small-scale and large-scale applications of photovoltaics for the benefit of electric utilities and their customers.

Utility PhotoVoltaic Group

88 Utility Members

- All Utility Classes
  - Investor Owned Utilities (IOU)
  - Public Power (PP)
  - Rural Electric Cooperatives (REC)

- Work Groups
  - Technology Transfer & Member Development
  - Commercialization Strategies & Markets
  - Planning and Evaluation
  - Engineering & Specifications

Utility PhotoVoltaic Group

UPVG Activities

- *TEAM-UP*
  - Grid-Connected Applications Program
  - Small-Scale Applications Program

- **Work Group Activities**
  - Workshops
  - Training
  - Education

Utility PhotoVoltaic Group

Small-Scale Applications Opportunity Notice

- Grid-Independent PV Applications

- Market Aggregation
  - Lower Cost Systems
  - Better Engineered Packages
  - Greater Volume
  - More Information Dissemination
  - Development of Infrastructure

- 6-8 Applications Targeted (2MW each)

- First Opportunity Notice Issued - May 1995

Utility PhotoVoltaic Group

Small-Scale Applications Opportunity Notice

- Market Development/Buyers Groups
- Funding NOT for Equipment Purchase
- Support to Develop Collective Market Actions Leading to Sustainable Markets
- UPVG Funding for the Formation and Implementation of Market Development Groups

Utility PhotoVoltaic Group

TEAM-UP Grid-Connected Award Package

- $36.4 Million of Projects Accepted
- 23 Utilities Involved
- 10 or More PV Technologies/Suppliers
- 4 or More Power Conditioner Suppliers
- 14 States Slated for Installations

Utility PhotoVoltaic Group

Selected *TEAM-UP* Package

- 7.6 MW Total
- Systems Sizes Range From 1kW to 5 MW
- Potentially 340 Individual PV Installations
- Price Range of $1.75 to $20.67 per Watt

TEAM-UP **Awards**

- **New World Power Corporation**
  - Building integrated, curtain wall, delta tracker
- **Amoco/Enron Solar Power Development**
  - 5 MW IPP connected to SDG&E system
- **Arizona Public Service Company**
  - Amonix concentrator, PV parking, T&D support
- **Ascension Technology, Inc.**
  - 8 utilities, PV Friendly residential/commercial
- **CUPV/Sacramento Municipal Utility District**
  - 7 utilities, residential/commercial, T&D support, DSM
- **Empire Electric Association**
  - T&D support
- **Hawaii Electric Light Company**
  - Commercial building
- **Niagara Mohawk Power Corporation**
  - T&D support with battery

Additional *TEAM-UP* Awards

- **ENTECH, Inc.**
  - 22X concentrator, 1.2 kW systems located at Northern States Power and City of Austin
- **Gainesville Regional Utilities**
  - 10 kW array powering and existing substation UPS
  - Financial support from their "Green Fund"
- **Natural Environments**
  - 13 kW commercial roof-top system & 7.4 kW ground-mount array
  - Little Rock, AR library
- **Solar Engineering Applications, Corporation**
  - 15X concentrator, 8 kW systems installed at museums
  - New York, NY; Durham, NC
- **UtiliCorp United/Nevada Power**
  - 20 residential/commercial 4kW systems
  - Pueblo, CO and Las Vegas, NV

Selected *TEAM-UP* Package

- **Ten Potential Technologies/Suppliers**
  - **single-crystal silicon**
  - **multicrystalline silicon**
  - **polycrystalline silicon**
  - **amorphous silicon (3 suppliers)**
  - **low and high concentration silicon**

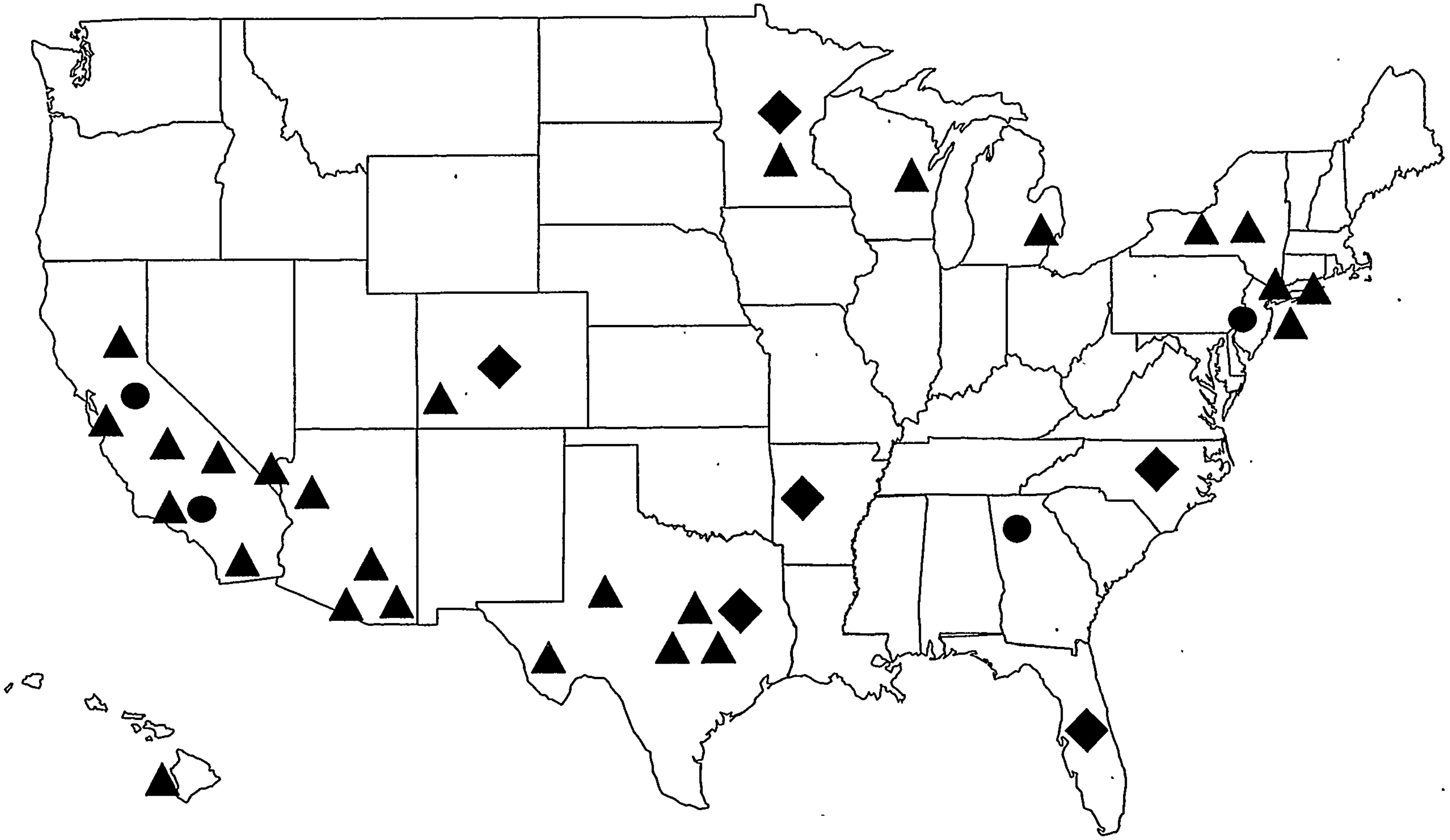
- **Four or more Inverter Suppliers**

Selected *TEAM-UP* Package

● *TEAM-UP* Precursor Projects

◆ New *TEAM-UP* Utilities

▲ *TEAM-UP* Proposed Site



Utility PV Interest Stimulated by UPVG

- Many utility programs started or increased due in part to the UPVG
  - Southern Cal Edison, Niagara Mohawk, SMUD, Detroit Edison, Arizona Public Service Co., City of Austin, City of Anaheim, Wisconsin Public Service, Hawaii Elec. Light, UtilitiCorp, Nevada Power, New York Power Authority, and several others

- UPVG's "value" related to technology experiences, market and application identification, and customer/utility partnership potential given as reasons for increased PV efforts

Utility PhotoVoltaic Group

Utility PV Interest Stimulated by UPVG

- World-wide interest in the UPVG's member efforts
- Business opportunities recognized due to increased visibility of utility PV
- International market demand seen as cost reduction driving force and makes PV a "serious" utility/customer service option

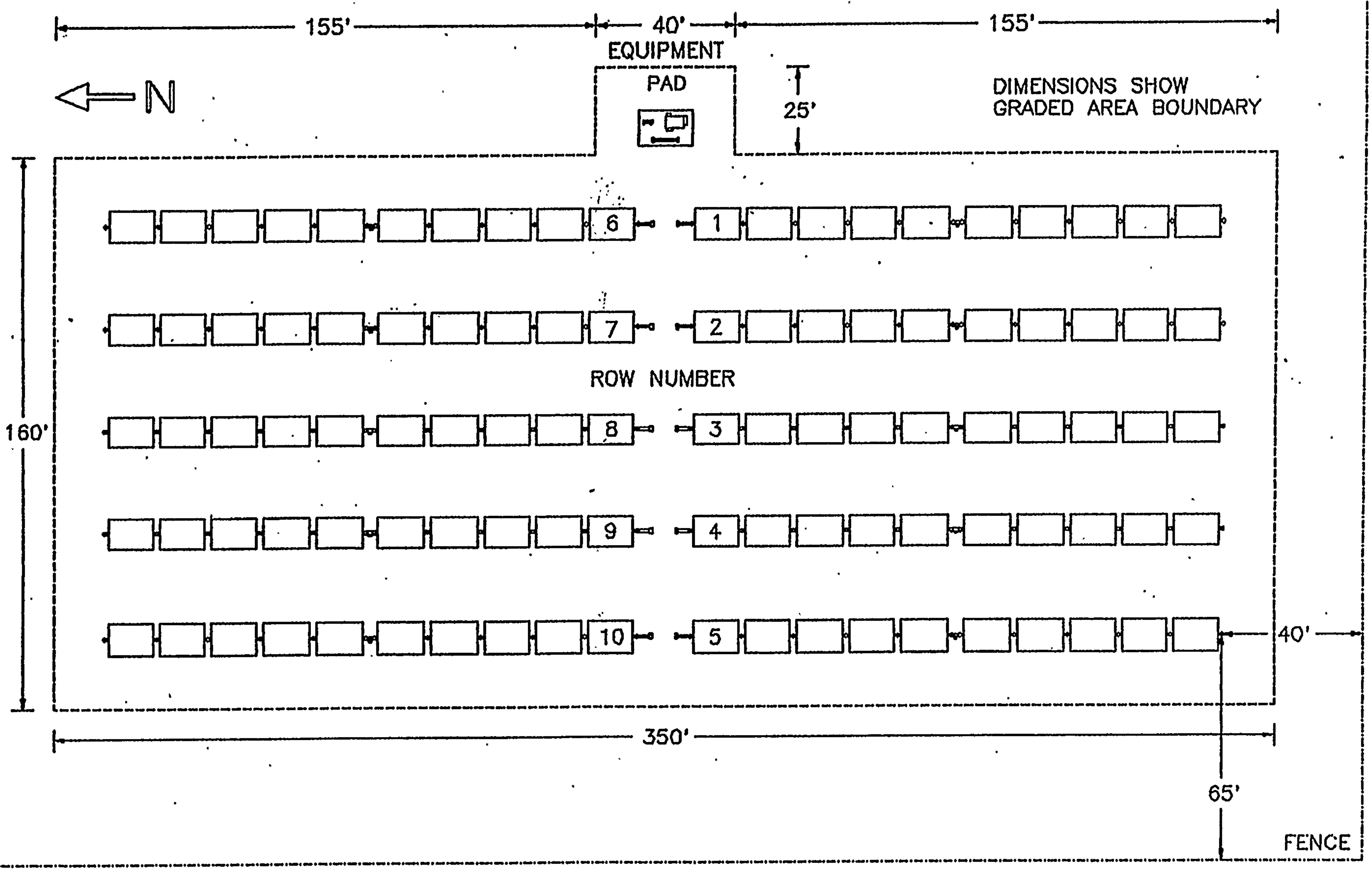
Experiences with Utility-Scale PV Systems

Brian Champion
Central & South West Corporation

DWG # STA001-REV B

PHOTOVOLTAIC SYSTEM LAYOUT, 100KW

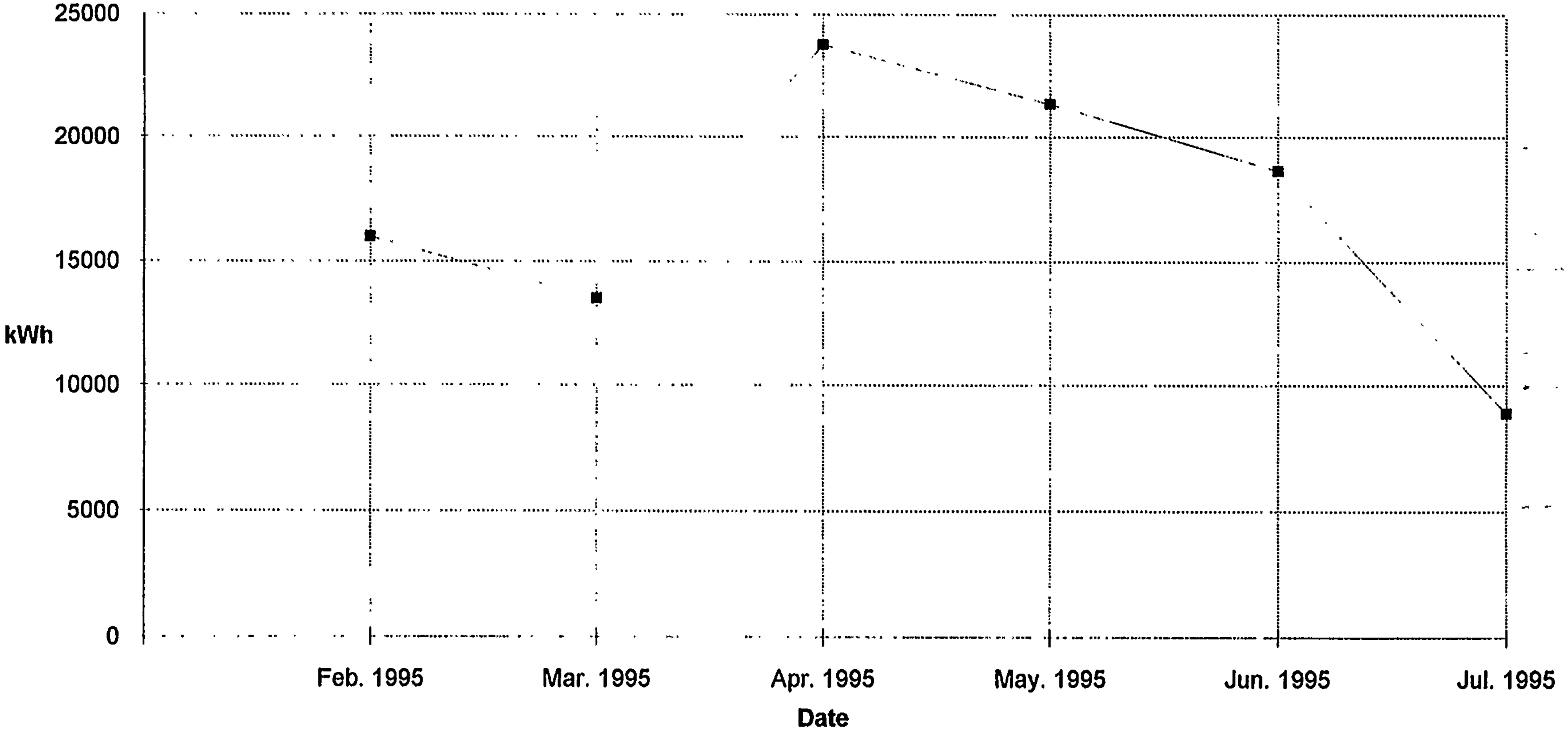
06/24/94

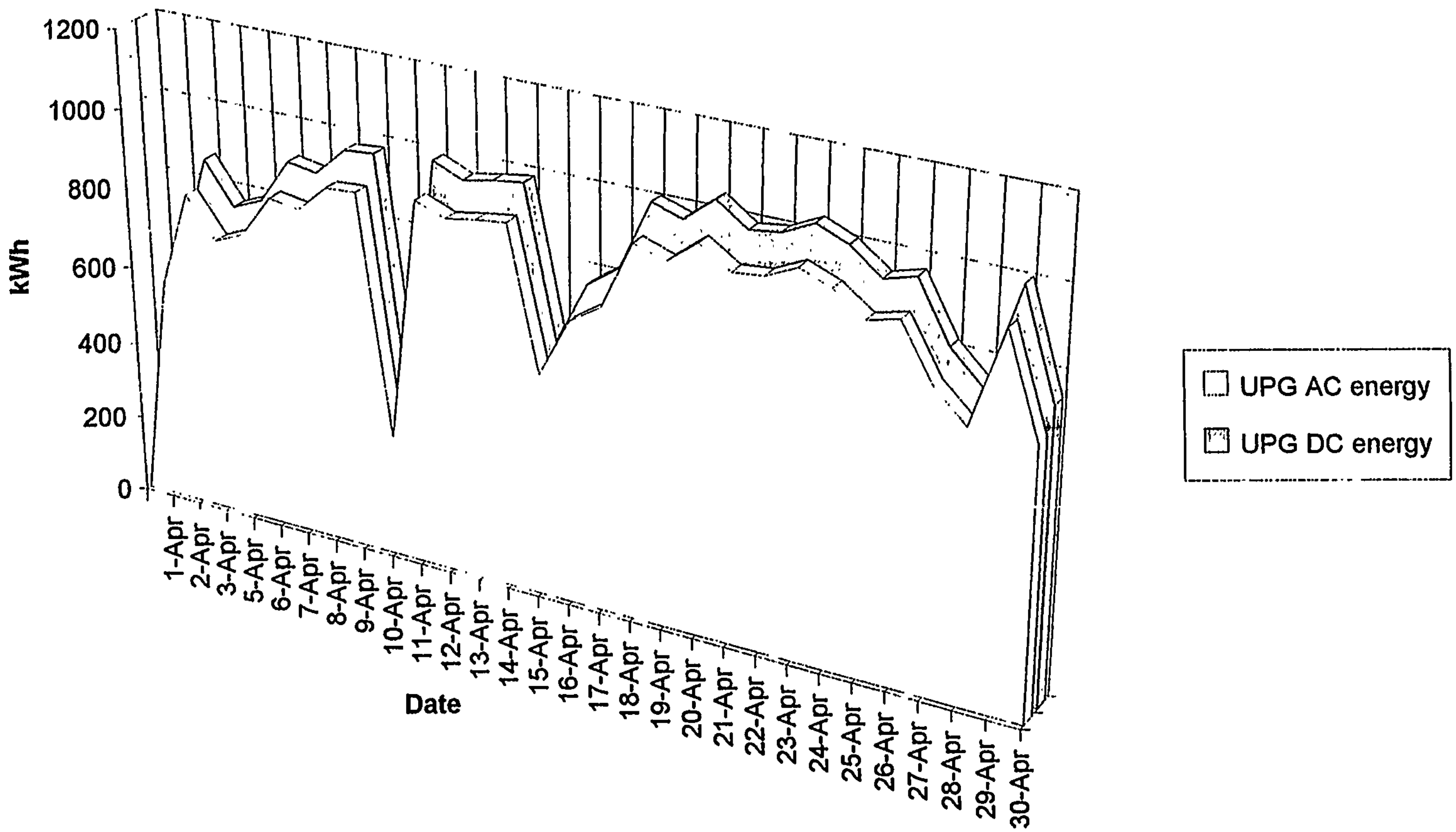


ODD ROWS ARE NEGATIVE POLARITY, EVEN ROWS POSITIVE
ROWS ARE 30' ON CENTER, ROW POLE SPACING 15'

UPG UTILITY POWER GROUP
9410-G DESOTO AVE, CHATSWORTH CA
FILE: ACDA\STA001B1.DWG
SHEET 1 OF 1

CSW Solar Park
Utility Power Group 100kW PV System Energy Production

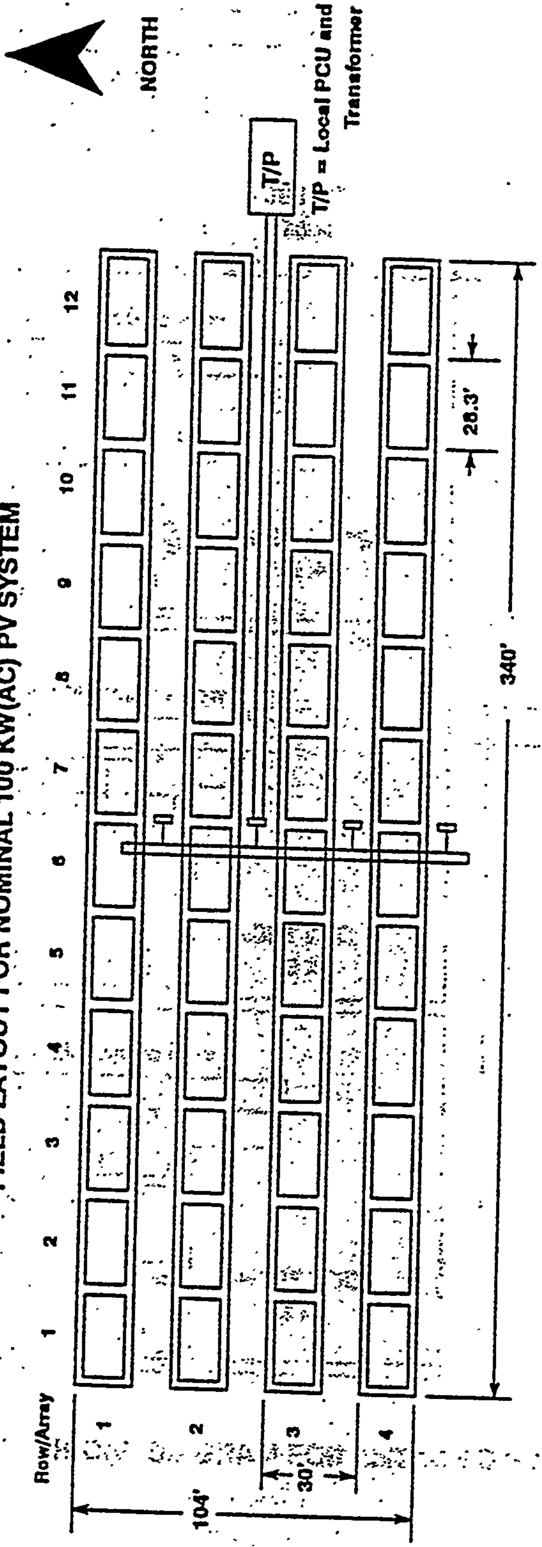




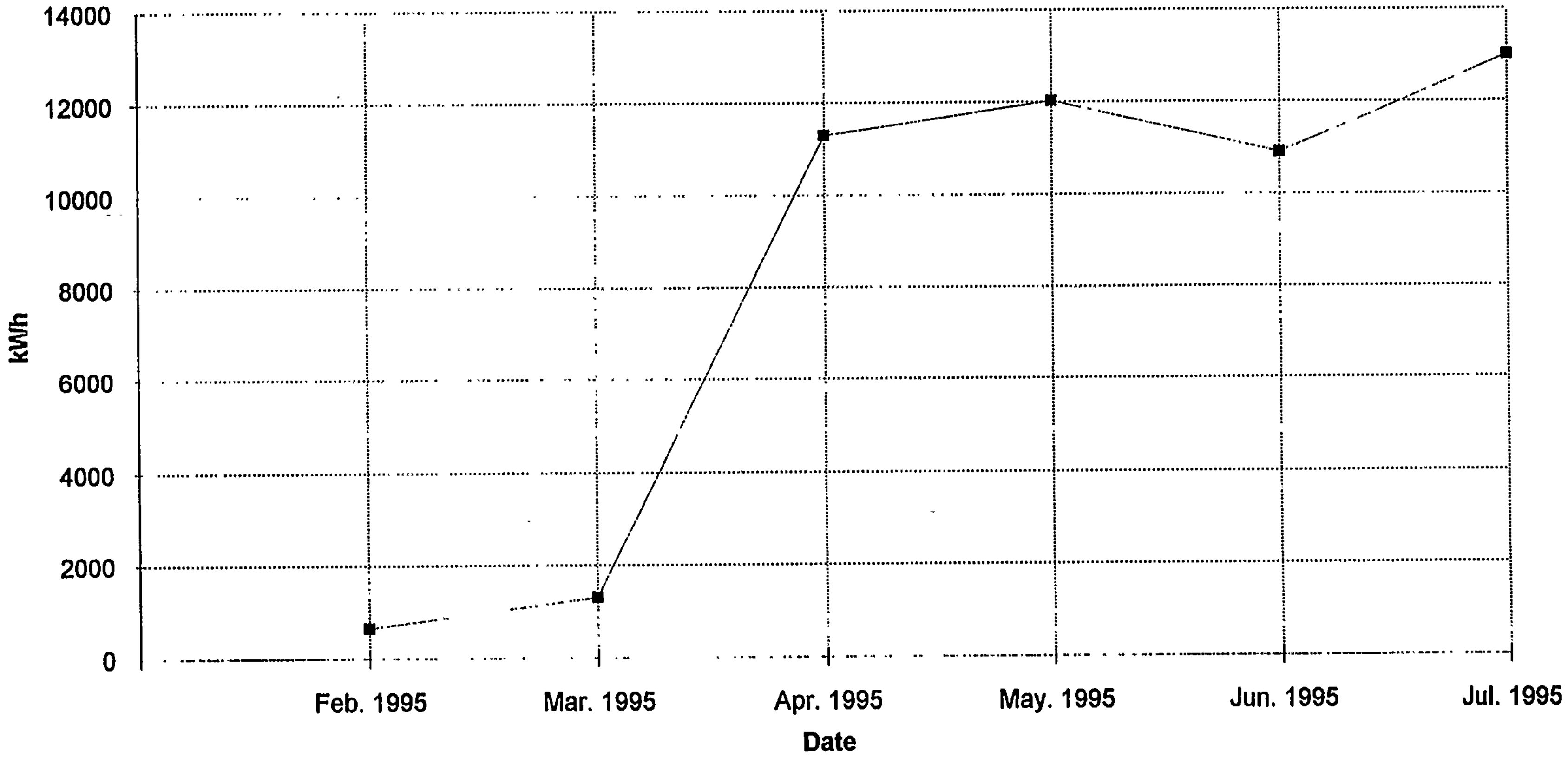
UPG AC and DC Energy for April 1995

FIGURE 2-2

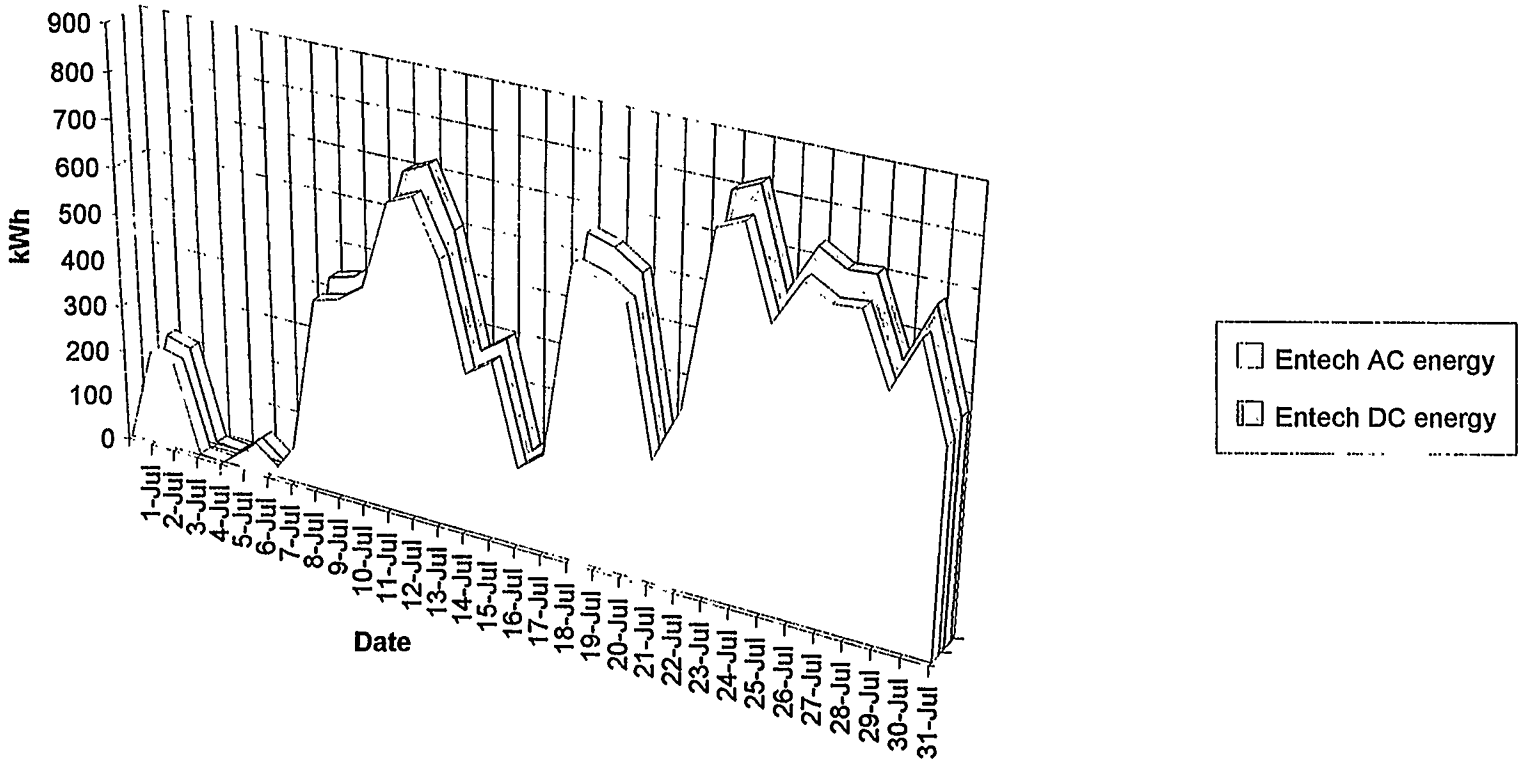
FIELD LAYOUT FOR NOMINAL 100 KW(AC) PV SYSTEM



CSW Solar Park
Entech 100kW PV System Energy Production



Entech AC and DC Energy for July 1995



Prepared for Presentation at the NREL PV Performance and
Reliability Workshop in
Golden, Colorado on 7 - 8 September 1995

Recent Advances in PV Systems Technology Development in Europe

M. Imamura, M. Grottke and I. Weiss
WIP Renewable Energies Division
Sylvensteinstr. 2
D-81369 Munich, Germany

PV SYSTEM TECHNOLOGY DEVELOPMENT

The objectives of this task were to study several aspects of plant design, monitoring, control, operation, and management of different types of PV plants. Unsolved problems were to be identified and analysed, and guidelines to improve the monitoring system were to be developed. Principal studies and development work done and their key conclusions are summarized.

RECENT R&D ACTIVITIES IN EC/DG XII JOULE II PROGRAMME

- **PV plant power output design rating and verification,**
- **Stand-alone system power conditioning,**
- **Real-time plant performance analysis method,**
- **Battery monitoring and guidelines on how to extend battery life,**
- **Design, test , and calibration methods for solar irradiance sensors, and**
- **Test method for PV modules and arrays: Their dark-forward I-V Curve.**

PV PLANT OUTPUT

One of the biggest complaints by the owners and users turned out to be the much lower than expected power output of the PV array in their plants. Our special study on at least 10 plants showed that the measured bus power was 8 to 27% lower than the "installed" module power (which is the number of modules times manufacturers rating).

The basic problem is that the actual output of the modules delivered is lower than the manufacturer's rating (by 8 to 20%) and the system designers failed to give the predicted bus power to the owner/user of the plant.

Simple in-situ method of bus power prediction was developed in this task for possible adoption by the international PV community.

BACKGROUND

Present practices:

- Array rating terminologies:
  - Installed Module Power
  - Installed Peak Power

Complete array level rating at the array main dc bus or connection point very seldom used

- System rating terminologies:
  - Inverter output bus (Pinv)
  - Substation (Transformer) output bus (Ptrans)

DEFINITION OF KEY PERFORMANCE TERMS

The purpose of this task was to define new parameters more useful to the operators and users. The new parameters developed:

- ***dc or array power rating*, P_{SAR}, which is the power output rating at the dc bus at STC, to distinguish from non-verifiable "installed module power" rating.**
- ***Array power capability*, P_{SAC},**
- **Array utilization factor, FAU, in power and energy**
- **Sun factor which quantifies the time of sunshine in a given day or month.**
- **Sunshine Index, in flux (W/m^2) and energy, relative to the maximum possible clear-sky irradiance.**
- **Clear-sky irradiance, an empirically derived profile for a given day and for a given site.**

PLANT RATING

The main aim:

Develop a method for calculating the PV array design power rating at the dc bus and how to verify it. The motivation of this task is that in virtually all plants, the operator asks, *"Why doesn't this plant put out power like they advertised?"*

This study goes into detail about the need for system designer to give the operator what power is expected at the dc bus and not the summation of *"installed module power"* which is not verifiable.

The significant finding:

Simple calculation method developed is effective and accurate, and it is a good candidate for standardization at the international level. The math model is also useful for sizing purposes.

PLANT POWER RATING (Concl'd)

1) In practically all plants, there is no proper array bus and inverter output rating at the system level; only kWp installed module power is reported. System-level dc and ac power ratings are very important because they provide a reference to which the performance can be verified, and state-of-health can be determined.

2) The installed PV array rated power compared to the power actually measured at the dc bus showed the following result: In most cases the measured bus power extrapolated to STC was 8 to 27% lower than the installed module power. The difference seems to be manufacturer-dependent since almost all the plants which used the same type of modules from the same supplier showed the same relative reduction in power.

To protect the final user who is typically charged for the Wp listed in the data sheet since he can not afford I-V measurements to determine the actually installed PV power.

To enable system engineers to design future PV systems properly, proper *system bus rating* should be reported from the beginning rather than the unverifiable *"installed" module power.* Another interesting and fascinating result is that our design prediction using simple power relationship of about 10 plants was within ± 6% of the verified measured bus power.

POWER RATING METHOD: *Prediction* of Design Power Rating at the dc bus

1) **Establish the max. power equation for your PV array at the dc bus at STC:**

$P_{SA} = \rho K_{SA} N_T P_{mo,}$ in Watts at STC **(1)**

where: ρ = Correction factor (ranges from 0.90 to 0.98, depending on the module supplier performance for all delivered modules for the PV plant).

K_{SA} = Product of array loss factors

= $\eta_{ms} \times \eta_{mp} \times \eta_{bw} \times \eta_d \times \eta_{deg}$ (see following charts)

N_T = Total number of modules in the array

P_{mo} = Manufacturer's rated power for the PV module at 1,000W/m^2 and 25° C cell temperature (STC)

2) **Select appropriate value for above parameters and calculate P_{SA}**

Note:
1) **If ρ and K_{SA} are chosen as 1.0, P_{SA} is the "installed" or "Nameplate" module power. This number is not easily verifiable.**
2) **If ρ and K_{SA} are fractions, P_{SA} is the array power rating at the dc bus.**

RECOMMENDED VALUES OF PARAMETERS IN POWER RATING EQUATION

	Low-power Plant (Bus voltage 12 to 60Vdc)	High-power Plant Bus voltage > 120 Vdc
η_{ms}	0.98	0.97
η_{mp}	0.98	0.98
η_{bw}	0.99	0.98
η_d	0.97	0.995
W/o η_{deg}	0.922	0.927
η_{deg}	0.95	0.95
W/5%$_{deg}$	0.876	0.881

Module (Si)	ρ	Module (Si)	ρ
ASE-Europe	0.92	Photowatt	0.93
BP Solar	0.95	Sharp	0.98
Isofoton	0.94	Siemens Solar	0.96
Kyocera	0.98	Solarex	0.95

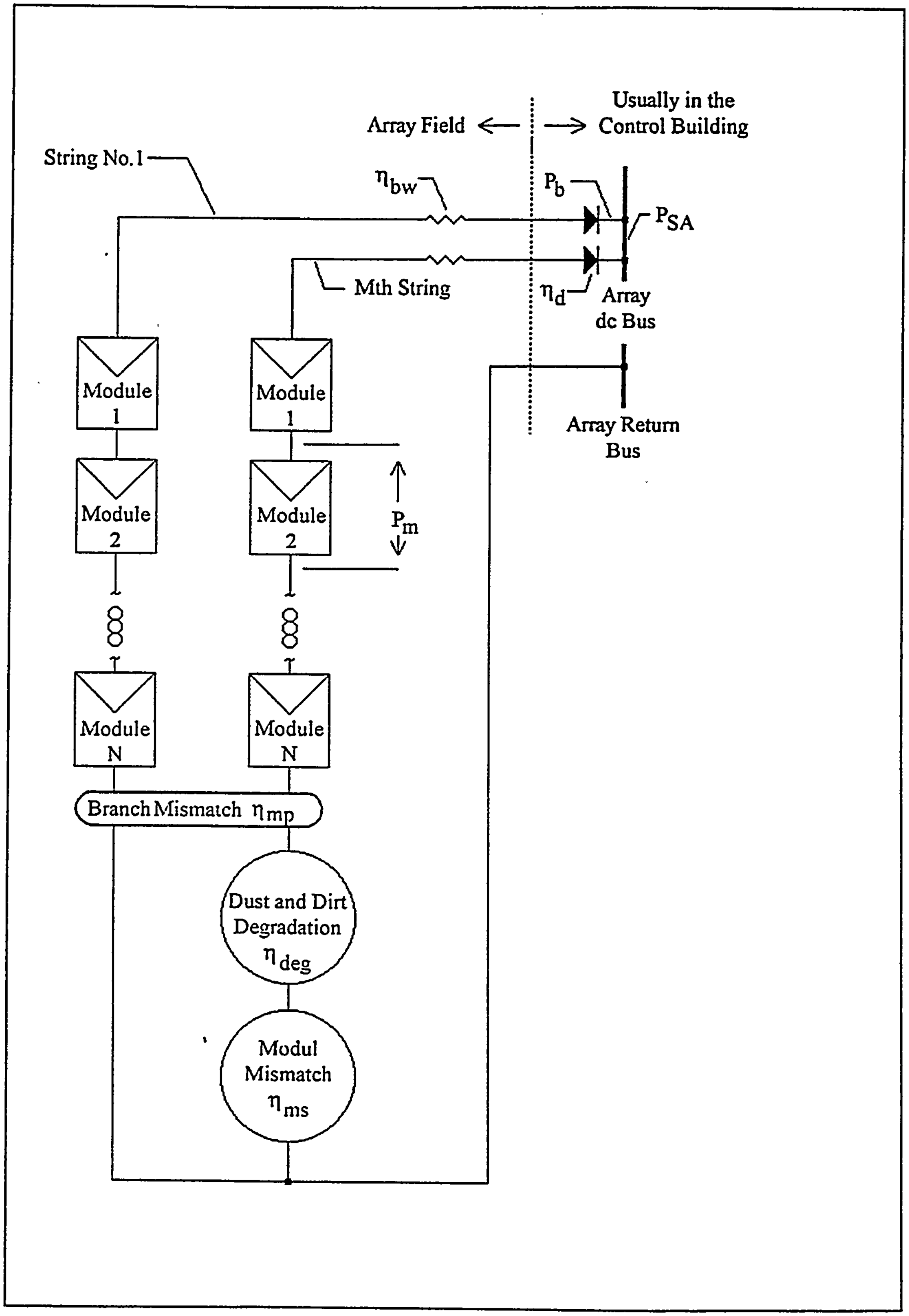


Figure 1. Simplified Power Flow Diagram of the PV Array for Use in Estimation of Number of PV Modules.

POWER RATING METHOD: *Verification* of Array Power Rating at the dc Bus

1) **Establish the max. power equation for your array at the dc bus as a function of in-plane irradiance and module temperature:**

$$P_{SA} = \rho K_{SA} N_T P_{mT} \quad (2)$$

$$= \rho K_{SA} N_T P_{mo} [1 + \beta (T_m - 25)] H_{POA}/1000 \quad (3)$$

where: β = **Temp. coefficient of array max. power**
T_m = **Module temp. (°C)**
H_{POA} = **Irradiance on plane-of array (W/m^2)**

2) **Record array V and I (or P), HPOA, and Tm at solar noon ± 0.5h (Manual readings are acceptable)**

For the grid-connected plants:	**Assume V and I are at MPP.**
For the stand-alone plants:	**Take measurements only when battery charge voltage is still rising and below its voltage limit.**

3) **Determine ρ' from measured P_{me} at local noon extrapolated to STC ($P_{me\text{-}stc}$):**

$$P_{me\text{-}stc} = \rho' P_{SA\text{-}stc}$$

where $P_{SA\text{-}stc}$ is the array rating predicted earlier. (Make sure that $P_{me\text{-}stc}$ is at the relatively flat part of the $P_{me\text{-}stc}$ vs time curve).

4) **Using eg. (3) and parameters defined earlier, calculate at STC between solar noon ± 0.5h and for solar incidence angle (α) less than 30°.**

RESULTS OF POWER RATING PREDICTION AND VERIFICATION ON SEVERAL GERMAN PV PLANTS

PV Plant		Date of measurements	Installed PV Module Pwr, P_{inst} (kWp)	P_{me} (kW)	H_{poa} (Wm-2)	T_m (°C)	α (Deg)	P_{me}- Extrapolated to STC (kW)	ρ_{pre}	K_{SA}	P_{SA}- STC (kW)	ρ_{ver}	Difference $P_{me\text{-}stc}$ to P_{SA}-STC (%)	Difference $P_{me\text{-}stc}$ to P_{inst} (%)
Plant A	Array	15.1.91	4.68	3.16*	862	26	2	3.68	0.95	0.89	3.96	0.86	-7	-21
Plant B	Subarray 1	5.3.94	0.16	0.09*	940	26	18	0.10	0.90	0.87	0.13	0.71	-22	-38
	Subarray 2	5.3.94	0.32	0.22*	940	26	18	0.23	0.90	0.89	0.26	0.81	-10	-28
	Subarray 3	5.3.94	0.64	0.48*	940	26	18	0.51	0.90	0.90	0.52	0.89	-1	-20
	Subarray 4	5.3.94	1.27	0.95*	940	26	18	1.01	0.90	0.91	1.04	0.88	-3	-20
	Subarray 5	5.3.94	2.54	1.83*	940	26	18	1.96	0.90	0.92	2.11	0.84	-7	-23
	Array	5.3.94	4.93	3.57	940	26	18	3.81	0.90	-	4.23	-	-10	-23
Plant C	Array	7.8.93	10.4	8.46	949	44	9	9.59	0.95	0.92	9.09	1.00	+6	-8
Plant D	Subarray 1	12.8.93	22.0	16.63	968	52.5	<30°	19.07	0.95	0.92	19.23	0.94	-1	-13
	Subarray 2	12.8.93	20.0	15.53	968	52.5	<30°	17.81	0.95	0.92	17.48	0.97	+2	-11
Plant E	Subarray 1	12.6.92	0.15	0.09+	967	55.5	<30°	0.11	0.90	0.87	0.12	0.84	-7	-27
	Subarray 2	12.6.92	0.30	0.2+	977	58.3	<30°	0.23	0.90	0.89	0.24	0.86	-4	-23
	Subarray 3	12.6.92	0.60	0.41+	985	59.3	<30°	0.48	0.90	0.90	0.49	0.89	-2	-20
	Subarray 4	12.6.92	1.20	0.82+	991	60.0	<30°	0.96	0.90	0.91	0.98	0.88	-2	-20
	Subarray 5	12.6.92	2.20	1.55+	997	59.0	<30°	1.80	0.90	1.00	1.82	0.89	-1	-18
	Array	12.6.92	4.50	3.07	-	-	<30°	3.58	0.90	-	3.65	-	-	-20
Plant F	Subarray 1 east	29.7.93	4.0	2.16	499	30	63**	4.42	-	-	-	-	-	-
	Subarray 2 south	29.7.93	4.0	1.28	334	27	65**	3.86	-	-	-	-	-	-
	Subarray 3 west	29.7.93	4.0	0.54	104	21	indirect sun	5.11	-	-	-	-	-	-
	Array	29.7.93	12.0	4.01	-	-	-	-	0.95	0.91	5.6	-	-	<-53
Plant G	Subarray 1 south	27.6.92	16.56	10.89	887	62	18	14.37	0.95	0.92	14.50	0.94	-1	-13
	Subarray 2 south	27.6.92	12.00	7.83	887	60	18	10.23	0.90	0.92	9.94	0.93	+3	-15
	Subarray 3 south	27.6.92	4.20	2.86	887	66	18	3.76	0.95	0.92	3.67	0.97	+3	-11
	Subarray 4 west	27.6.92	2.10	1.27	766	55	39	1.87	0.95	0.92	1.84	0.97	+2	-11
	Array	27.6.92	34.86	22.85	-	-	-	30.23	-	0.92	29.92	-	+1	-13
Plant H	Array	22.5.93	50.4	37.9	918	47	11	45.0	0.95	0.92	44.10	0.97	+2	-11
	Array	9.7.93	50.4	39.6	938	52	18	46.7	0.95	0.92	44.10	1.01	+6	-7

* MPP tracker probably not working efficiently (Plant A)or no MPP tracker available at all (Plant B).

** Monitoring Hpoa with a domed sensor at such sun incidence angles (α > 60°) leads to unacceptable errors. This data must not be used for extrapolation of Pme to STC.

\+ Measurements performed with STELLA I-V tracer

STAND-ALONE SYSTEM POWER CONDITIONING

The basic objective of this study was to define design improvements and guidelines for the PV system designers and users on power conditioning for low-power stand-alone PV systems. The key conclusions are:

- **The stand-alone PV systems must be more reliable than the grid-connected plants. To do so, provisions must be made to properly control, protect, and maintain batteries.**
- **It is essential to implement flexibility in control thresholds for charging and discharging of batteries and to provide minimum battery monitoring capability on site.**
- **All electronic circuits and moving parts must operate in harsh hot, cold, and salty environments. Thus, they must be selected according to military standards to achieve the highest reliability possible.**
- **Designing of "super" charge controllers advocated in several development projects is not the key solution — what is needed is for the users to understand how to look at the battery behavior and make timely adjustments manually.**

It is not practical to build a "super" electronic controller to detect and correct all bad operating conditions of the battery. A smart monitoring system which provides intelligent trend information to the operator (EODV, RF, SOC, available solar energy), combined with a flexibility in the system controller to alter the operating state is a better solution.

PERFORMANCES OF HIGH-VOLTAGE BATTERIES

Batteries at the Zambelli PV plant (near Verona) and Brunnenbach PV plant (near München) have been carefully monitored over the past five years for the purpose of investigating how best to monitor and extend battery life, effects of forced-air electrolyte agitation, and integration of new cells into an old battery bank. The main conclusions are as follows:

1) A precise state of health (SOH) assessment is very difficult, but some simple rules have been formulated to provide enough guidance for the operator to maintain the battery. To do so, PC is an essential part of this monitoring. For a full SOH determination, actual battery capacity test must be performed and the mismatch among the cells in the battery needs to be evaluated. This requires individual cell (or monoblock) voltages to be collected.
2) To extend battery life, two basic rules must be obeyed: batteries must be recharged via a separate power source periodically or preventing battery energy to slowly deplete with each cycle, and reverse-polarity charging of cells must be prevented.
3) Forced-air agitation of electrolyte in theory is beneficial but properly conducted experimental analyses to prove it are still lacking.
4) A simple procedure is needed to allow proper integration of new cells into a bank of old cells. All cells, new and old, need to be fully charged before they are inserted into the battery bank.

BATTERY PERFORMANCE RULES

1) What comes out (i.e., Ah capacity) depends on what (Ah) you put in, which in turn is severely affected by how (charge rate) the battery was recharged.

   - The lower the charge rate (up to a limit), the higher the input capacity. This means the efficiency of fully charging the active plates is higher for lower charge rates.
   - If very high charge rate is used, the net capacity input can be half or lower than if a lower rate is used, eventhough the cell or the battery string reached its prescribed voltage limit (e.g., 2.35 V per cell).

2) The available capacity increases as the discharge rate decreases (use manufacturer's data on the same cell).

3) After the first 25 to 100 cycles of what appears to be normal recharging (i.e., the battery attains its charge voltage limit and Rfah is 1.05 or higher), do not expect any battery operating in the PV cycle regime to have the rated battery capacity.

4) The "80% capacity" rule is used by many battery manufacturers as the criteria for cell replacement . It means that if capacity of a cell at any time goes below 80 % of its rated capacity during operation, that cell needs to be replaced.
   This is completely incorrect.In a PV cycle regime, the operating capacity may range between 20 and 60 % of the rated value much of the time depending on solar energy availability. What's important about the S-O-H of the battery is whether or not it is capable of accepting sufficient capacity if the conditions are suitable (low charge rate, cool temperture, sufficient solar or other power sources available for recharging, etc.)

5) Any of the math modules for SOC calculation of absolute capacity available is not reliable, no matter how sofisticated it is. For absolute capacity (i.e., residual capacity) determination, the best method is actual discharge into the normal system load.

6) The effects of electrolyte agitation systems on battery life have shown in some controlled experiments to be positive. However, the real benefits have not yet been proven and quantified effectively. Thus, do not assume that the battery capacity stays near the rated capacity if the electrolyte agitator is incorporated.

7) Cell manufacturers cannot supply battery-level performance data; the best sources of system data are the owners of operational stand-alone PV plants.

BATTERY RULES (Concl'd)

8) There is a severe lack of cycle life vs DOD data for PV designers and users. To assure long-life time, always limit the daily operating DOD as low as practical (say, 10 to 20 % max.).

9) The available or residual battery capacity will decay asymptotically to a level consisting with the cycle regime (i.e., time available to recharge, charge and discharge rate, and PV energy available), operating battery temperature, and DOD.

10) Many battery "experts" and "pseudo-experts" claim that past failures in the PV batteries are due to *overcharging*. A diametrically opposite view is put forth herein as a critical rule: a large majority of PV batteries are *undercharged*, rather than overcharged. So, whenever evaluating batteries in the field, remember to look also for undercharging and cell match level as the source of problems.

11) Replacing old cells with new ones: make sure all cells (new and old) are fully charged before connecting them in series. Otherwise, mismatch levels may become worse with cycling.

12) "Equalization" recharge can be and often desirable to apply to selected cells which are known to be low-capacity cells.

13) Before replacing cells because of suspected low capacity, try recharging both "average" cell and the "bad" cells fully and run full discharge/charge cycle at least twice. Then, compare these two cells to see if the low capacity found before was a temporary condition.

BATTERY MAINTENANCE GUIDELINES

Simple guidelines and procedures on how to maintain, test, and monitor batteries in stand-alone and hybrid systems are usually unknown to the operators and users. Batteries need the most attention in the PV system and the users/operators do not know how to maintain and take care of the battery.

In a majority of stand-alone plants, the batteries are often not fully recharged or inadequately recharged. This is diametrically opposite to the wide-spread belief among the PV system and battery specialists that batteries are being fully recharged and failing because of overcharging. Reasons for this thinking is the general lack of understanding on behaviour of battery operating in PV environments, how to fully recharge, and how to detect such conditions.

WHY MONITOR BATTERIES?

The monitoring of batteries in stand-alone PV systems must be done in the context of

1) enhancing the reliability of the total system and

2) extending the battery lifetime.

It must be clearly understood that battery is an important chain in the proper functioning and long-term operation of the total system. Thus, monitoring the battery performance has two basic aims, first to prevent conditions conducive to curtailment of its lifetime and second to define maintenance actions needed to change what appears to be a downward trend in its available state of charge. By increasing its relative SOC, one can surmise that battery minimum discharge voltage will increase, chances of reverse charging will decrease, etc.

DARK FORWARD I-V CURVE AND ITS APPLICATION

Objectives:

To investigate the usefulness of the diode property of any PV device for

1) checking the quality of the PV device without illuminating it and

2) predicting the illuminated I-V curve if simple-to-get measurements of actual Isc, Voc, and dark forward I-V curve are available.

The major conclusion is that the diode characteristics can be an effective test method to complement or even substitute in some cases, for the more expensive scanning of I-V curve indoors or outdoors.

SOLAR IRRADIANCE SENSORS AND CHARACTERIZATION

The experimental evaluation of solar sensors over the past 6 years has resulted in the following conclusions:

1) **Si-based sensors, if adequately constructed, are technically better substitutes for the higher-priced thermopile pyranometers for long-term outdoor monitoring of solar irradiance.**
2) **Two or three carefully selected thermopile instruments should be kept indoors and maintained for use as references for calibrating other sensors.**
3) **All solar sensors should be calibrated at the time of installation and initial plant operation.**
4) **The simplified field calibration method developed in the JOULE II Concerted Actions projects for solar sensors is better than other existing international standards, and it will be proposed for adoption in the IEC.**
5) **Cosine response (reflection) characterisation, also fully analyzed in the above projects is essential for all solar irradiance sensors. Simple method for its determination based on outdoor measurements has been developed and validated under this project.**

PERFORMANCE MEASUREMENT STANDARDS

IEC/TC82 (set up in 1981)

- IEC 904 - 3 (89) : Measurement Principles
- IEC 904 - 1 (87) : Measurement of module I-V characteristics
- Reference solar irradiance sensors (calibration, construction, etc.)
- Extrapolation to STC.

JRC

- On-site measurement of array characteristics
  - o 700 W/m² minimum as seen by a ref. sensor.
  - o In case of large arrays, string or subarray I-V curves are measured.
  - o Incidence angle ≤45°
- Extrapolation to STC.

SIMPLIFIED FIELD CALIBRATION METHOD FOR SOLAR IRRADIANCE SENSORS

1) Place test sensor in the same plane as the calibration ref. sensor.
   Ref. sensor to be used: one to three units CM11 or CM21.
2) Simultaneously record the sensor outputs at solar noon ±0.5h.
3) Use the data-pairs available during the following conditions to calculate the calibration factor (CF) for the test sensor:

Conditions

- Relativels clear sky at the time of measurements
- Only one (1) day of test
- Solar incident angle < 30°
- $H_{ref} > 800$ W/m²

Calibration formula:

$$CF = \frac{1}{\eta} \sum^{n} (V_S / H_{ref})_i$$

where V_s = Test sensor output voltage

H_{ref} = Ref. sensor W/m² output

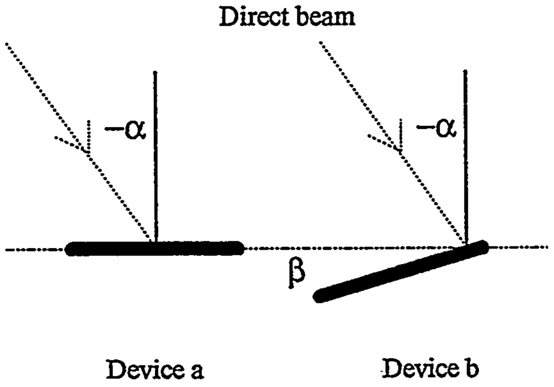
DETERMINATION OF THE COSINE RESPONSE CHARACTERISTIC OF SOLAR SENSOR OR PV MODULE

1) **Install the test and ref. sensors on a south-oriented flat platform outdoors.**
2) **Simultaneously record sensor data-pairs over the whole day. Conditions: Relatively clear-sky day over a whole day with clear sky radiation.**
3) **Determine the difference in H_{poa} reference sensors using:**

$$\left[\left(\frac{H_{test-sensor}}{H_{ref-sensor}}\right)-1\right]x100$$

4) **Plot the above calculated difference versus the calculated beam incidence angle (α).**

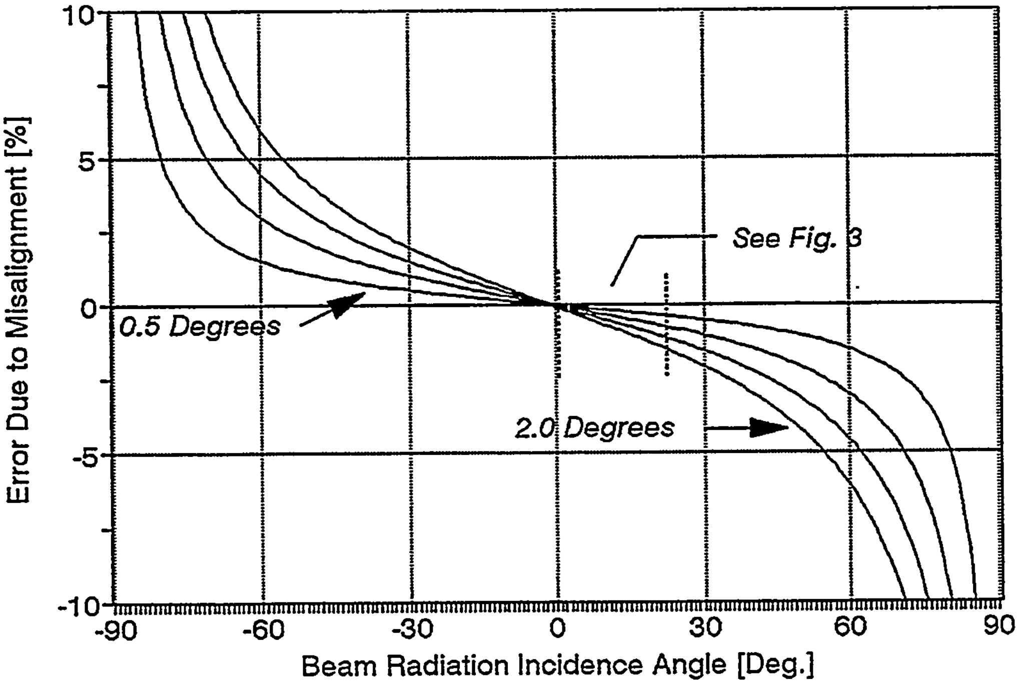
SOLAR SENSOR CALIBRATION: EFFECTS OF MISALIGNMENT



α = Sun incidence angle

β = Angle of misalignment between device a and device b

Illustration of the misalignment between two devices (sensor or module).



Change in sensitivity due to misalignment of the device.

→ The higher the α-angle, the higher the calibration error due to misalignment

SUMMARY AND CONCLUSIONS

Key achievements and recommendations:

1) Simplified methods of design power rating and field verification developed and validated; suggested for adoption as an international standard.

2) Test, calibration, and construction criteria for Silicon-based solar irradiance sensors established; also suggested for adoption as an international standard.

3) Preliminary battery monitoring, maintenance, and operating guidelines defined, focusing on life extension for PV plants.

4) Applications of dark-forward I-V characteristics evaluated: module, string, and array testing.

Design and Field Performance of the KENETECH Photovoltaic Inverter System

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Summary of Presentation

KENETECH Windpower has recently adapted the power conversion technology developed for the company's variable speed wind turbine to grid-connected photovoltaic applications. KENETECH PV inverter systems are now in successful operation at the Sacramento Municipal Utility District's (SMUD) Hedge Substation and the PVUSA-Davis site, with additional systems scheduled to be placed into service by the end of 1995 at SMUD, the New York Power Authority, Xerox Corporation's Clean Air Now project, and the Georgia Tech Aquatic Center.

With over 500 MW of inverter capacity in service, KENETECH's photovoltaic inverter design reflects the results of a five-year, $10 million investment in a power electronics development program aimed at both cost reductions and reliability improvements. Design features implemented to increase reliability on the wind turbine converter, such as fiber optic isolation between the inverter power and control stages, and utilization of intelligent power semiconductor modules, have been replicated in the PV inverter product.

Additional control software, unique to the photovoltaic application, has been developed to maximize both system power output and availability. The KENETECH PV inverter topology and maximum power tracking and power limiting control algorithms decouple the array voltage from the utility line voltage, allowing maximum power tracking down to zero volts on the array, and protect against inverter trips due to overpower conditions on the array due to enhanced insolation effects.

KENETECH's PV inverters have passed their field acceptance tests and been released for service within two to three days of completion of field wiring. To date, no inverter faults or other performance problems have occurred. Valuable customer feedback from these initial installations has resulted in design improvements being implemented on current orders.

Design and Field Performance of the KENETECH Photovoltaic Inverter System

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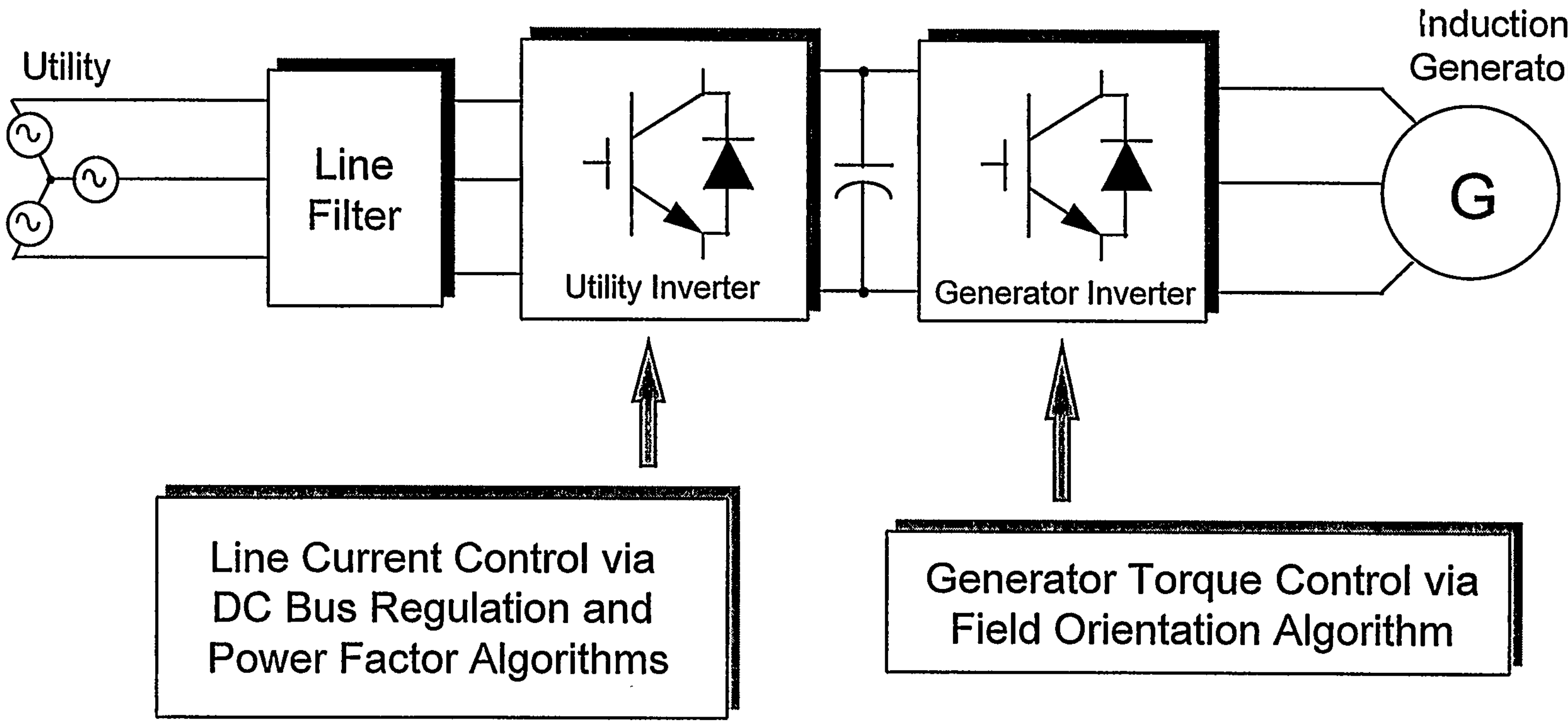
Power Electronics Program History

- 1989-90: USW/EPRI/Utility Variable Speed WT Consortium
- Q2, 1991: Installation of first variable speed turbine
- Q3, 1993: Creation of 4500 ft^2 Power Electronics manufacturing area for initial production rate of 25 converters/month
- Q1, 1994: Non-wind converter development begins (motor drives, PV inverters, battery energy storage converters)
- Q1, 1995: Fourth-generation ("Smart power") wind converter production begins at volume of 80/month
- Q3, 1995: Installed inverter capacity surpasses 500 MW
- Ten patents issued or pending for utility interfaces, renewable energy applications and subcomponents

Power Electronics Hardware Features

- Insulated Gate Bipolar Transistor (IGBT) based
- Intelligent Power Module ("Smart Power") design
- TMS320C30 digital signal processor based embedded controller
- Fiber optic isolation between power and control sections
- Active filtering of line currents for IEEE-519 compliance

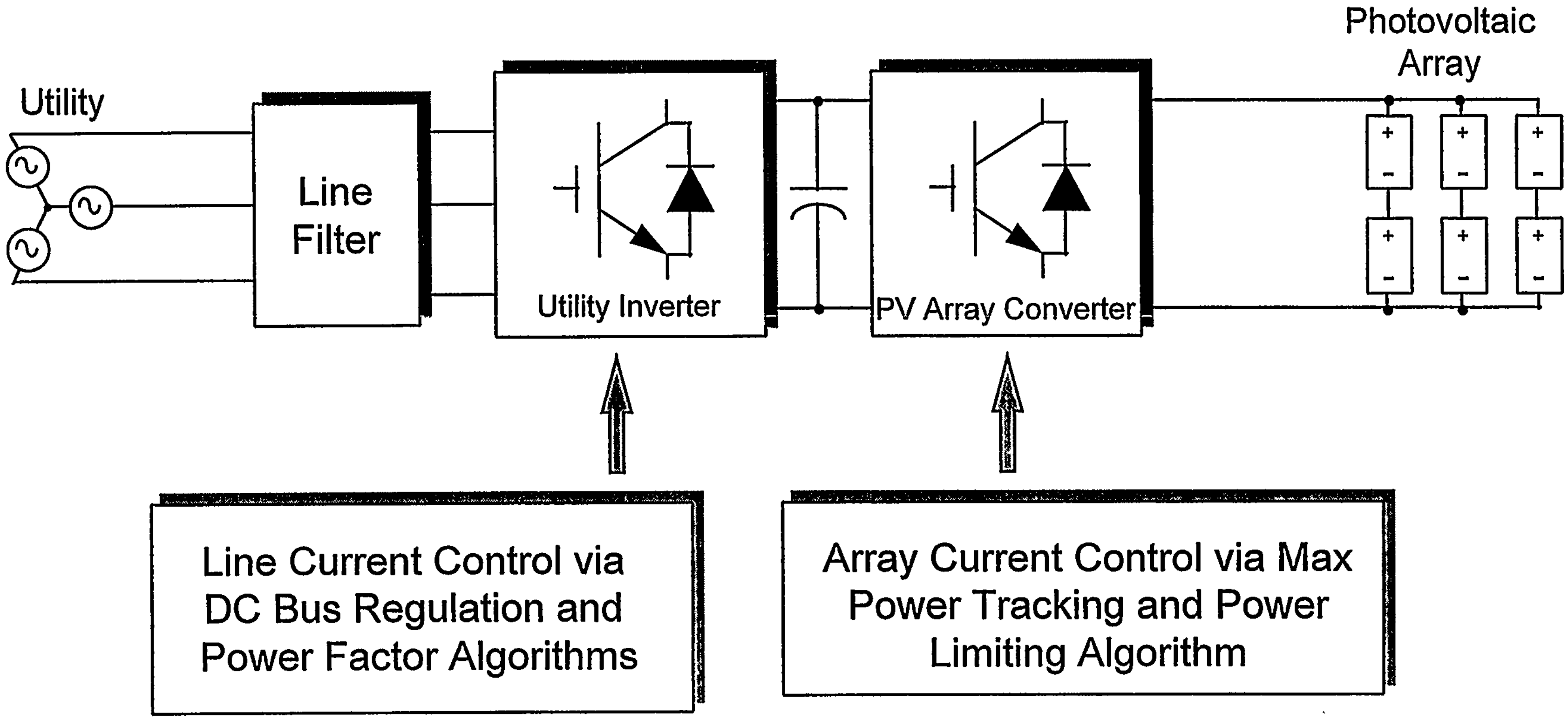
Wind Turbine Converter Topology



Line Current Control via DC Bus Regulation and Power Factor Algorithms

Generator Torque Control via Field Orientation Algorithm

Photovoltaic Inverter Topology



Utility

Line Filter

Utility Inverter

PV Array Converter

Photovoltaic Array

Line Current Control via DC Bus Regulation and Power Factor Algorithms

Array Current Control via Max Power Tracking and Power Limiting Algorithm

Power Tracking / Power Limiting Algorithm

- Perturb and observe method
- Controlled variable is array <u>current</u>
- Array current limit = (nominal array power output) ÷ (nominal array MPP voltage)
- Array power limit = inverter nominal power rating
- Power limit implemented by rapidly moving off MPP when available array power exceeds inverter capability
- Algorithm runs in inverter inner control loop (6 kHz interrupt rate)

Advantages of Control Strategy

- Array voltage and AC line voltage are completely decoupled
- Max power tracking of array down to zero volts
- Proper selection of Δ I eliminates inverter trips due to overpower condition from enhanced insolation on array

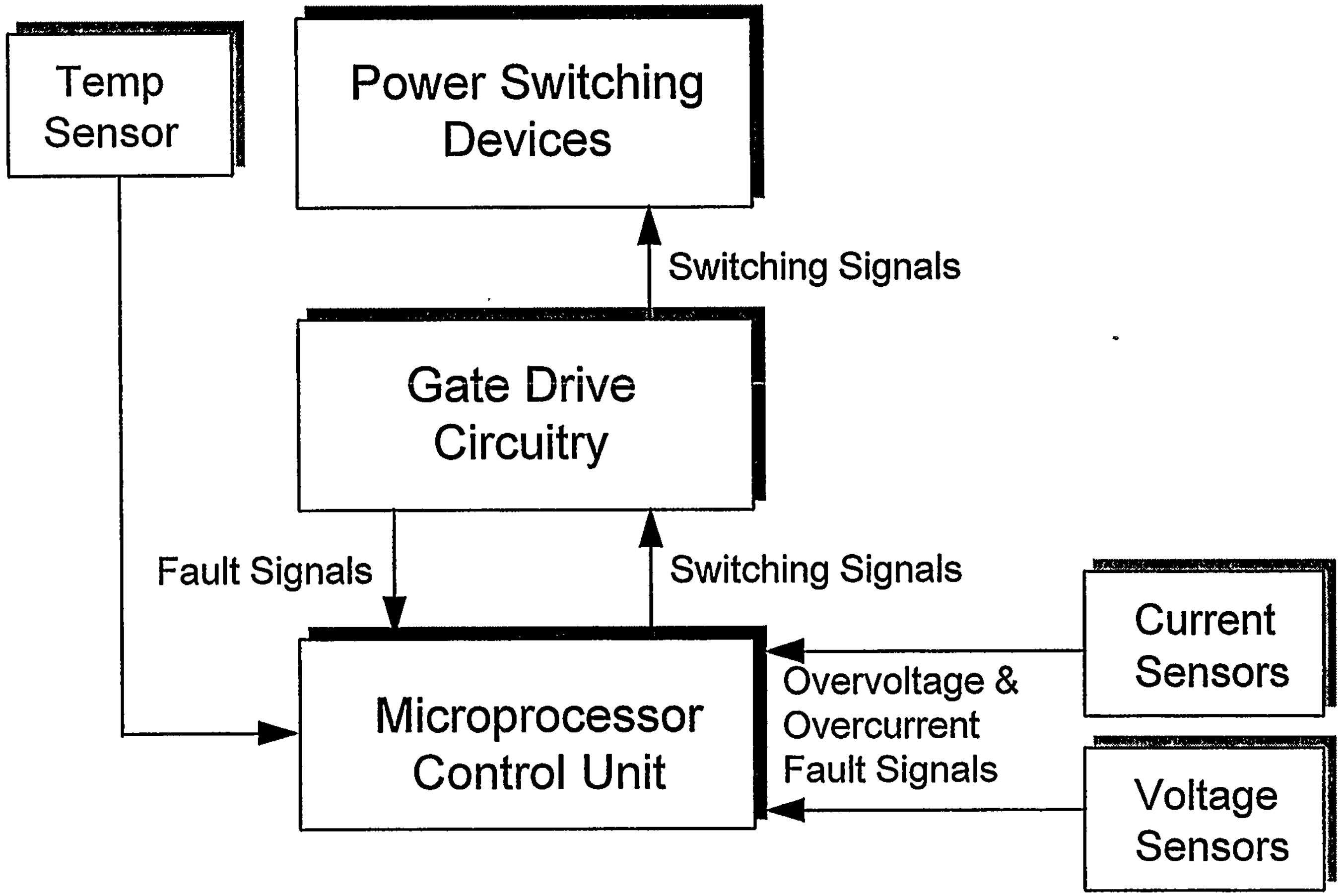
<u>Example</u>: Δ I = 0.5 A, Δ T = 1/6 kHz

Ramp Rate = 0.5 / (1/6000) = 3000 A/sec

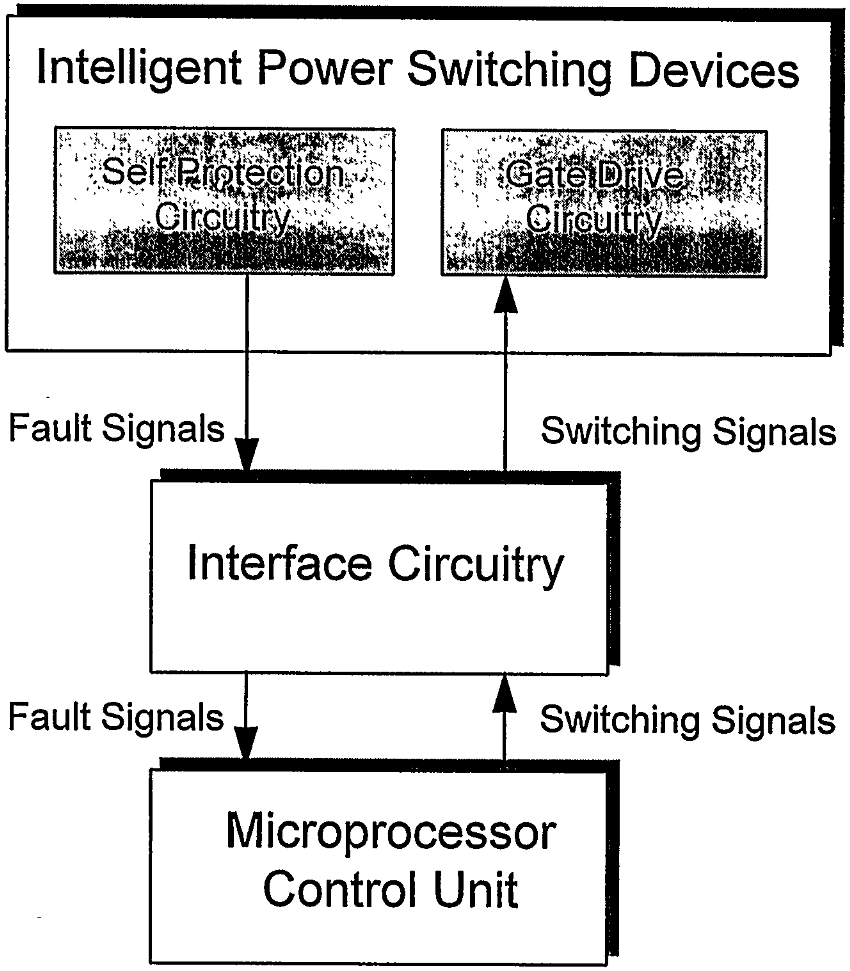
“Smart Power” Technology

- Integration of IGBT gate drive and protection circuitry into device package
- Reduces complexity of interface circuitry between device and controller → higher MTBF
- Self-protection:
  - Overcurrent
  - Short Circuit
  - Overtemperature
  - Control supply undervoltage
- Reduces secondary and tertiary faults

Traditional Converter Topology



"Smart Power" Converter Topology



Intelligent Power Switching Devices

Self Protection Circuitry

Gate Drive Circuitry

Fault Signals

Switching Signals

Interface Circuitry

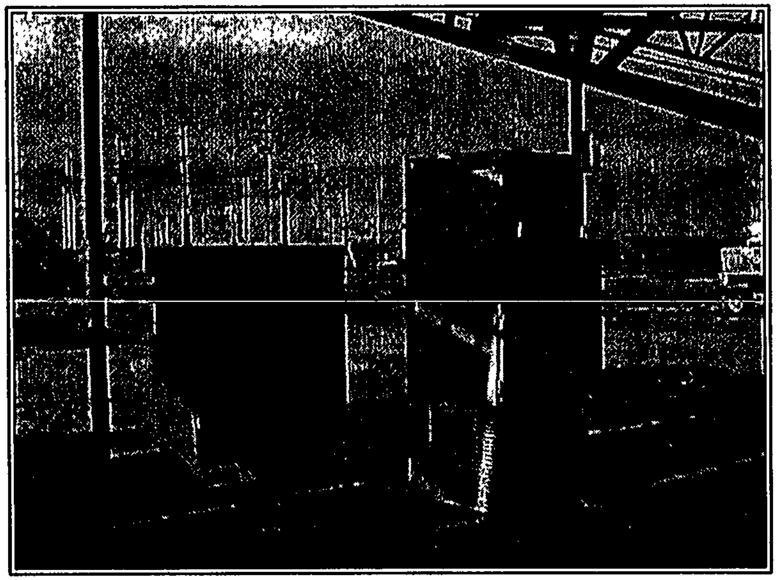
Fault Signals

Switching Signals

Microprocessor Control Unit

PV Inverter Operating History

- **<u>SMUD Hedge Substation</u>**
- 100 kW Unit
- Delivered 12/29/94, 12 Weeks ARO (20 Weeks Quoted)
- Field Wiring Completed 5/23/95
- Passed SMUD Acceptance Test 5/24/95, Released for Service
- Through 9/2/95, Continuous Operation with No Faults or Performance Problems



PV Inverter Operating History

PVUSA Davis Site

- 225 kW Unit
- Delivered 8/15/95, 13 Weeks ARO (14 Weeks Quoted)
- Field Wiring Completed 8/28/95
- Release for Service 8/31/95, Following PVUSA Acceptance Test

Customer Feedback

- Audible Noise

  Solution: Increase switching frequency and offset line and array inverter frequencies

- Air Filter UV Resistance

  Solution: Replacement with aluminum mesh filter

NATIONAL RENEWABLE ENERGY LAB
PV Performance & Reliability Workshop
September 7-8, 1995
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