PROCEEDINGS

Ice Sphere Impact Testing of Photovoltaic Solar Panels

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ADDRESSING THE BUILDING ENVELOPE

ABSTRACT

The use of alternative renewable energy sources such as photovoltaic solar panels is becoming more common worldwide. Substantial investments are being made by residential and commercial entities. The relative hail resistance of photovoltaic solar panels, however, may not be clearly understood. Several photovoltaic solar panel manufacturers list a hail resistance of up to 1 inch in diameter, which is not an unexpected meteorological event for most areas of the United States.

Jim Koont & Associates (JKA) tested, per ASTM standards, several photovoltaic solar panels using the impact of ice spheres of various diameters. JKA illuminated the photovoltaic solar panels and measured their electrical output both before and after impact. The effects of ice sphere impact on the performance of the photovoltaic solar panels will be discussed.

SPEAKER

Jim D. Koontz, RRC, PE — Jim D. Koontz & Associates, Inc. - Hobbs, NM

JIM D. KOONTZ, RRC, PE, has been involved in the roofing industry for 50+ years. Koontz obtained a BS in engineering and a master's in business administration from Tulane University in New Orleans and is a registered engineer in multiple states. He began his career as a roofer and roofing contractor in 1960; and in 1976, he started one of the first roof engineering firms in the United States.

As a researcher, Koontz has authored numerous technical articles on roofing, covering a variety of technical subjects. Koontz has also been a guest speaker for organizations such as NRCA, ASTM, RCI, international symposia, and others. As a consulting engineer, Koontz has worked in over 40 states, Canada, Mexico, and the Caribbean. Notable projects include the Kingdome in Seattle, the Denver International Airport, and the Church Street USPO at Ground Zero in New York during the aftermath of 9/11.

Ice Sphere Impact Testing of Photovoltaic Solar Panels

The use of alternative renewable energy sources such as photovoltaic (PV) panels is becoming more common worldwide. Data from the Solar Energy Industry Association[1] indicate that in the United States alone, from 2005 through 2010, PV electrical generation increased by approximately 1,000%.

As the nation struggles to develop a comprehensive energy plan, the use of alternative renewable energy sources such as PV panels is clearly becoming more commonplace. Substantial investments are being made to install large PV farms, many of which are within geographical areas that are subject to large hail events. The relative resistance of many of these PV panels to hail impact may not be clearly understood. Currently, several panel manufacturers list a hail resistance of up to only 1.0 in. in diameter. Hail of that size is not an unexpected meteorological event for many areas of the United States.

In reviewing weather data, it is clear that a large portion of the U.S. is subjected to 0.75-in. hail or greater on a frequent basis.[2] As the PV market grows, damage to panels and loss of power because of hail impact may be a significant consideration for both users and insurance carriers.

PRIOR RESEARCH

Some of the first research on the potential for hail damage to solar collectors was performed by the U.S. Department of Energy's Office of Solar Heat Technologies in Washington, DC, in 1982. David Jenkins and Robert Mathey authored a study titled "Hail Impact Testing Procedure for Solar Collector Covers."[3] The U.S. had gone through the Arab oil embargo in the early 1970s. In response to the increase in energy prices, the use and research of alternative energy sources became an important issue. During the Carter administration (1977-1981), solar thermal collectors were installed on numerous federal buildings, including the White House. Many of the early solar thermal collectors have since been removed.

The majority of the research by Jenkins and Mathey focused on the impact resistance of different types of tempered glass, reinforced plastics, and plastic films. These cover materials were typically installed as a double-thickness panel to provide some insulative value above the underlying absorber. Testing showed that those covers failed when impacted with 1.0- to 2.0-in.-diameter ice spheres.

CURRENT STANDARDS

Testing PV panels for hail impact resistance has been limited. Two ASTM standards currently utilized are ASTM E8224, *Determining Resistance of Solar Collector Covers to Hail by Impact With Propelled Ice Balls*, and ASTM E1038-05, *Determining Resistance of Photovoltaic Modules to Hail by Impact With Propelled Ice Balls*. ASTM E822 deals primarily with the physical damage to the cover of solar collectors, whereas ASTM E1038 measures variation in electrical output of the PV modules before and after impact. Both methods involve pneumatically launched ice spheres. The velocity of the ice spheres is measured with a ballistic timer.

Factory Mutual Global (FM) has developed FM 44766, *Approval Standard for Flexible Photovoltaic Modules*; and FM 44787, *Approval Standard for Rigid Photovoltaic Modules*. The FM standards, using steel spheres, allow for testing using both the "Moderate Hail Test" (Class MH) and "Severe Hail Damage Resistance Test" (Class SH), generating an impact energy of 8 foot-pounds and 14 foot-pounds, respectively. This impact energy is equivalent to impact from ice spheres approximately 1.50 and 1.75 in. in diameter, according to data from the National Bureau of Standards (NBS), as reported in "Hail Resistance of Roofing Products," BSS #238.

The Underwriters Laboratory (UL) Standard 17039 requires PV panels to be impacted with steel spheres of 2.0-in. diameter that generate impact energy of 5 foot-

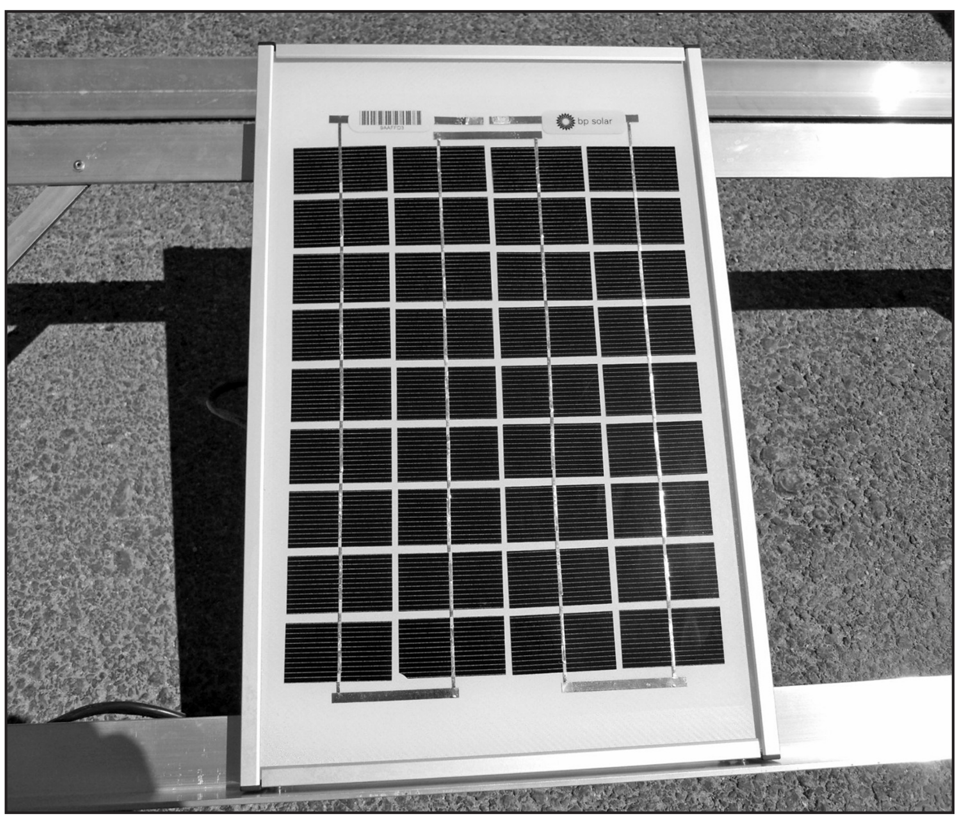
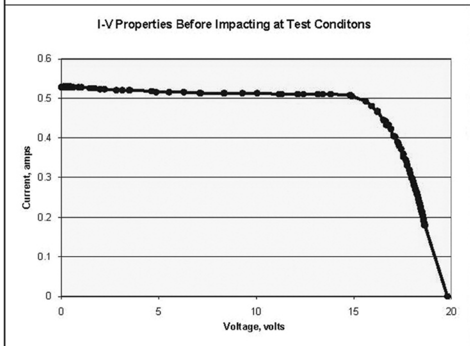


Figure 1 – Panel 1 before hail.

Pre-Hail Ball Impacting Test Results			
Test Conditions			
Date, Time, Wind Speed (mph)	7/28/11, 11:14 AM (2.5)	Air Temperature / Cell Temperature,°F	98 / 123.5
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m²	903
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	7.70	Maximum Power, P_{MAX}, watts	9.41
Short-Circuit Current, I_{SC}, amps	0.53	Short-Circuit Current, I_{SC}, amps	0.58
Open-Circuit Voltage, V_{OC}, volts	19.81	Open-Circuit Voltage, V_{OC}, volts	21.87



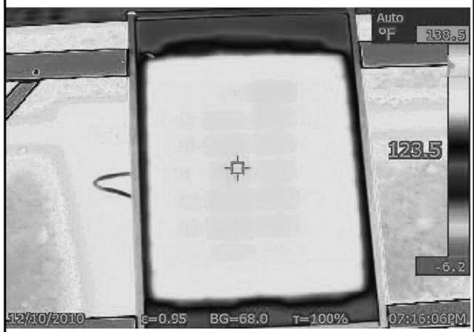


Figure 2 – PV Panel 1.

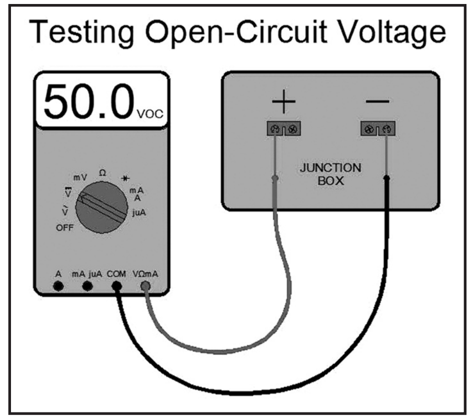


Figure 3A – Open-circuit voltage testing.

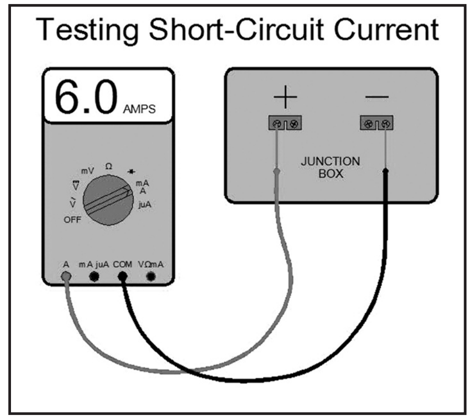


Figure 3B – Short-circuit current.

pounds. According to NBS, this is equivalent to the impact from an ice sphere with a diameter of between 1.25 and 1.50 in. According to NBS, the characteristic of a 2.0-in.-diameter free-falling ice sphere is approximately 22 foot-pounds.

The use of steel spheres dropped from various heights by UL and FM may not provide an accurate assessment of the true impact resistance of a PV panel because of the difference in impact energy of same-

Figure 4 – Hail gun.

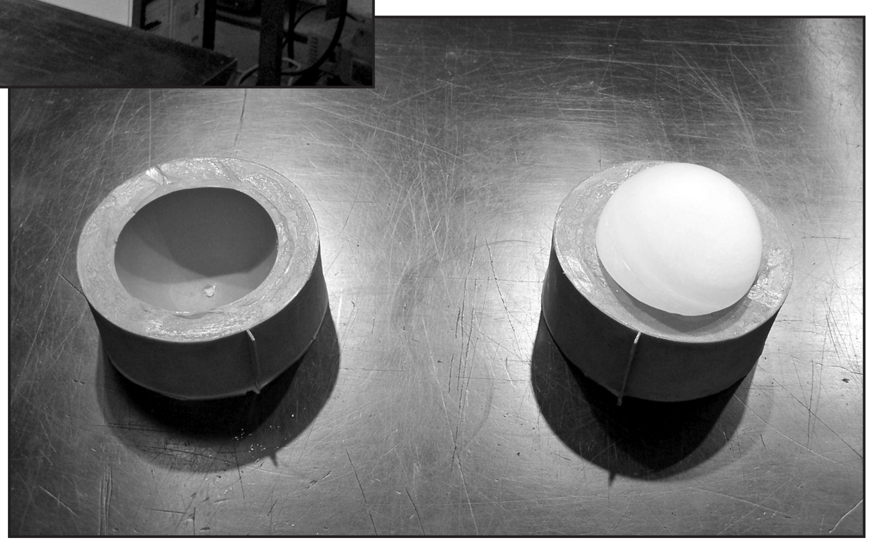


Figure 5 – Ice sphere mold.

sized steel spheres and ice spheres. When UL and FM test for fire, they use fire, not equivalently hot air. Hail testing should follow a protocol that is as close to replicating real-world conditions as possible.

PV IMPACT TESTING

JKA tested five different PV panels following the protocols set forth in ASTME 1038. Panels 1, 2, and 5 were rigid; Panels 3 and 4 were flexible. Initially, each test panel was exposed to natural sunlight at 32.70° N latitude, -103.14 W longitude, and 18° inclination. The initial electrical characteristics of each PV panel were then determined. See *Figure 1*.

The conditions of testing the PV panels in natural sunlight vary. In order to have comparable data, the original data were collected and then normalized to 1000 watts per square meter of panel area, with a cell temperature of 25°C (77°F). By normalizing the data, the electrical characteristics of the PV panels can be compared. See *Figure 2*.

The initial testing performed involved connecting the PV panel to a high-input-resistance voltmeter without any type of electrical loading. The panels are connected to a rheostat that can be adjusted, thus producing a current, amps/voltage, and volts curve. The curve may vary, depending upon the characteristics of a particular PV panel. As a result of the variable load test, the maximum power in watts is calculated.

Two additional tests were performed, which included a short-circuit test (ISC Amps) and an open-circuit voltage test (VOC volts). One acceptable procedure for measuring open-circuit voltage and short-circuit current is found in ASTM E1036-10. See *Figures 3A* and *3B*.

The PV panels were impacted with 1.0-, 1.5-, and 2.0-in-diameter ice spheres. When impacted with 1.0-in.-diameter ice spheres, all of the panels passed. As testing proceeded, if a panel was damaged with 1.5-in.-diameter ice spheres, testing was halted. See *Figures 4* and *5*.

The open-circuit voltage (VOC) and the short-circuit current (ISC) were measured both prior to and after impacting the PV panel at room temperature. See *PV Panel 1*.

Each panel was illuminated with artificial light during the ice sphere impact testing. As each panel was impacted, the voltage output was collected and graphed on an oscilloscope scan. At the point-of-failure, 2.0-in.-diameter ice sphere, a substantial drop in voltage output was recorded on PV Panel 1. See *Figure 6*.

Hail Ball Impact Test Results, Room Temperature

Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	13.66	0.00237	14.04	0.00287	Pass	
1.5"	14.04	0.00287	15.10	0.00426	Pass	
2"	15.10	0.00426	11.62	0.00234	Fail	Cell Edge at Mid-Panel

PV Panel 1.

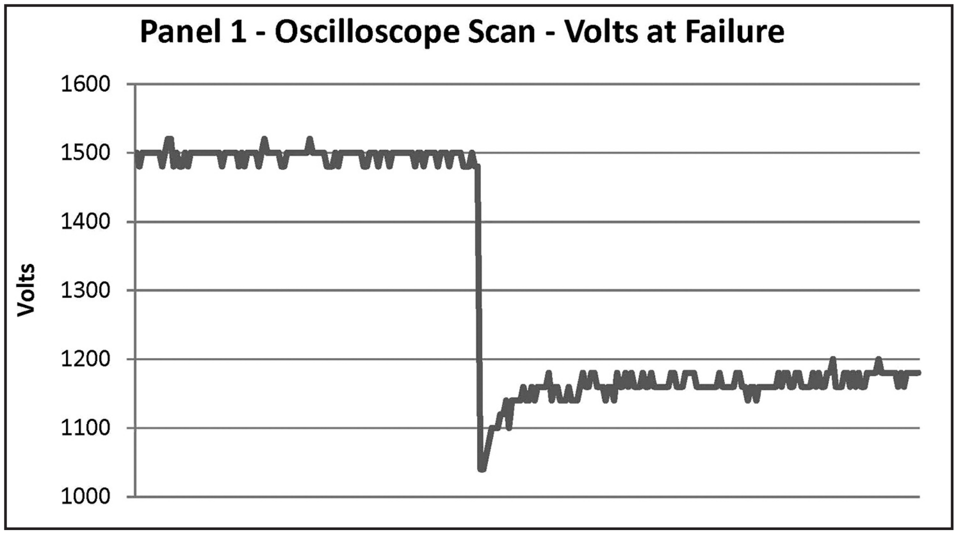
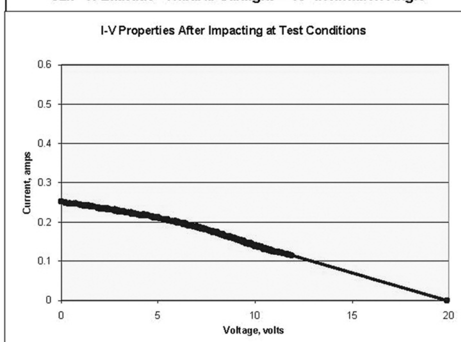
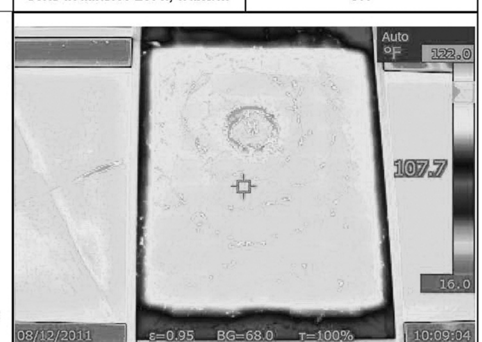


Figure 6 – Panel 1 oscilloscope scan.

Post Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	8/12/11, 10:09 AM (2.6)	Air Temperature / Cell Temperature,°F	84 / 107.7
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m²	807





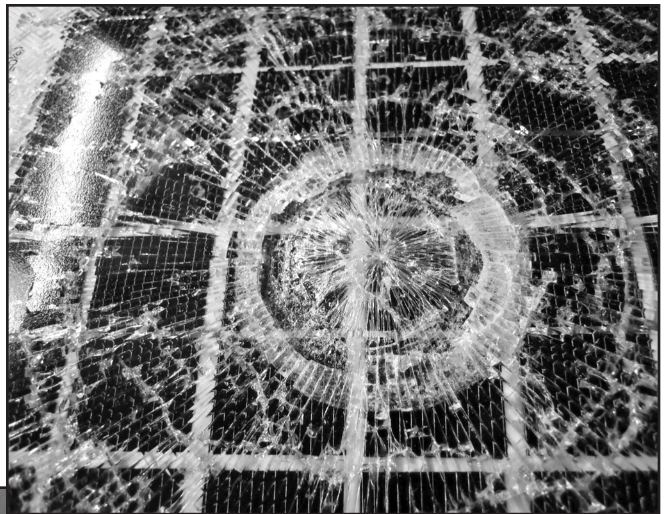
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	1.44	Maximum Power, P_{MAX}, watts	1.90
Short-Circuit Current, I_{SC}, amps	0.25	Short-Circuit Current, I_{SC}, amps	0.31
Open-Circuit Voltage, V_{OC}, volts	19.89	Open-Circuit Voltage, V_{OC}, volts	21.26
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)

Figure 7 – PV Panel 1 after hail impact.

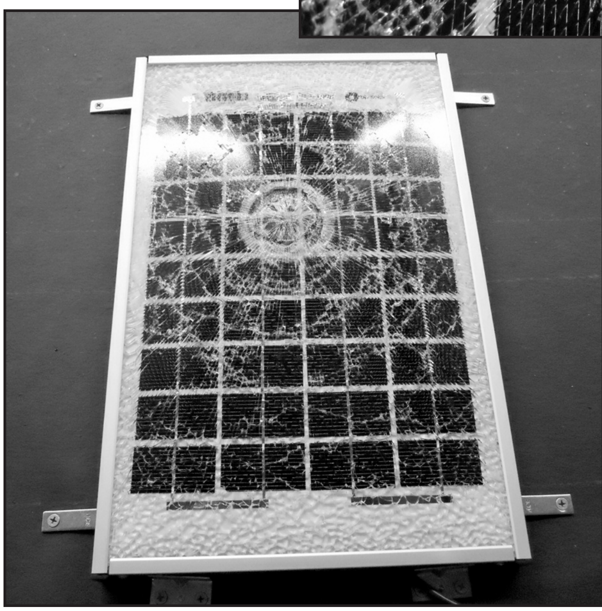
Upon completion of the ice sphere impact testing, the same electrical characteristic tests were performed and compared to the original results. An additional test to measure insulation current leakage or insulation integrity was performed following ASTM E1462-11. See *Figure 7*.

Substantial changes in the electrical characteristics of the panels were observed following impact failure. The maximum power (PMAX) watts dropped from 9.41 to 1.90. The short-circuit amps (ISC) changed from 0.58 to 0.31.

The points of impact were examined visually and microscopically. At the time of impact, slow-motion video was captured to document the impact characteristics at the



Figures 8A and 8B – Panel 1 failure.



precise point of impact. The overall data for each of the five PV panels tested are included in Appendix 1. See *Figures 8A* and *8B*.

CONCLUSIONS

All five of the PV panels tested passed when impacted with 1.0-in.-diameter ice spheres. Out of the five panels tested, three failed when impacted with 1.5-in.-diameter ice spheres. Two of the five panels did not fail until impacted with 2.0-in.-diameter ice spheres. See *Table 1*.

Diameter of Ice Sphere at Failure				
Panel	Type	1.0-in. Ice Sphere	1.5-in. Ice Sphere	2.0-in. Ice Sphere
1	Rigid	Pass	Pass	Fail
2	Rigid	Pass	Pass	Fail
3	Flexible	Pass	Fail	-
4	Flexible	Pass	Fail	-
5	Rigid	Pass	Fail	-

Table 1

Damage to some of the PV panels was very subtle and not easy to see. Following a hail event, a user may want to monitor the PV system, comparing performance before and after a hail event to determine if there has been any substantial drop in electrical output.

Reliance upon the use of PV panels will continue to increase in the future. Users will become dependent upon the reliable performance of the PV energy sources. Protecting this source of energy from catastrophic failure or even damage should be one of the goals of the PV industry.

PV panel manufacturers should test and provide users with the relative hail resistance of their particular product. Current warranties from many manufacturers only represent that the PV product is resistant up to 1.0-in.-diameter hail. The warranties do not reflect the requirements of FM or UL.

PV systems will be installed in geographical areas that experience large and frequent hail events. Manufacturers of these PV systems should develop assemblies that are resistant to large hail, or should provide protective covers (i.e., hail screens), or both, to shield the PV panels from large hail.

Special thanks to Gerald B. Curtis, RRC, and Richard Fricklas for their assistance with this article.

REFERENCES

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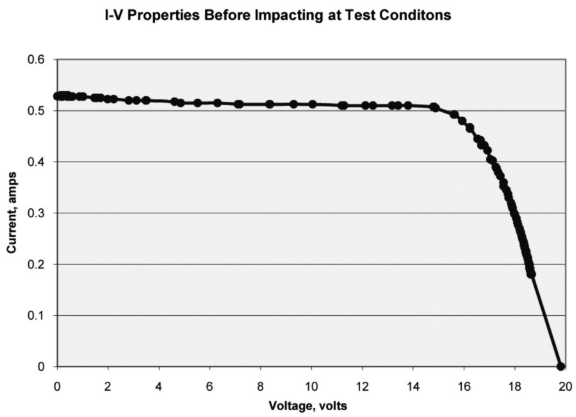
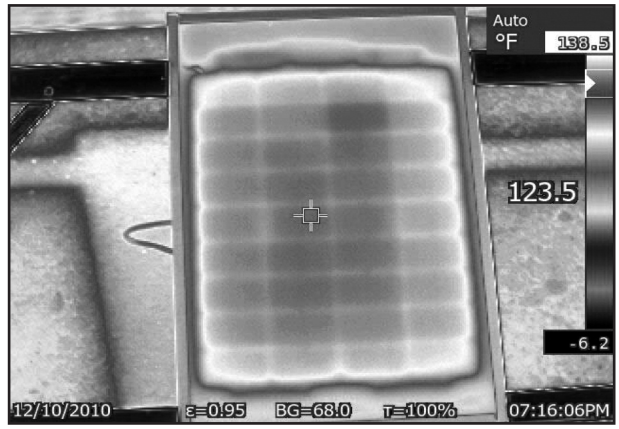
Photovoltaic Research • ASTM E 1038 • Test Data Sheet
Panel Identification: **PV Panel #1**

Pre Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	7/28/11, 11:14 AM (2.5)	Air Temperature / Cell Temperature,°F	98 / 123.5
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	903





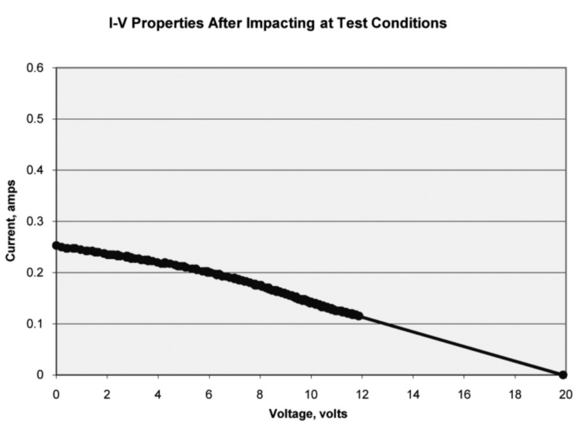
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	7.70	Maximum Power, P_{MAX}, watts	9.41
Short-Circuit Current, I_{SC}, amps	0.53	Short-Circuit Current, I_{SC}, amps	0.58
Open-Circuit Voltage, V_{OC}, volts	19.81	Open-Circuit Voltage, V_{OC}, volts	21.87

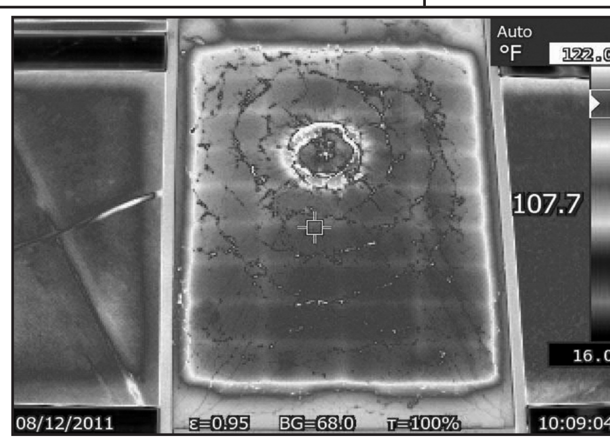
Hail Ball Impact Test Results, Room Temperature

Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	13.66	0.00237	14.04	0.00287	Pass	
1.5"	14.04	0.00287	15.10	0.00426	Pass	
2"	15.10	0.00426	11.62	0.00234	Fail	Cell Edge at Mid-Panel

Post Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	8/12/11, 10:09 AM (2.6)	Air Temperature / Cell Temperature,°F	84 / 107.7
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	807





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	1.44	Maximum Power, P_{MAX}, watts	1.90
Short-Circuit Current, I_{SC}, amps	0.25	Short-Circuit Current, I_{SC}, amps	0.31
Open-Circuit Voltage, V_{OC}, volts	19.89	Open-Circuit Voltage, V_{OC}, volts	21.26
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)

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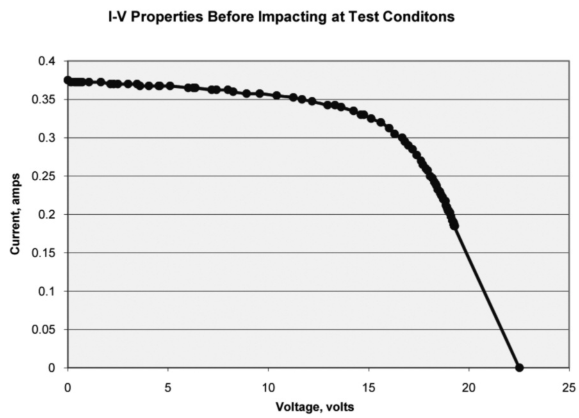
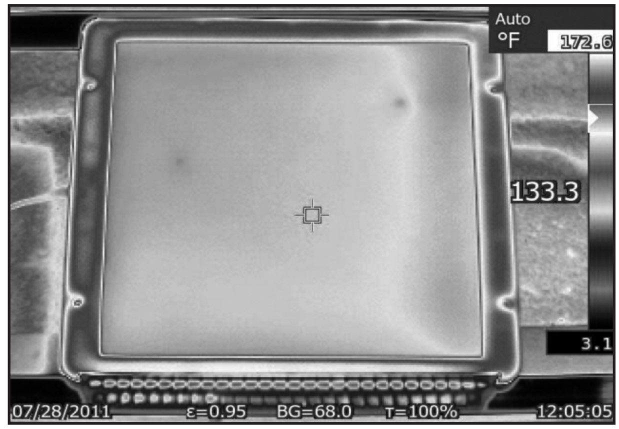
Panel Identification: **PV Panel #2**

Pre Hail Ball Impacting Test Results			
Test Conditions			
Date, Time, Wind Speed (mph)	7/28/11, 12:05 PM (1.3)	Air Temperature / Cell Temperature,°F	98.5 / 133.3
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	960



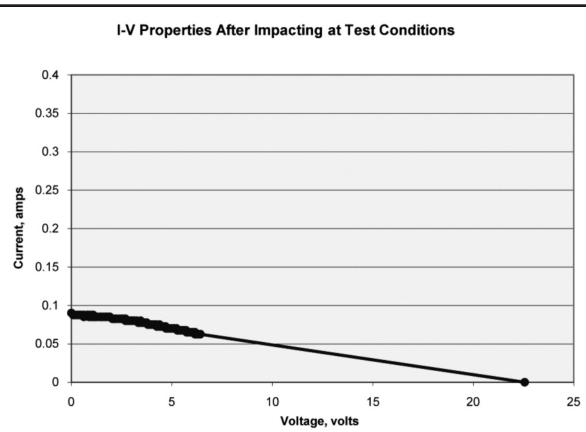


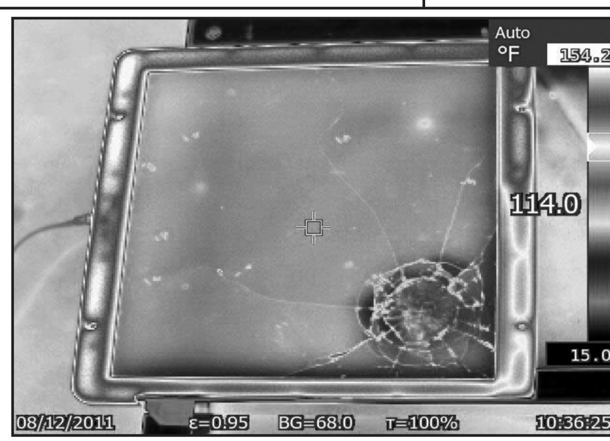
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	5.01	Maximum Power, P_{MAX}, watts	5.65
Short-Circuit Current, I_{SC}, amps	0.38	Short-Circuit Current, I_{SC}, amps	0.39
Open-Circuit Voltage, V_{OC}, volts	22.52	Open-Circuit Voltage, V_{OC}, volts	24.41

Hail Ball Impact Test Results, Room Temperature

Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	4.58	0.0096	4.48	0.0092	Pass	
1.5"	4.48	0.0092	5.13	0.0111	Pass	
2"	5.13	0.0111	3.76	0.0051	Fail	Center of Cell

Post Hail Ball Impacting Test Results			
Test Conditions			
Date, Time, Wind Speed (mph)	8/12/11, 10:36 AM (0.3)	Air Temperature / Cell Temperature,°F	90 / 114
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	889





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	0.40	Maximum Power, P_{MAX}, watts	0.48
Short-Circuit Current, I_{SC}, amps	0.09	Short-Circuit Current, I_{SC}, amps	0.10
Open-Circuit Voltage, V_{OC}, volts	22.56	Open-Circuit Voltage, V_{OC}, volts	23.80
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)

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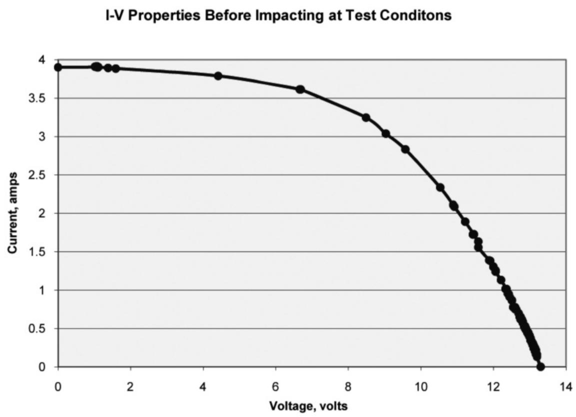
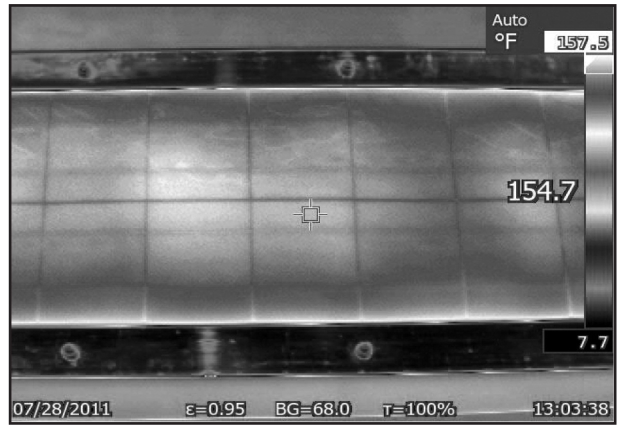
Panel Identification: **PV Panel #3**

Pre Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	7/28/11, 1:03 PM (1.2)	Air Temperature / Cell Temperature,°F	100 / 154.7
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	996





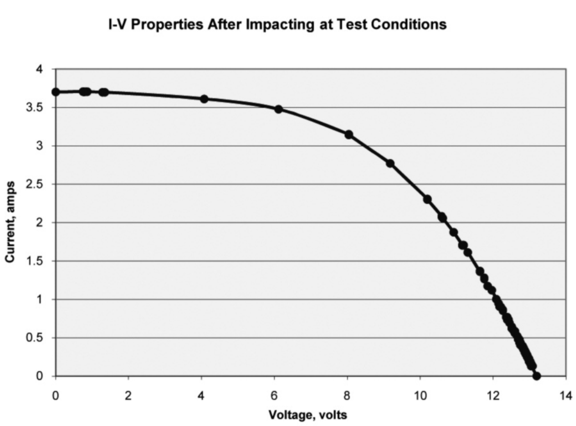
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	27.55	Maximum Power, P_{MAX}, watts	33.08
Short-Circuit Current, I_{SC}, amps	3.90	Short-Circuit Current, I_{SC}, amps	3.92
Open-Circuit Voltage, V_{OC}, volts	13.30	Open-Circuit Voltage, V_{OC}, volts	15.90

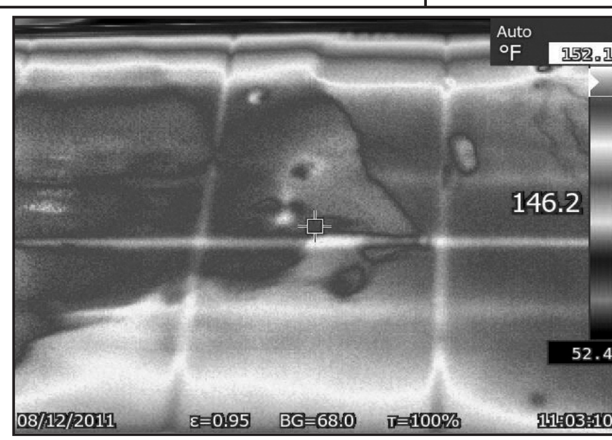
Hail Ball Impact Test Results, Room Temperature

Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	7.94	0.04450	7.94	0.05030	Pass	Visible Damage
1.5"	7.94	0.05030	7.54	0.05130	Fail	Center of Cell
2"						

Post Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	8/12/11, 11:03 AM (2.5)	Air Temperature / Cell Temperature,°F	92 / 146.2
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	942





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	25.45	Maximum Power, P_{MAX}, watts	31.33
Short-Circuit Current, I_{SC}, amps	3.70	Short-Circuit Current, I_{SC}, amps	3.93
Open-Circuit Voltage, V_{OC}, volts	14.52	Open-Circuit Voltage, V_{OC}, volts	16.84
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)

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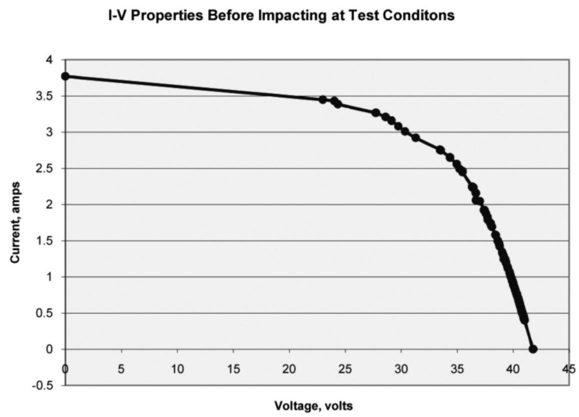
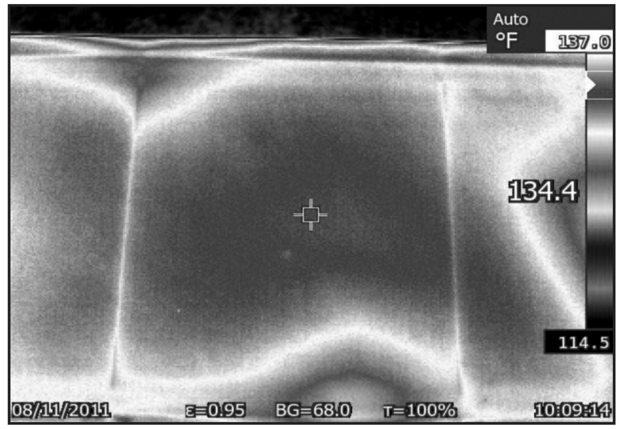
Panel Identification: **PV Panel #4**

Pre Hail Ball Impacting Test Results

Test Conditions

Date, Time, Wind Speed (mph)	8/11/11, 10:09 AM (3.5)	Air Temperature / Cell Temperature,°F	86 / 134.4
32.7° N Latitude - Natural Sunlight - 0° Inclination Angle		Solar Irradiance Level, watts/m^2	635





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	92.24	Maximum Power, P_{MAX}, watts	145.67
Short-Circuit Current, I_{SC}, amps	3.77	Short-Circuit Current, I_{SC}, amps	5.94
Open-Circuit Voltage, V_{OC}, volts	42.30	Open-Circuit Voltage, V_{OC}, volts	42.42

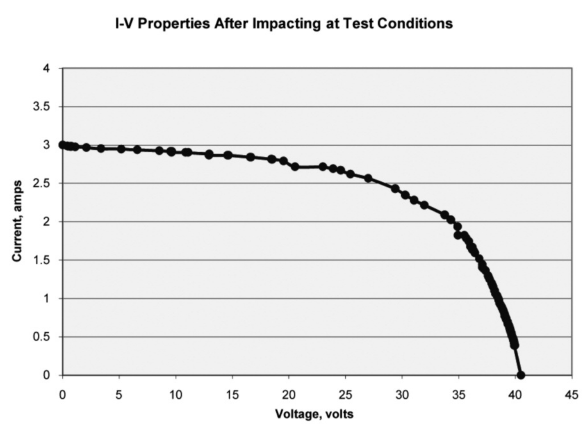
Hail Ball Impact Test Results, Room Temperature

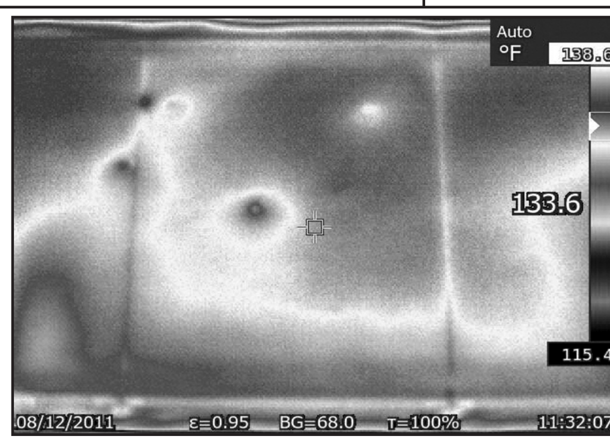
Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	5.57	0.00473	5.61	0.00479	Pass	
1.5"	5.61	0.00479	4.65	0.00439	Fail	Edge of Cell
2"						

Post Hail Ball Impacting Test Results

Test Conditions

Date, Time, Wind Speed (mph)	8/12/11, 11:32 AM (1.0)	Air Temperature / Cell Temperature,°F	93 / 133.6
32.7° N Latitude - Natural Sunlight - 0° Inclination Angle		Solar Irradiance Level, watts/m^2	576





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	71.52	Maximum Power, P_{MAX}, watts	124.52
Short-Circuit Current, I_{SC}, amps	3.25	Short-Circuit Current, I_{SC}, amps	5.64
Open-Circuit Voltage, V_{OC}, volts	41.00	Open-Circuit Voltage, V_{OC}, volts	41.12
Insulation Resistance Test, MΩ, (Pass / Fail)			0.2 (Fail)

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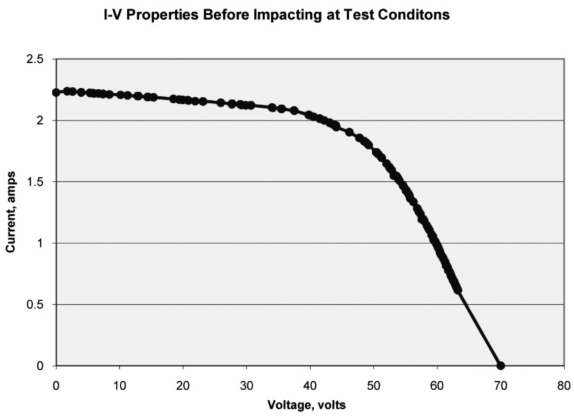
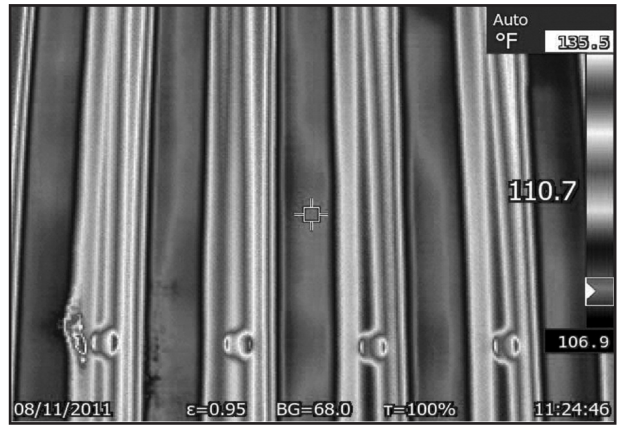
Panel Identification: **PV Panel #5**

Pre Hail Ball Impacting Test Results

Test Conditions

Date, Time, Wind Speed (mph)	8/11/11, 11:24 AM (0.8)	Air Temperature / Cell Temperature,°F	93 / 110.7
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	930





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	88.77	Maximum Power, P_{MAX}, watts	95.55
Short-Circuit Current, I_{SC}, amps	2.23	Short-Circuit Current, I_{SC}, amps	2.40
Open-Circuit Voltage, V_{OC}, volts	70.00	Open-Circuit Voltage, V_{OC}, volts	70.07

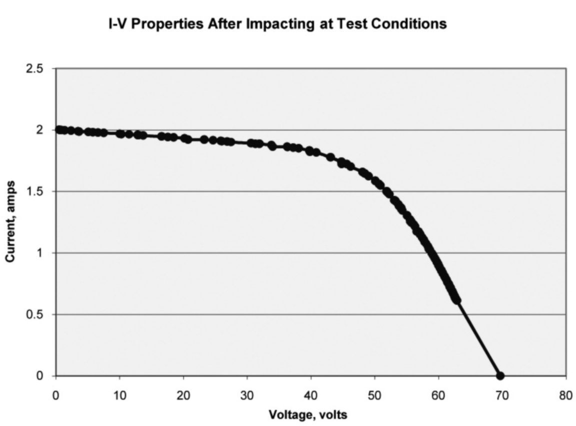
Hail Ball Impact Test Results, Room Temperature

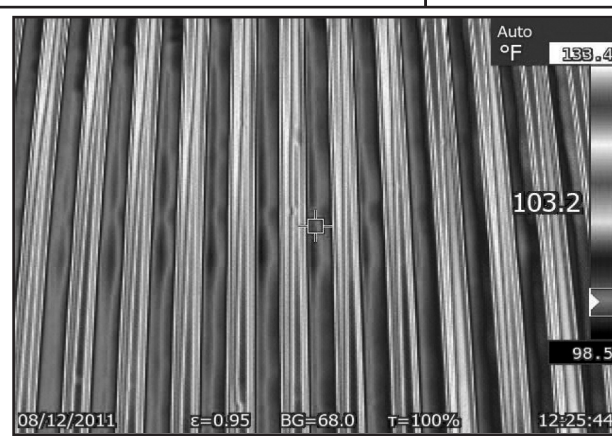
Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	49.6	0.1737	49.6	0.1737	Pass	
1.5"	49.6	0.1737	47.9	0.1592	Fail	Center & Edge of Cell
2"						

Post Hail Ball Impacting Test Results

Test Conditions

Date, Time, Wind Speed (mph)	8/12/11, 12:25 PM (2.0)	Air Temperature / Cell Temperature,°F	86.0 / 103.2
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	916





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	79.83	Maximum Power, P_{MAX}, watts	87.22
Short-Circuit Current, I_{SC}, amps	1.97	Short-Circuit Current, I_{SC}, amps	2.15
Open-Circuit Voltage, V_{OC}, volts	69.70	Open-Circuit Voltage, V_{OC}, volts	69.76
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)

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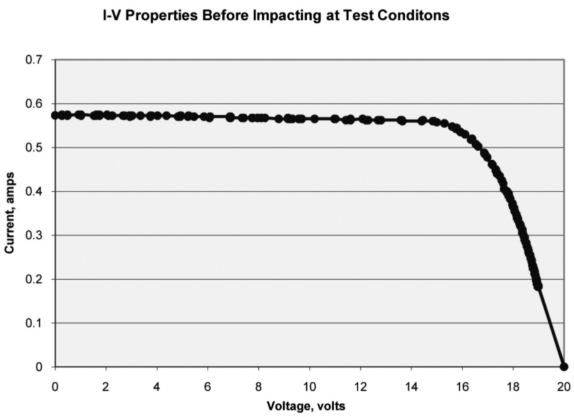
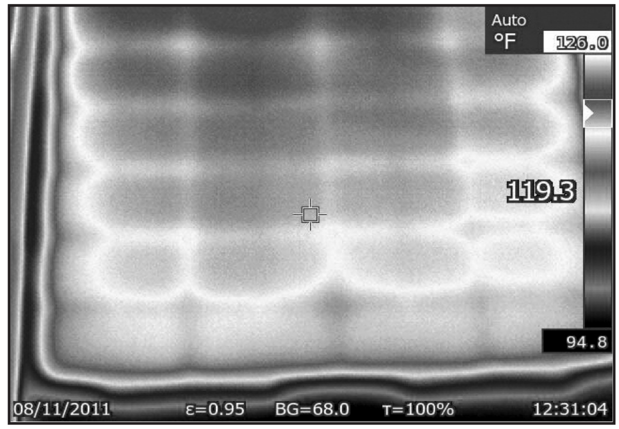
Panel Identification: **PV Panel #6**

Pre Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	8/11/11, 12:31 PM (3.0)	Air Temperature / Cell Temperature,°F	97 / 119.3
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	970





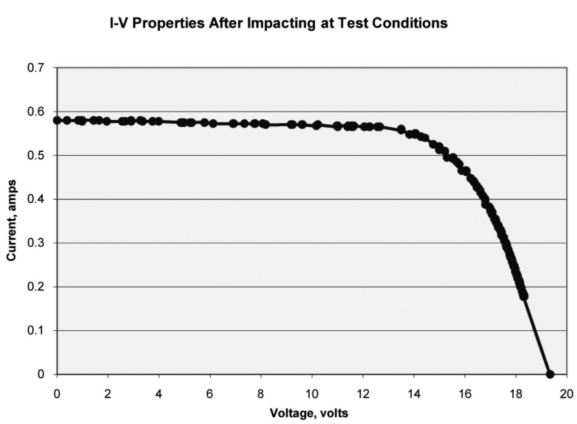
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	8.60	Maximum Power, P_{MAX}, watts	9.67
Short-Circuit Current, I_{SC}, amps	0.57	Short-Circuit Current, I_{SC}, amps	0.59
Open-Circuit Voltage, V_{OC}, volts	20.61	Open-Circuit Voltage, V_{OC}, volts	22.49

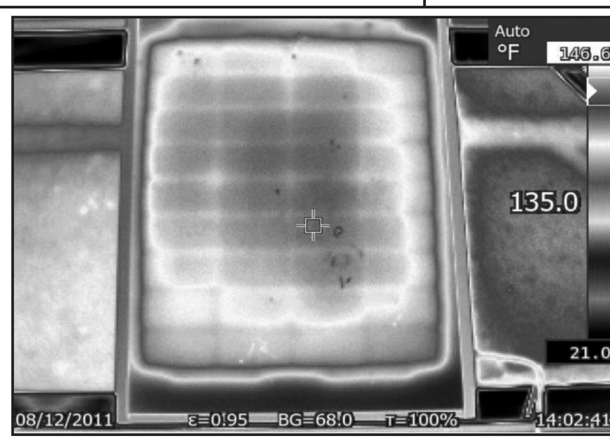
Hail Ball Impact Test Results, Room Temperature

Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	17.99	0.00355	17.99	0.00355	Pass	
1.5"	17.99	0.00355	17.99	0.00355	Pass	
2"	17.99	0.00355	15.90	0.00399	Fail	No Visible Damage

Post Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	8/12/11, 2:02 PM (0.9)	Air Temperature / Cell Temperature,°F	96 / 135.0
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	1019





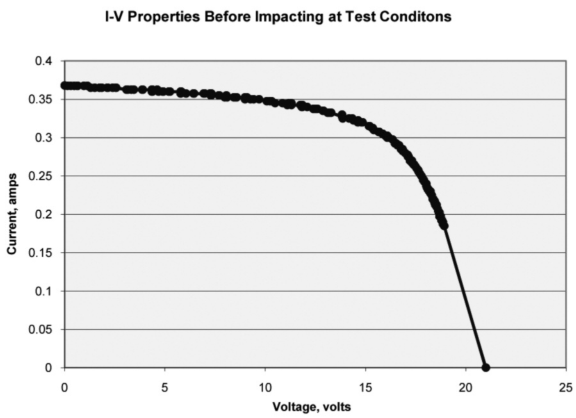
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	7.80	Maximum Power, P_{MAX}, watts	8.67
Short-Circuit Current, I_{SC}, amps	0.58	Short-Circuit Current, I_{SC}, amps	0.57
Open-Circuit Voltage, V_{OC}, volts	19.34	Open-Circuit Voltage, V_{OC}, volts	21.92
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)

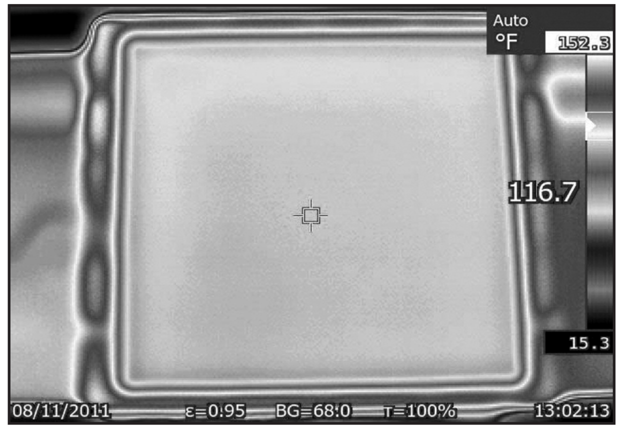
Panel Identification: **PV Panel #7**

Pre Hail Ball Impacting Test Results

Test Conditions

Date, Time, Wind Speed (mph)	8/11/11, 1:02 PM (0.5)	Air Temperature / Cell Temperature,°F	98 / 116.7
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	983





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	4.86	Maximum Power, P_{MAX}, watts	5.25
Short-Circuit Current, I_{SC}, amps	0.37	Short-Circuit Current, I_{SC}, amps	0.37
Open-Circuit Voltage, V_{OC}, volts	22.22	Open-Circuit Voltage, V_{OC}, volts	23.55

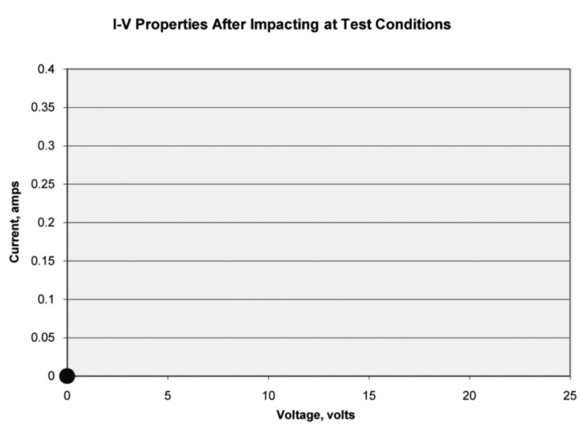
Hail Ball Impact Test Results, Room Temperature

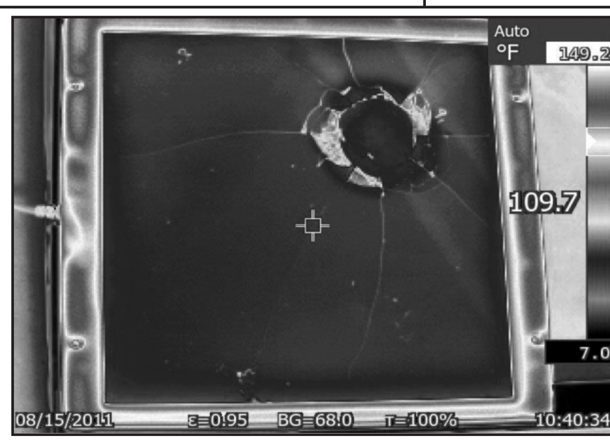
Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	1.61	0.0075	1.61	0.0070	Pass	
1.5"	1.61	0.0070	1.88	0.0091	Pass	
2"	1.88	0.0091	5.32	0.0029	Fail	Center of Cell, Corner of Panel

Post Hail Ball Impacting Test Results

Test Conditions

Date, Time, Wind Speed (mph)	8/15/11, 10:40 AM (1.0)	Air Temperature / Cell Temperature,°F	90 / 109.7
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	900





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	0.00	Maximum Power, P_{MAX}, watts	0.00
Short-Circuit Current, I_{SC}, amps	0.00	Short-Circuit Current, I_{SC}, amps	0.00
Open-Circuit Voltage, V_{OC}, volts	0.00	Open-Circuit Voltage, V_{OC}, volts	0.00
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)

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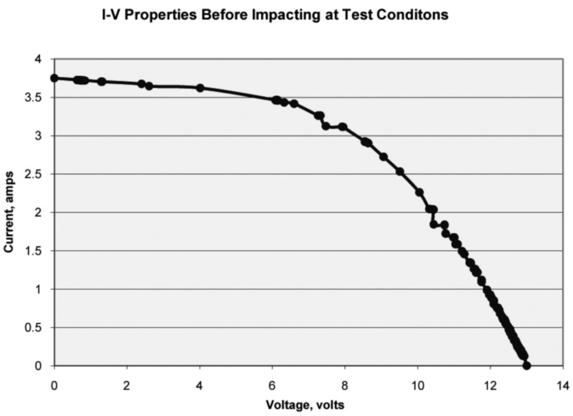
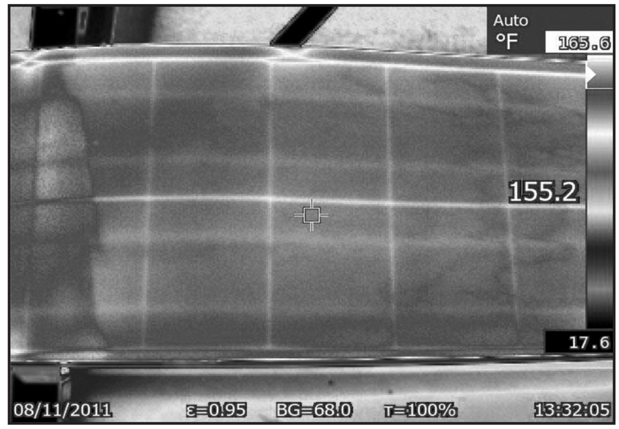
Panel Identification: **PV Panel #8**

Pre Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	8/11/11, 1:32 PM (3.0)	Air Temperature / Cell Temperature,°F	100 / 155.2
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	980





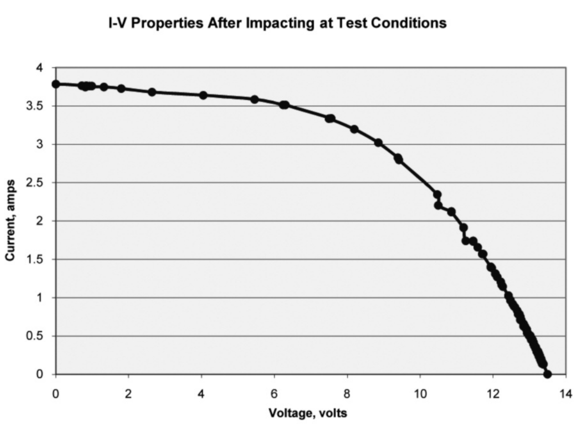
Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	25.10	Maximum Power, P_{MAX}, watts	30.61
Short-Circuit Current, I_{SC}, amps	3.75	Short-Circuit Current, I_{SC}, amps	3.83
Open-Circuit Voltage, V_{OC}, volts	13.42	Open-Circuit Voltage, V_{OC}, volts	16.04

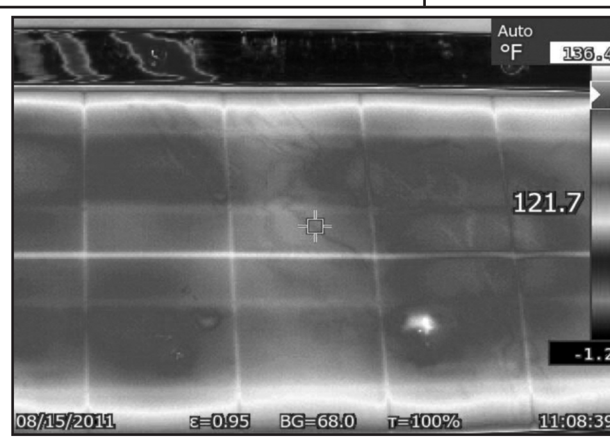
Hail Ball Impact Test Results, Room Temperature

Hail Ball Dia.	Initial V_{OC}	Initial I_{SC}	Final V_{OC}	Final I_{SC}	Pass / Fail	Failure Location
1"	6.74	0.0290	6.11	0.0228	Pass	
1.5"	6.11	0.0228	7.63	0.0373	Fail	Cell Edge
2"	7.83	0.0373	7.99	0.0424	Fail	Visible Damage

Post Hail Ball Impacting Test Results

Test Conditions			
Date, Time, Wind Speed (mph)	8/15/11, 11:08 AM (1.5)	Air Temperature / Cell Temperature,°F	91 / 121.7
32.7° N Latitude - Natural Sunlight - 18° Inclination Angle		Solar Irradiance Level, watts/m^2	935





Electrical Characteristics at Test Conditions		Electrical Characteristics Normalized to STC, Approximation Method	
Maximum Power, P_{MAX}, watts	26.75	Maximum Power, P_{MAX}, watts	31.56
Short-Circuit Current, I_{SC}, amps	3.79	Short-Circuit Current, I_{SC}, amps	4.05
Open-Circuit Voltage, V_{OC}, volts	14.50	Open-Circuit Voltage, V_{OC}, volts	16.00
Insulation Resistance Test, MΩ, (Pass / Fail)			∞ (Pass)