FLORIDA SOLAR ENERGY CENTER

Creating Energy Independence

High Voltage Bias Testing of Specially Designed c-Si PV Modules

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Outline

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- Earlier Generation a-Si:H PV modules
- Specially Designed c-Si PV modules
- Sister Projects
- Summary

Introduction

- Certification process currently employed for PV modules though reduces infant mortality does not duplicate the real time conditions completely.
- In grid connected PV systems the PV modules may be at voltage of as much as ±600 volts with respect to ground in USA and as high as ±1000 volts or higher with respect to ground in Europe and elsewhere.
- The voltage gradient between PV circuit and ground can cause the leakage current to flow.

Leakage Current

- Energy that dissipates from the PV circuit through the encapsulation to the ground is termed leakage current.
- Leakage current may be composed of charge carriers that move under the influence of voltage and concentration gradients through the insulation, reacting with it and cell and frame metals to produce corrosion products and can lead to electromigration and degradation.
- Leakage current levels are also determined in large part by the insulation electrical conductivity that varies greatly with temperature and relative humidity.

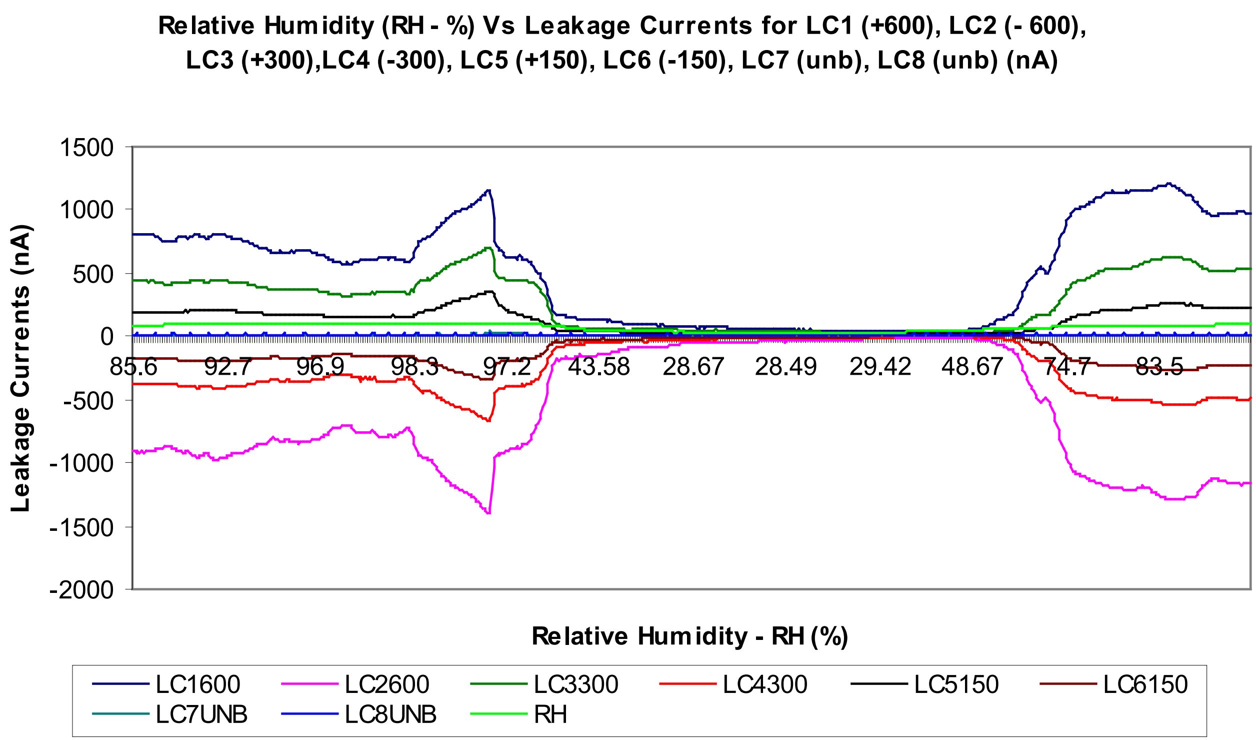
High voltage bias testing

- Pioneering research by Joe del Cueto and colleagues
- The effect is considerably more prevalent in the hot and humid climate.
- Hence they encouraged and supported the initiation of the research plans at FSEC for high voltage bias testing in the hot and humid climate.
- Recent research on high voltage bias acceleration testing by Peter Hacke and colleagues.

Earlier Research at FSEC

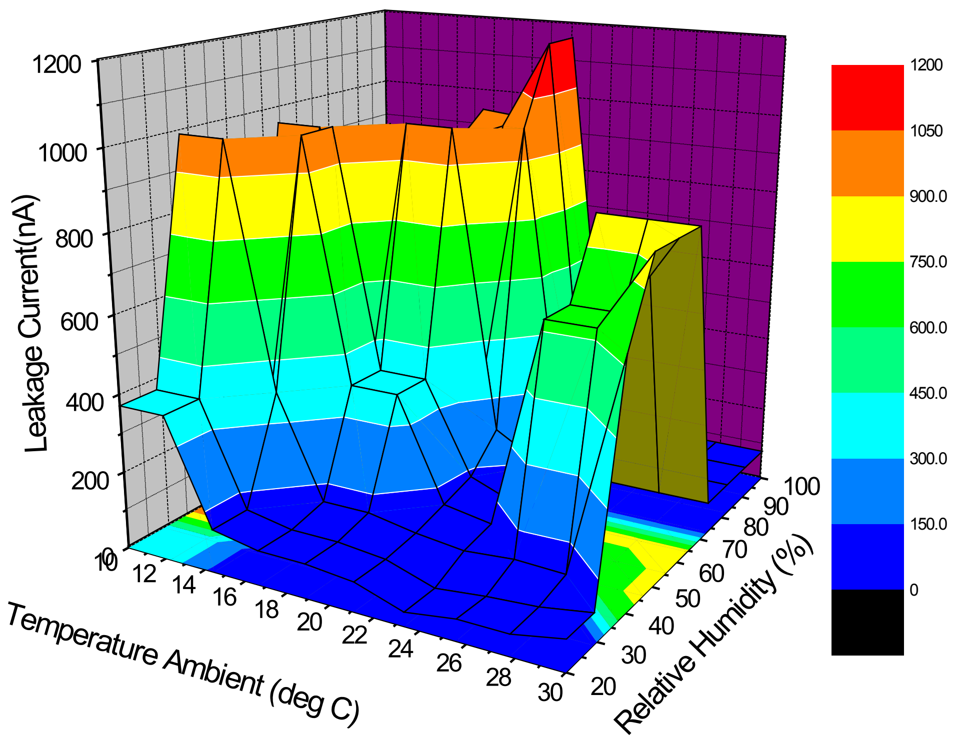
- BP solar a-Si:H modules deployed in hot and humid climate of Florida
- Six modules at the following fixed bias voltages : +600 V, -600 V, +300 V, -300 V, +150 V, and -150 V, and two unbiased modules.

RH Vs Leakage Current



☼ Sunny Day

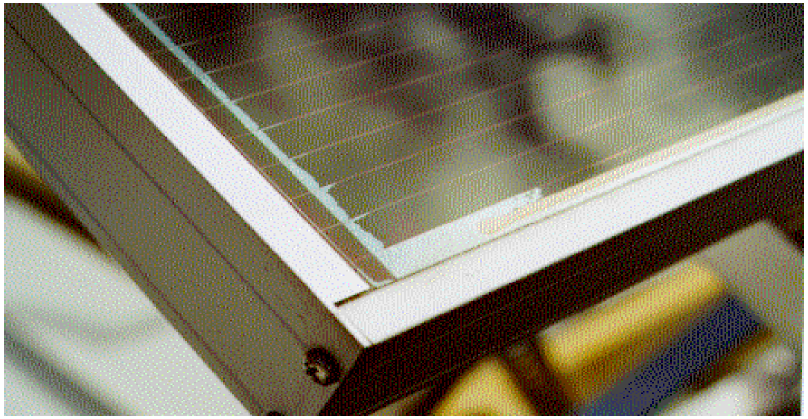
RH & T Vs Leakage Current



Degradation and Analysis

- Delamination of SnO_2:F layer together with the a-Si:H cell from glass surface due to diffusion of sodium from sodalime glass.
- Thus sodium free glass as described by Dr. James Webb, Corning as well as low sodium, treated glass (described earlier in AFG, Siemens, FSC) will be valuable.
- Damage is caused by electrocorrosion
- Corrosion initiated near the bottom edges of individual cell strips and moved inwards.

Degradation



-600 V Module – 8 months

-600 V – 27 months

-300 V – 32 months

-150 V – 32 months

Degradation and Analysis

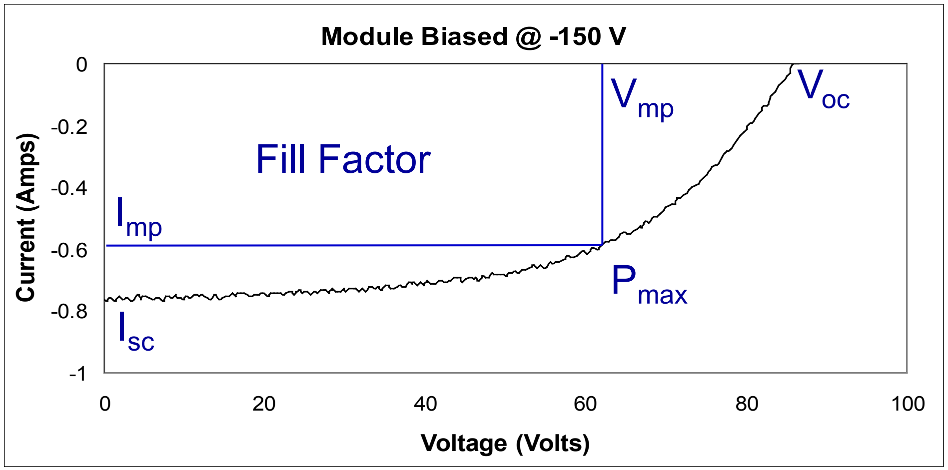
- Corrosion was not found in the positively biased modules.
- Some amount of corrosion was found in the unbiased modules.due to self bias.

Degradation Process

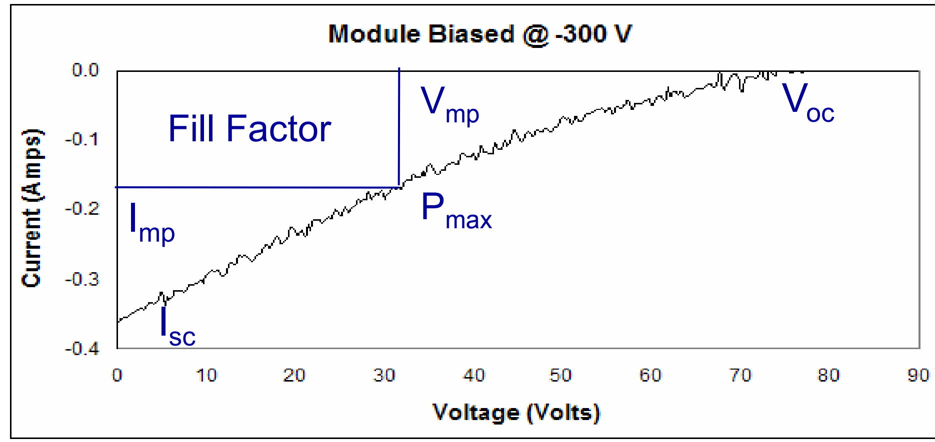
- Initially no ingress paths hence incubation period.
- Damage initiated at lower edge and corners with the lattitude tilt.

Degradation of -600 V with time

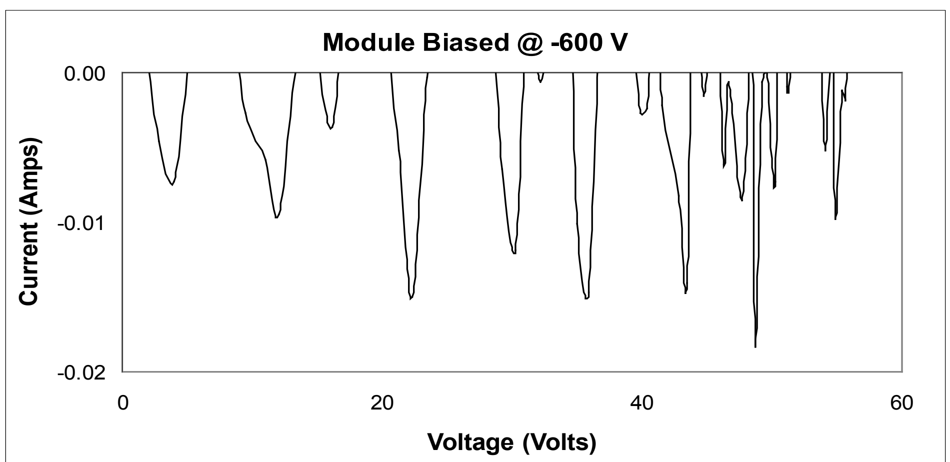
I-V Curves



Module Biased @ -150 V
Current (Amps)
Voltage (Volts)
Fill Factor
Vmp
Voc
Imp
Pmax
Isc
0
-0.2
-0.4
-0.6
-0.8
-1
0
20
40
60
80
100



Module Biased @ -300 V
Current (Amps)
Voltage (Volts)
Fill Factor
Vmp
Voc
Imp
Pmax
Isc
0.0
-0.1
-0.2
-0.3
-0.4
0
10
20
30
40
50
60
70
80
90



Module Biased @ -600 V
Current (Amps)
Voltage (Volts)
0.00
-0.01
-0.02
0
20
40
60

I- V Measurement Data Analysis

- Power Reduction (%)

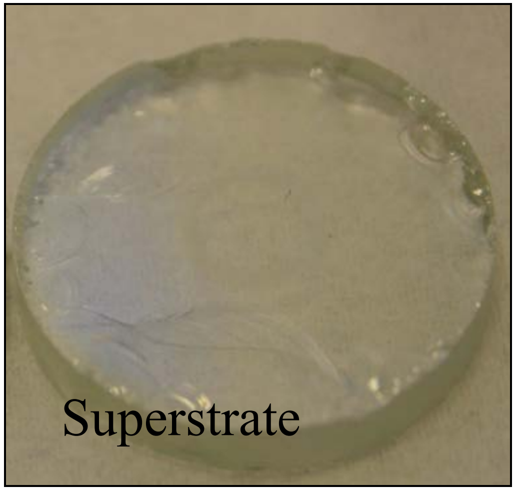
Bias	Oct - 2003	After Decommissioning
-150 V	11.4	21
-300 V	40.7	85.8
-600 V	NA	98
+600 V	NA	6
UB	NA	3.82
Control	NA	

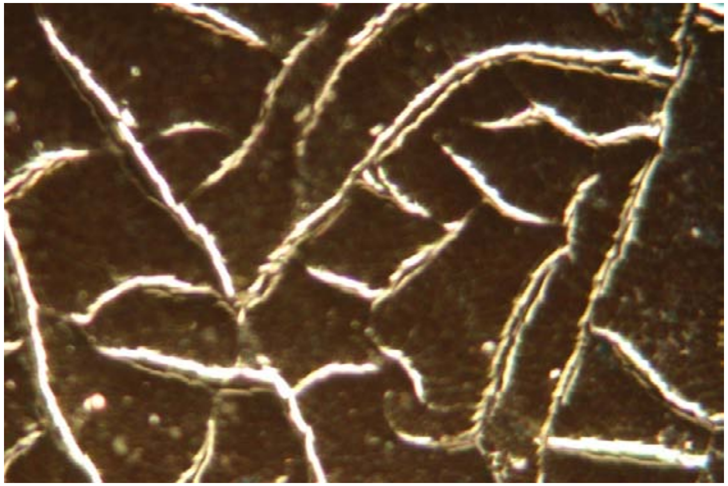
- Series Resistance

Bias	Control	-150 V	-300 V	-600 V
Series Resistance (Ω)	15	30	382	NA

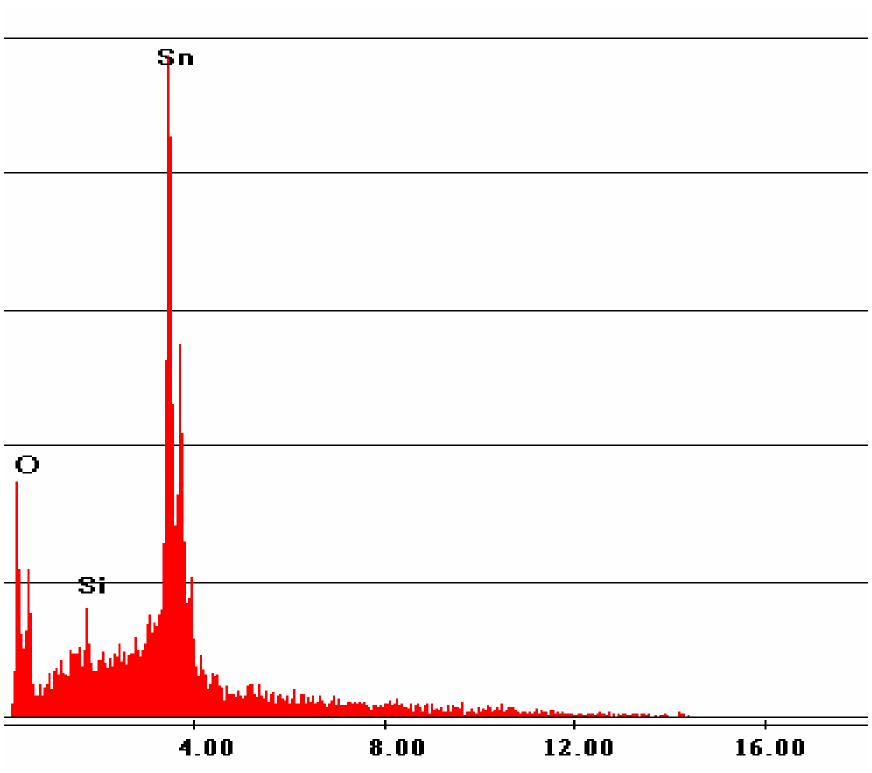
Coring and Analysis

- The a-Si:H cell delaminated and transferred itself entirely to the bottom glass/EVA surface.
- Adhesional strength was completely lost in the damaged area.
- Resistance above the range of measurement.
- The tendrils appeared as cracks

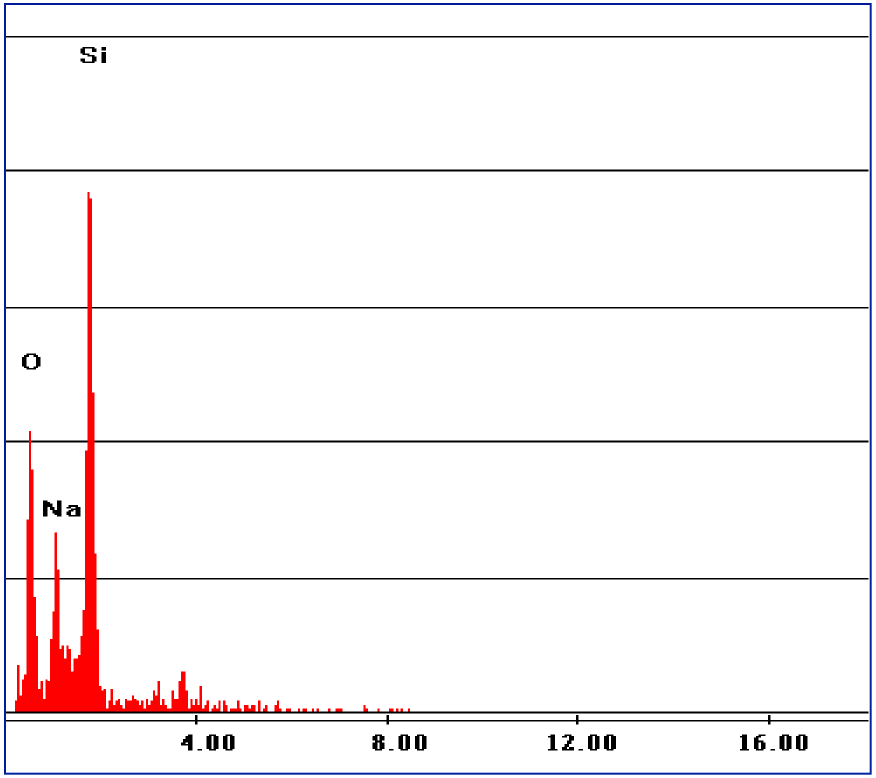




XEDS Analysis



Cell Sample



Superstrate Sample

Field deployed Thin Film PV Modules

- Side by side testing of thin-film PV module arrays self biased to voltages up to ± 600 V.
- Test bed designed and built by Graduate students

Continued work

- EPV and USSC continued the testing after the NREL project was over.
- USSC is very pleased with the work and is extending the Project for 3 more years
- Results are being submitted to IEEE PVSC, Seattle.

Advantages of this method

- Module are under real system bias
- Multiple voltages-different modules under different voltages, unbiased at night
- Reproduces real-time conditions and provides better statistics

Very High voltage bias testing of c-Si modules

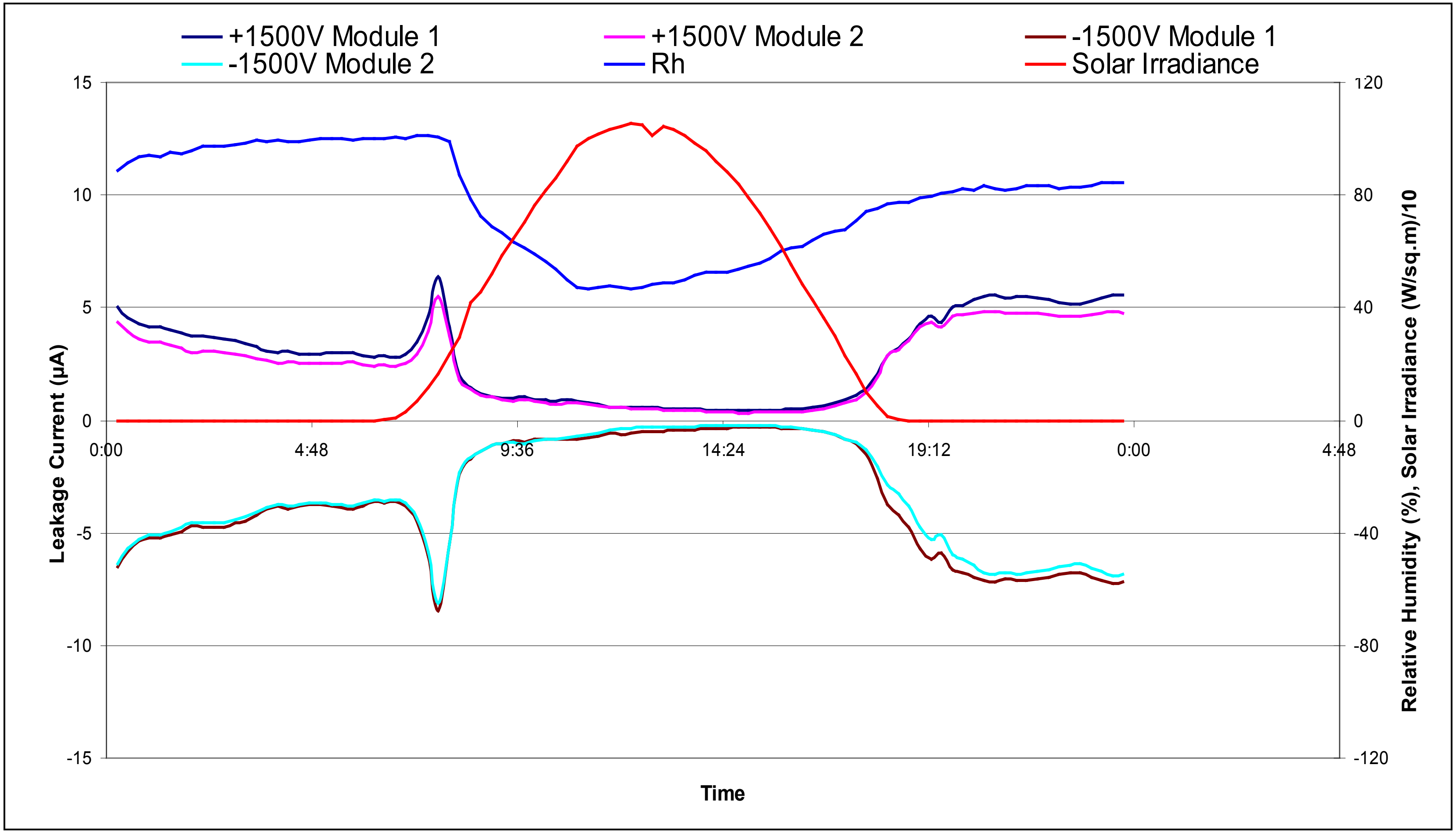
- BP Solar/DOE supported project.
- The platform was designed with the participation of Graduate students.
- Especially meant for carrying out high voltage testing at voltages > than 600 V up to 3000 V.
- The design was certified by an engineering firm and approved by UCF EH&S.
- Satisfies the required NEC codes

High voltage test bed

Specially Designed c-Si PV modules

- BP Solar c-Si modules specially designed for operation at the system voltage of 1000 V were tested in the hot and humid conditions of Florida. The modules were individually biased to +1500 V and -1500 V.
- One of the first observations made during this test was that the magnitude of leakage current for negatively biased modules was higher than that for positively biased modules.

Variation of leakage current in c-Si PV modules

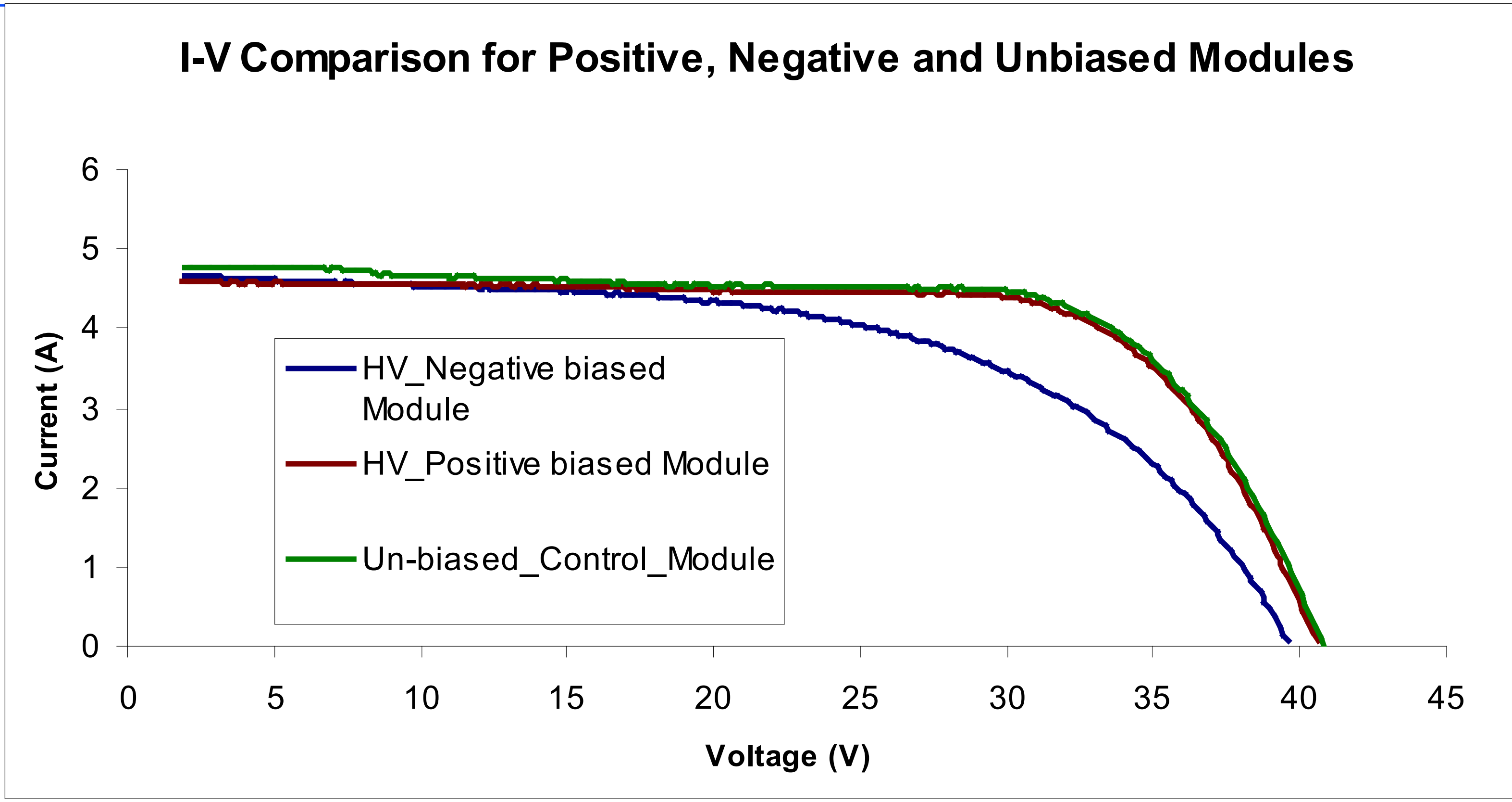


☼ Sunny Day

Specially Designed c-Si PV modules

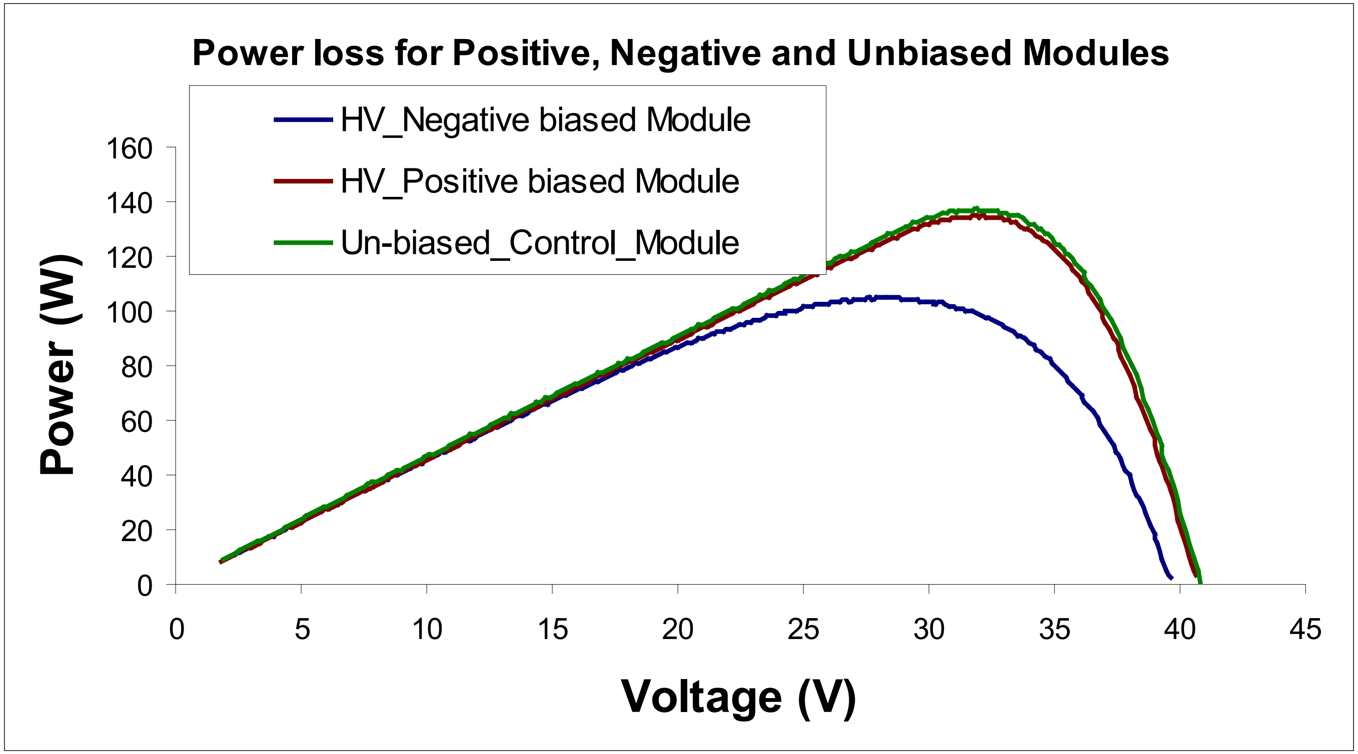
- Periodic current-voltage (I-V) measurements were carried out on the high voltage biased modules.
- Comparison of I-V, power-voltage characteristics, and calculations of the power loss, at the end of Year 1, are provided in the following Figures and a Table.

Current vs voltage I-V comparison



- Current versus voltage comparison of the control, positively biased and negatively biased modules.

Power loss comparison



- ☼ Power versus voltage comparison of the control, positively biased and negatively biased modules.

Power loss comparison

- As can be seen, at the end of Year 1, the control module, the two positively biased modules and the two negatively biased modules exhibited a power loss of 8.1%, 9%, 7.9%, 25.6% and 25.7% respectively with respect to their rated power.

Power loss Calculation

	Power loss (%)				
Module type	**Nov-08**	**Dec-08**	**Mar-09**	**Feb-11**	**SPIRE**
c-Si_P1	NA	12.2	9.0	9.8	6.9
c-Si_P2	9.0	10.7	7.9	9.3	5.9
c-Si_N1	30.9	30.1	25.7	NA	NA
c-Si_N2	29.3	29.2	25.6	21.5	18.6
c-Si_Control	NA	7.5	8.1	NA	NA

Comparison of PV Parameters

- Periodic current-voltage (I-V) measurements were carried out on the high voltage biased modules.
- Comparison of the normalized peak power and the photovoltaic parameters of the control, positively biased and negatively biased modules is provided in the following Table.
- Normalized peak power and PV parameters were calculated from the I-V curves.

Comparison of PV Parameters

PV Parameter	Unbiased Module	-1500 V biased module	+1500 V biased module
Normalized Peak Power	157.22 W	118.8 W	149.22
Fill Factor	70.4%	55.75%	70.6 %
Normalized O.C. voltage	46.17 V	44.63 V	44.83 V
Normalized S.C. current	5.16 A	5.11 A	5.0 A
Series Resistance	1.38 Ω	1.87 Ω	1.37 Ω
Shunt Resistance	175 Ω	68.5 Ω	161.3 Ω

Conclusion from Comparison of PV Parameters

- As can be seen from the Table, the power loss of the -1500 V biased modules is mostly due to the 15~% reduction in fill factor.
- Fill factor loss and power loss could be due to the increase of the series resistance and decrease of shunt resistance.
- One of the two degraded, negatively biased modules was sent back to BP Solar.

New c-Si modules

- Two new c-Si modules were received from BP Solar.
- One was negatively biased and other was deployed as control module in the field.

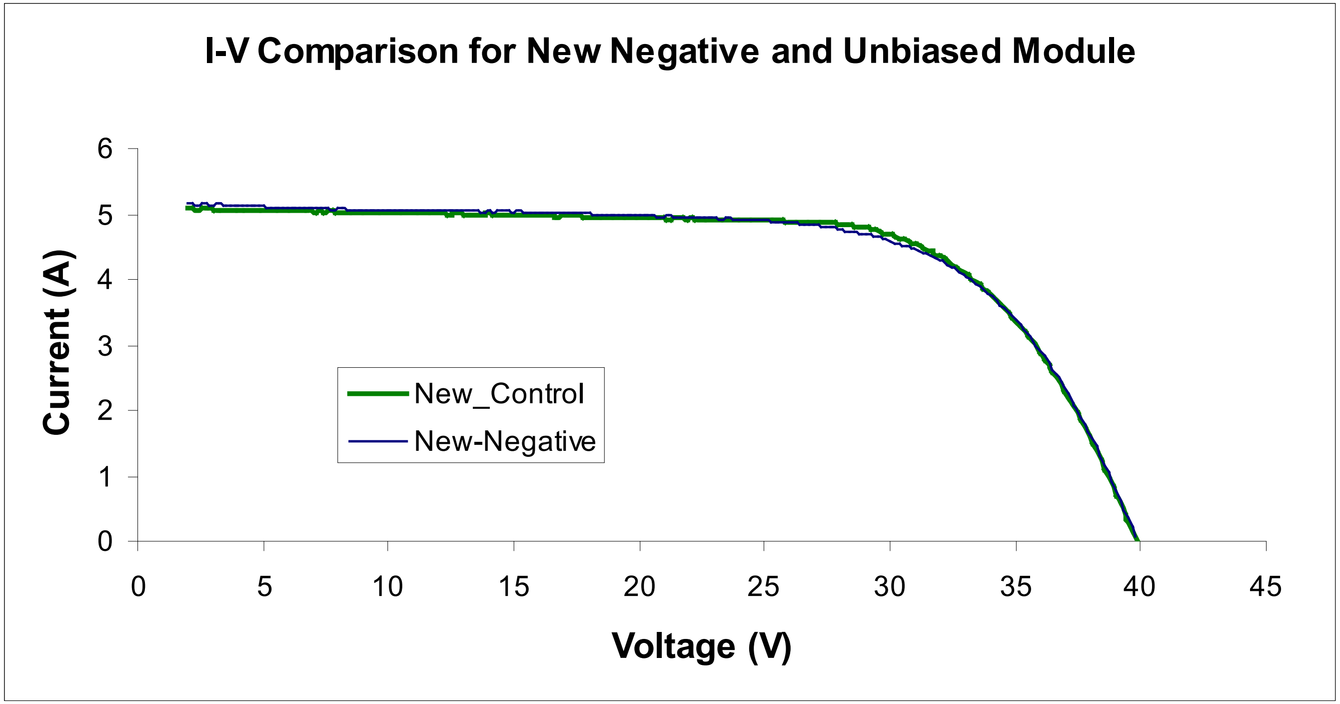
Important Clarification

- Here it must be stated clearly that all the results and any conclusions of the continued research must be considered as tentative and very preliminary because of the lack of opportunity to analyze the data systematically, as well as to carry out the essential and usual complementary measurements.
- It is planned to carry out the systematic analysis of the data as well as to carry out the essential and usual complementary measurements during the next few months.

New c-Si modules

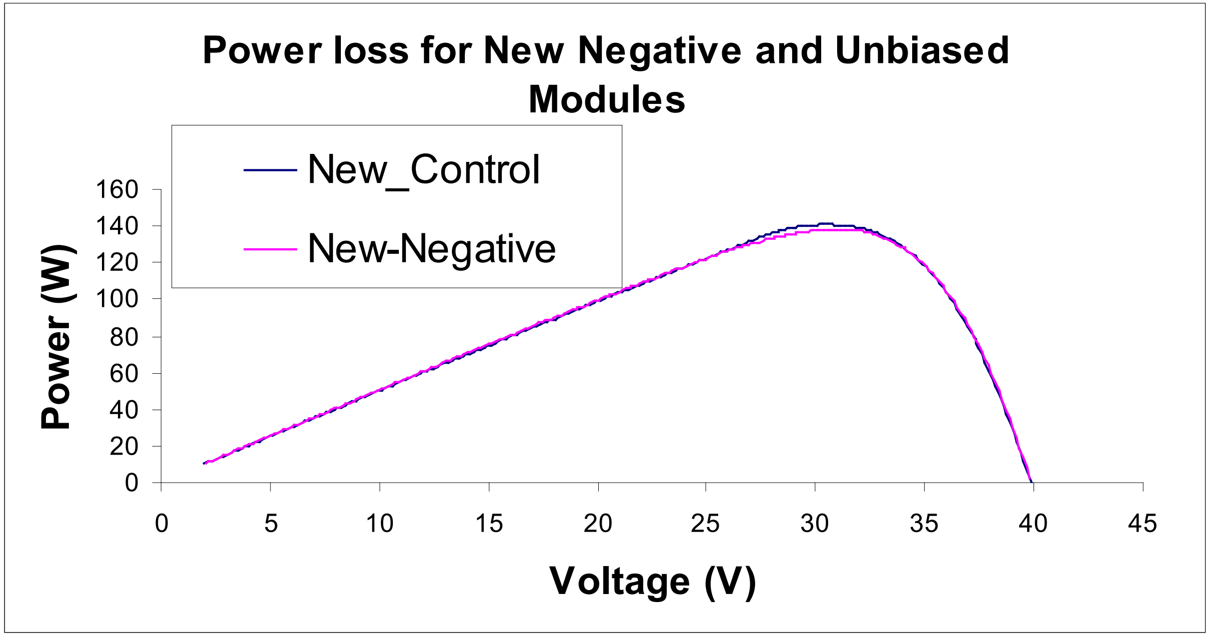
- Preliminary comparisons of current-voltage (I-V) and power-voltage characteristics after additional ~ 1 ½ years of field deployment in hot and humid climate are provided in the following Figures.

Preliminary I-V comparison



- Preliminary comparison of current-voltage (I-V) characteristics after ~ 1 ½ of field deployment in hot and humid climate.

Preliminary power loss comparison



- Power loss calculated based on the rated power of the c-Si modules.

Effect of hot and humid climate

- Both modules showed significant power loss calculated based on the rated power within a very short period
- There was only a 2% difference in power loss between unbiased and biased module.
- Apart from the negative bias the hot and humid climate itself had a significant impact on the module power loss within a period of 1 ½ years of field deployment.

Preliminary power loss calculation

	Power loss (%)				
Module type	**Nov-08**	**Dec-08**	**Mar-09**	**Feb-11**	**SPIRE**
c-Si_New_Negative	NA	NA	NA	11.9	9.6
c-Si_New_Control	NA	NA	NA	10.0	7.0

Preliminary power loss calculated from the I-V measurements with respect to rated power

Power loss Summary

	Power loss (%)				
Module type	**Nov-08**	**Dec-08**	**Mar-09**	**Feb-11**	**SPIRE**
c-Si_P1	NA	12.2	9.0	9.8	6.9
c-Si_P2	9.0	10.7	7.9	9.3	5.9
c-Si_N1	30.9	30.1	25.7	NA	NA
c-Si_N2	29.3	29.2	25.6	21.5	18.6
c-Si_Conrol	NA	7.5	8.1	NA	NA
*c-Si_New_Negative	NA	NA	NA	11.9	9.6
*c-Si_New_Control	NA	NA	NA	10.0	7.0

*Tentative and Preliminary

Comparison of PV Parameters for new c-Si modules

PV Parameter	New Unbiased Module (Control Module)	New -1500 V biased module
Normalized Peak Power	157.5 W	154.2 W
Fill Factor	69.85%	67.4%
Normalized O.C. voltage	43.0 V	43.1 V
Normalized S.C. current	4.98 A	5.0 A
Series Resistance (SPIRE)	0.95	0.98
Shunt Resistance (SPIRE)	162.84	173.68

Acceleration Factors (AF)

- Since the module are biased 24 hours a day preliminary calculations of the acceleration factors were carried out from the magnitude of the leakage current.

- The formula used is :

$$AF = \frac{\text{Total leakage current during day and night}}{\text{Total leakage current during the day}}$$

Acceleration Factors

Day	+1500 V P1	+1500 V P1	-1500 V N1	-1500 V N2
Cloudy Day	2.5	2.44	2.32	2.5
Clear Sunny Day	4.54	4.76	3.7	4.76

HV bias testing of Dow Chemical c-Si modules

- High voltage bias testing of c-Si modules with specially developed encapsulants of Dow Chemical Company.
- Modules with different encapsulation types biased individually to ± 600 V in hot and humid climate of Florida.
- Results from this research is being jointly submitted to IEEE PVSC Seattle conference (Currently awaiting approval).

Summary

- The results from the HV bias testing of c-Si modules have been presented.
- The tentative preliminary results from two new c-Si modules are also included after 1 ½ year of HV bias at -1500 V
- The acceleration factors have been calculated for a rainy day and clear sunny day.
- It can be inferred that the study of leakage currents in photovoltaic modules is effective in early detection of design, material, as well as process flaws.

Acknowledgement

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- The authors gratefully acknowledge encouragement by and useful discussions with Dr. John Wohlgemuth, Dr. Dan Cunningham, Dr. Rajeewa Arya, BP Solar and Dr. Joe del Cueto, Dr. Harin Ullal, Dr. Bolko von Roedern and Dr. Peter Hacke, NREL and Dr. James Webb, Corning.

Questions and Comments