Reliability and Application Challenges for Flexible Thin-Film (BIPV) Modules

Samir Sharma & Doug Herron
United Solar Ovonic LLC

PV Module Reliability Workshop
Golden, CO
February 17, 2011

Flexible BIPV Thin-Film PV Modules and their applications

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United Solar Ovonic amorphous silicon-based flexible thin-film module

Advantages:

- Requires no roof penetrations
- Lightweight, durable, flexible
- Ideal for Building Integrated (BIPV)
- Easy to install
- Tested and proven products in real-life conditions since 1983

BIPV application for United Solar Ovonic modules (attached to metal and various roofing membranes/substrates)

Product Development Process – Reliability

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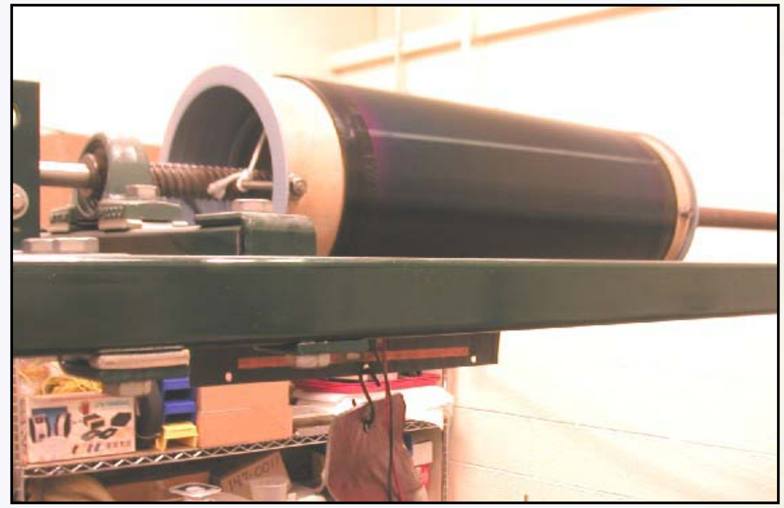
	GATE 1 CONCEPT	GATE 2 DEVELOP	GATE 3 VALIDATION	GATE 4 AUDIT
Marketing	Business Case	Update Business Case	Update Business Case including Roadmap	Audit Business Case and Roadmap
	Market Size and Pricing	Update Market Size, Price	Update Market Size, Price	Audit Market Size, Price
	Channel Strategy	Update Channel Strategy	Prepare Channel for Launch	Audit Channel Performance
Engineering	Product Specification (Prelim)	Detailed Product Specification	Finalize Product Specification	Verify Performance to Product Specification
	Product Layout (Concept)	Detailed Product Design and BOM	Finalize Product Design	Develop Continuous Improvements
	FMEA and Risk Reduction	Perform Internal Qualification	Perform External Qualification and Beta Tests	Reliability Audit with Corrective Actions
Operations	Preliminary Mfg Concept	Detailed Mfg and Quality Plan	Demonstrate Mfg Plan and Quality System	Audit Mfg Performance and factory quality
	Sourcing	Detailed Sourcing Plan	Production Suppliers under contract	Audit Supplier performance and quality
	Mfg Cost Estimates	Detailed Cost Estimates	Validate Cost Estimates	Confirm cost actuals meet business case
Field Service	Install and Field Support Concept	Detailed Install and Field Support Plan	Demonstrate Installation, maintenance procedures	Audit installation and maintenance procedures
	Installation and O&M cost estimate	Detailed Installation and O&M estimates	Validate Install and O&M cost estimates	Audit Install and O&M costs, warranty issues.
Legal	IP Search and Filing	Update IP Search and Filing	Update IP Search and Filing	Check for infringement

Unique Reliability Testing – Flexible PV

Cyclic Flex Test (Fatigue test): Useful for evaluating interconnect and bus bar designs, thin-film and encapsulant mechanical integrity. Flexible modules are subjected to flexing and coiling conditions



Hot water immersion is used for down-selection testing of polymeric materials; Inexpensive technique with high sample throughput and comparative analysis. Voltage/current biasing can be used for highly accelerated comparative testing

Application Challenges for BIPV Products

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- BIPV/BAPV modules are integrated or attached to roofs or other part of the building (flexible membranes, metal etc), so it's critical to evaluate the application reliability of the BIPV module
  - BIPV modules are not only required to meet PV standards <u>but also</u> roofing/building material requirements and codes
- Several organizations are working on creating effective standards for BIPV modules, e.g. IEC TC82 (WG3), FM global and ICC-ES
- Several building/roofing material requirements, applicable to BIPV
  - Higher wind pressures for coastal regions (up to 150 mph),
  - Requirements for Hail Resistance
  - Heat aging requirements
  - Fire classification requirements per *2009 International Building Code® (2009 IBC)*
  - Wind-driven Rain test, *per Florida Building code*
  - Ultraviolet Exposure- up to 2000 hrs of exposure, *per International Building code (Double of UL/IEC requirements)*
  - Roof penetration test – *per ICC-ES, AC -07*
  - Resistance to Foot Traffic Test – *per FM 4470*

Basic Roof Construction and Application of BIPV

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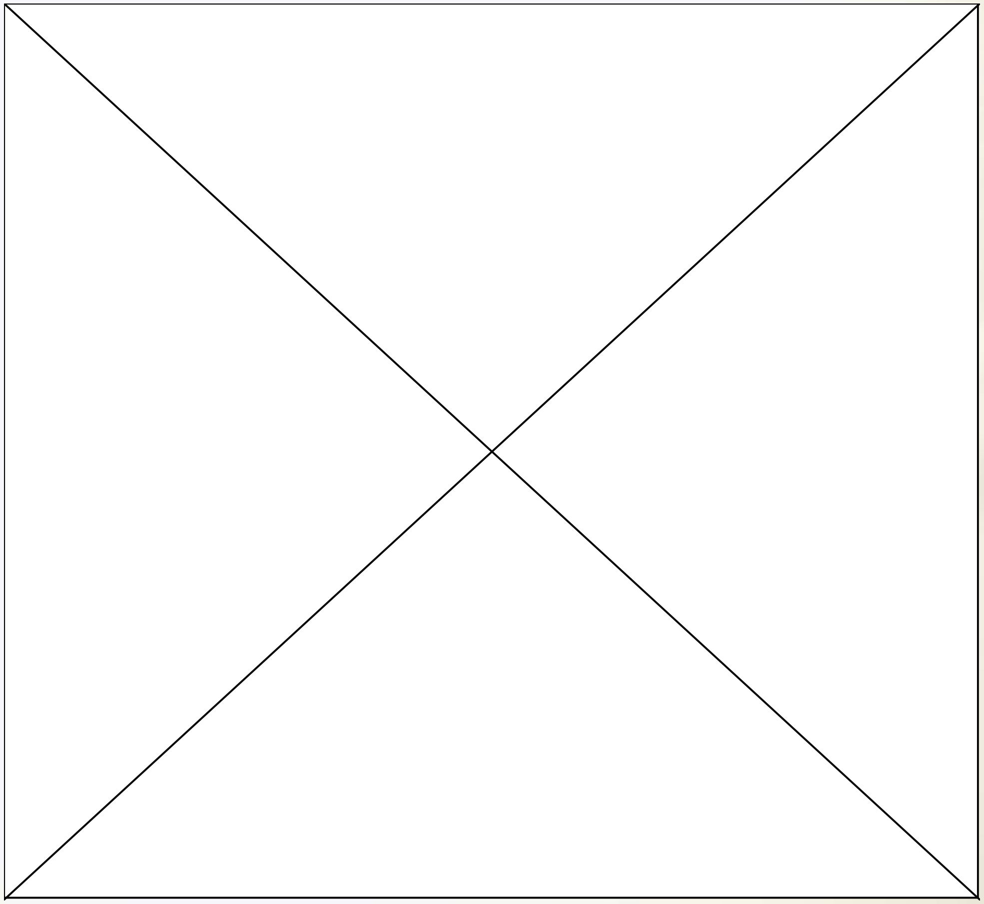
- BIPV modules can be attached to the roof membrane or uppermost layer of the roof
- BIPV modules must meet building and roofing codes and standards
  - *International Building Codes* (IBC)
  - US building codes published by *American Society of Civil Engineers* (ASCE)
  - Local code requirements (e.g. Miami-Dade), Factory Mutual (FM), *National Building Code* (BOCA)*, the Standard Building Code,* (SBCCI); and the *South Florida Building Code* (SFBC), *ICC-ES* etc

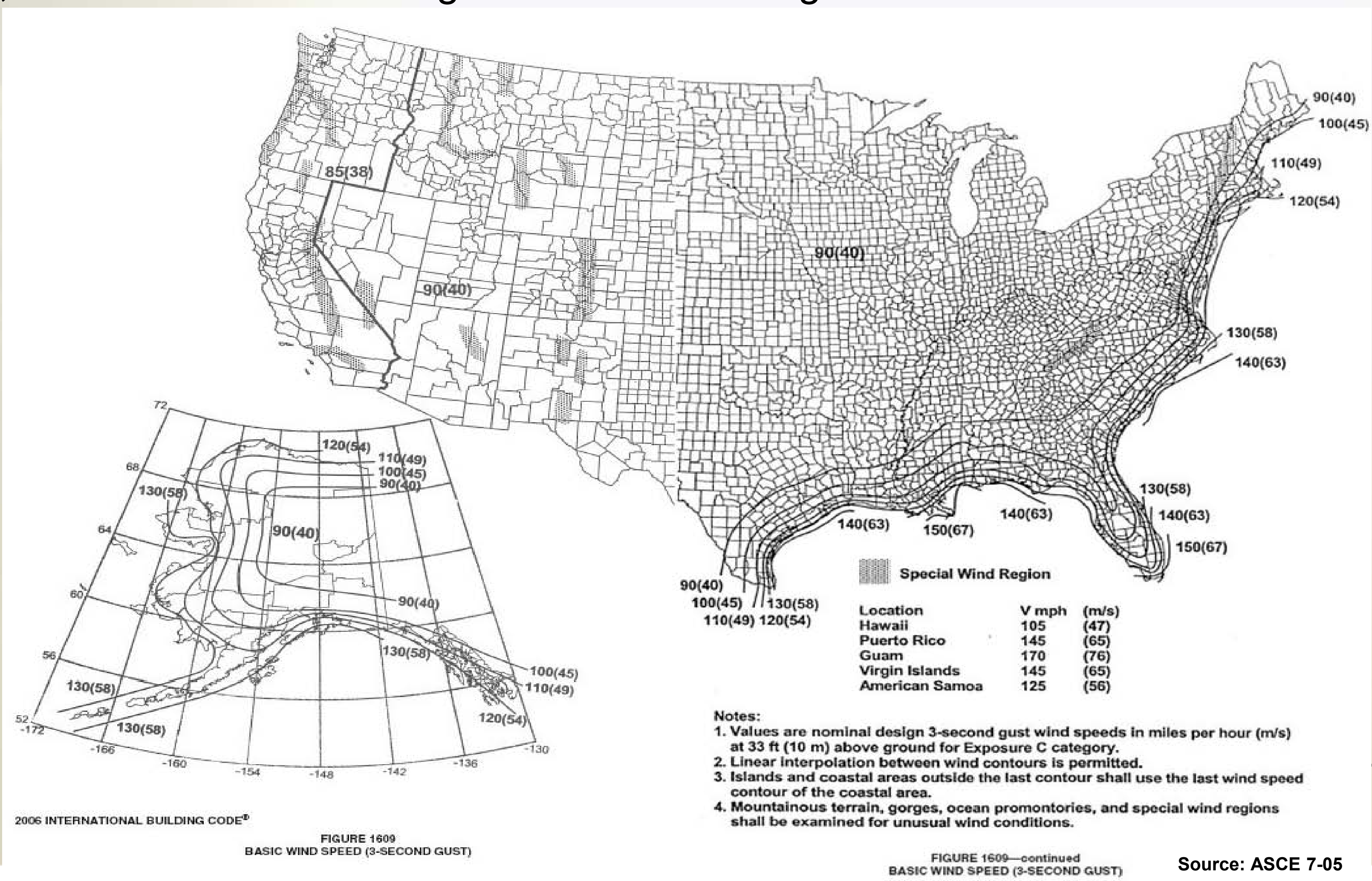


Courtesy: Carlisle SynTec

Heavy Wind Effects and Code Requirements

Certain parts of the US face heavy hurricanes, tropical storms, thunderstorms and high winds, so there are specific requirements set by regulatory bodies for building structures

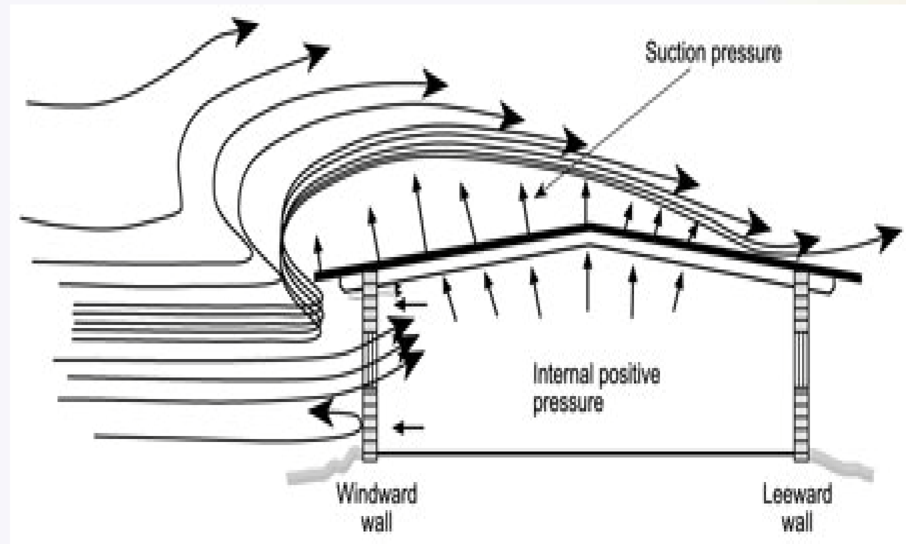
US building codes use the engineering standard published by the American Society of Civil Engineers, ASCE7 “Minimum Design Loads for Buildings and Other Structures”



Source: ASCE 7-05

Wind Uplift Resistance

- Roof /PV damage occurs when wind pressure directly above the roof is lower than below
- The result is a net upward force on the roofing system. This force is referred to as **wind uplift**.
- For hurricane zone areas the requirement for wind uplift resistance is very high
- *Standard Building Code,* (SBCCI); the *South Florida Building Code* (SFBC) and FM set the requirements for wind uplift resistance and BIPV systems. Other building/roofing materials must also comply with these codes/requirements .



BIPV System Design for Wind Uplift Resistance

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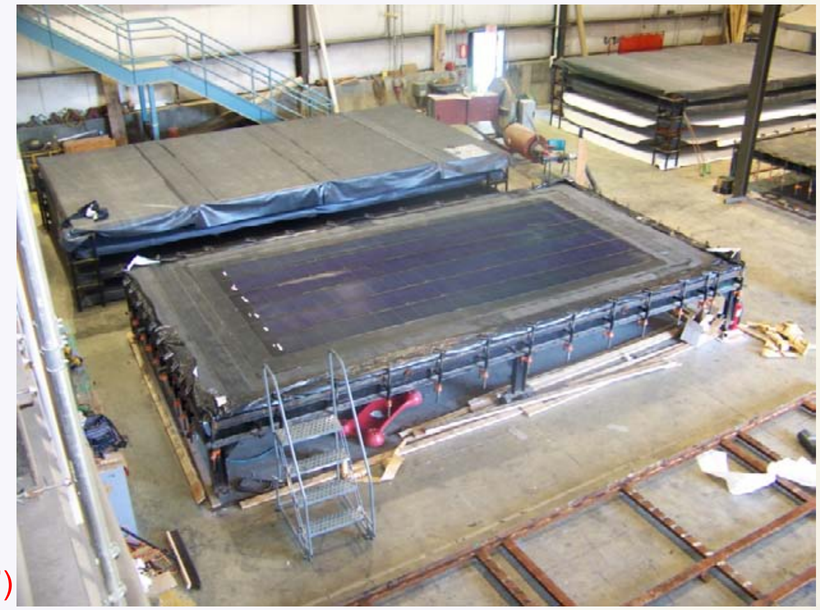
- BIPV system must be designed to withstand heavy wind uplifts
- ANSI/FM 4474 standard provides a test for wind uplift resistance. The ratings are measured in psf, which correlates to wind speed using various parameters (multipliers):
  - The building's overall height
  - The terrain surrounding the structure
  - The type of roof deck on the building
  - Roof slope
  - Location of the building (city/state)
  - Usage of building
  - Location of BIPV on the roof deck/structure

(test rig – 12'x24'x4')



Uni-Solar modules tested for wind-uplift

- Solar roof (BIPV) samples are tested for wind uplift resistance using the 12' x 24' Simulated Wind Uplift Pressure Test
- Air pressure applied in 15 psf increments for one minute until failure occurs (or the limit of test equipment), ratings are given in 1-60, 1-90 or 1-120 (psf)
- All membranes and photovoltaic modules shall:
  a) not tear, puncture, fracture or develop any through openings
  b) not delaminate or separate from adjacent components

BIPV System Design for Wind Uplift Resistance

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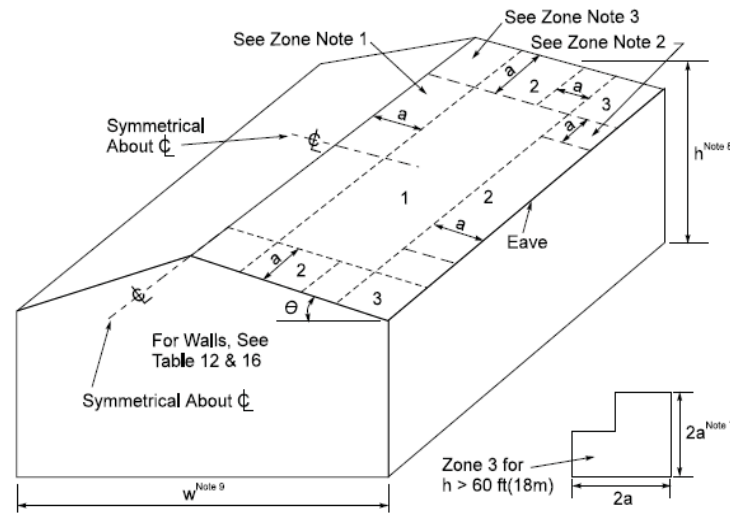
Table 5. Roof Field Area (Zone 1) Uplift Design Pressure, p, for Exposure D, Flat or Gable Roof, Θ ≤ 7° slope (For 60 ft (18 m) < h < 90 ft (27 m), limited to h/w ≤ 1); Enclosed Building

$p = 0.00256\, K_z\, K_{zt}\, K_d\, V^2\, I\, [(GC_p) - (GC_{pi})]$ in pounds per ft² (psf)												
Enclosed Building; Roof Zone 1 (Field Area), Effective Wind Area 1 to 10 ft²; K_{zt} = 1.0; z = h; (GC_p) = - 1.0 for h < 90 ft and (GC_p) = - 1.4 for h ≥ 90 ft; (GC_{pi}) = 0.18												
Mean Roof Height h (ft)	Basic Wind Speed, V, 3-sec gust, (mph)											
	≤ 85	90	100	110	120	130	140	145	150	160	170	185
	Roof Field Area Uplift Design Pressure, p, Exposure D (psf)											
0-15	22	25	31	37	44	51	60	64	68	78	88	104
30	25	28	34	42	49	58	67	72	77	88	99	117
60	28	31	39	47	56	65	76	81	87	99	112	133
89	30	34	42	50	60	70	81	87	93	106	120	142
90	40	45	56	67	80	94	109	117	125	142	161	190
100	41	46	57	69	82	96	111	119	127	145	164	194
200	46	52	64	77	92	108	125	134	144	164	185	219
300	50	56	69	83	99	117	134	144	154	176	198	235
400	52	58	72	87	104	122	141	152	162	185	208	247
500	54	61	75	91	108	127	147	158	169	192	217	257

Source: FM Global Property Loss Prevention Data Sheets



Roof Design Negative Pressure Multipliers Zones 1, 2, 3 for Flat and Gabled Roofs							
Apply multipliers to pressure values in Tables 3, 4, and 5, as appropriate.							
Mean Roof Height, h	*Roof Slope*	*Enclosed Building*			*Partially Enclosed Building*[6]		
		Zone 1	*Zone 2*	*Zone 3*	*Zone 1*	*Zone 2*	*Zone 3*
h ≤ 60 ft (18 m); and when h/w ≤ 1 for 60 < h < 90 ft (18 < h < 27 m)	Θ ≤ 7°	1.0	1.68	2.53	1.31	1.99	2.85
	7° < Θ ≤ 27°	0.92	1.59	2.36	1.23	1.91	2.67
	27° < Θ ≤ 45°	1.0	1.17	1.17	1.31	1.48	1.48
when h/w > 1 for 60 ft < h < 90 ft (18 < h < 27 m) See Note 6 below	Θ ≤ 10°	1.34	2.10	2.86	1.65	2.42	3.18
	10° < Θ ≤ 27°	0.92	1.59	2.36	1.23	1.91	2.67
	27° < Θ ≤ 45°	1.0	1.17	1.17	1.31	1.48	1.48
h ≥ 90 ft (27 m) See Note 6 below	Θ ≤ 10°	1.0	1.57	2.14	1.23	1.80	2.37
	10° < Θ ≤ 27°	0.68	1.19	1.76	0.92	1.42	1.99
	27° < Θ ≤ 45°	0.75	0.87	0.87	0.98	1.11	1.11

Zone Notes:
1. Zone 1 except Zone 2 if Θ > 7°.
2. Zone 2 except Zone 3 if Θ ≤ 7° and h > 60 ft (18 m).
3. Zone 2 except Zone 3 if Θ > 7° and h ≤ 60 ft (18 m).
4. If a parapet height ≥ 3 ft (1 m) is provided around the perimeter of the roof with Θ ≤ 7°, treat Zone 3 as Zone 2.
5. 7° = 1½ in./12 in. (125 mm/m); 10° = 2 in./12 in. (167 mm/m); 27° = 6 in./12 in. (500 mm/m); 45° = 12 in./12 in. (1 m/m).
6. Partially enclosed building multipliers for roofs are based only on openings affecting the top story.
7. Value of "a":
   a) For h ≤ 60 ft (18 m), "a" is the smaller of 0.1 times the building lesser plan dimension or 0.4 times h, and never less than 4% of the least horizontal dimension, or 3 ft (0.9 m). Zone 3 is a square with dimensions "a".
   b) For h > 60 ft (18 m), "a" is 0.1 times the building lesser plan dimension, but not less than 3 ft (0.9 m). Zone 3 is an ell with dimensions "2a".
8. Value of "h":
   a) For slopes ≤ 7°, h = eave height
   b) For slopes > 7°, h = mean roof height
9. Value of "w" is based on the lesser plan dimension.

BIPV System Design for Heavy Wind Resistance

- BIPV systems must also be designed to resist higher direct wind pressures
- ASTM D 3161: *Standard Test Method for Wind-Resistance of Asphalt Shingles (Fan-Induced Method) at a wind velocity of 160mph;* this method is primarily used for evaluating wind resistance of roofing Shingles and is also applicable to BIPV roofing systems

Test conditions:
Test time: 120 minutes
Wind speed: 160 mph at 75 ± 5°F
Roof slope: 2:12 or as applicable

Pass criterion:
No damage to roofing material/system

Uni-Solar laminates (performance test at **170mph)**

Effects of Hail and Code Requirements

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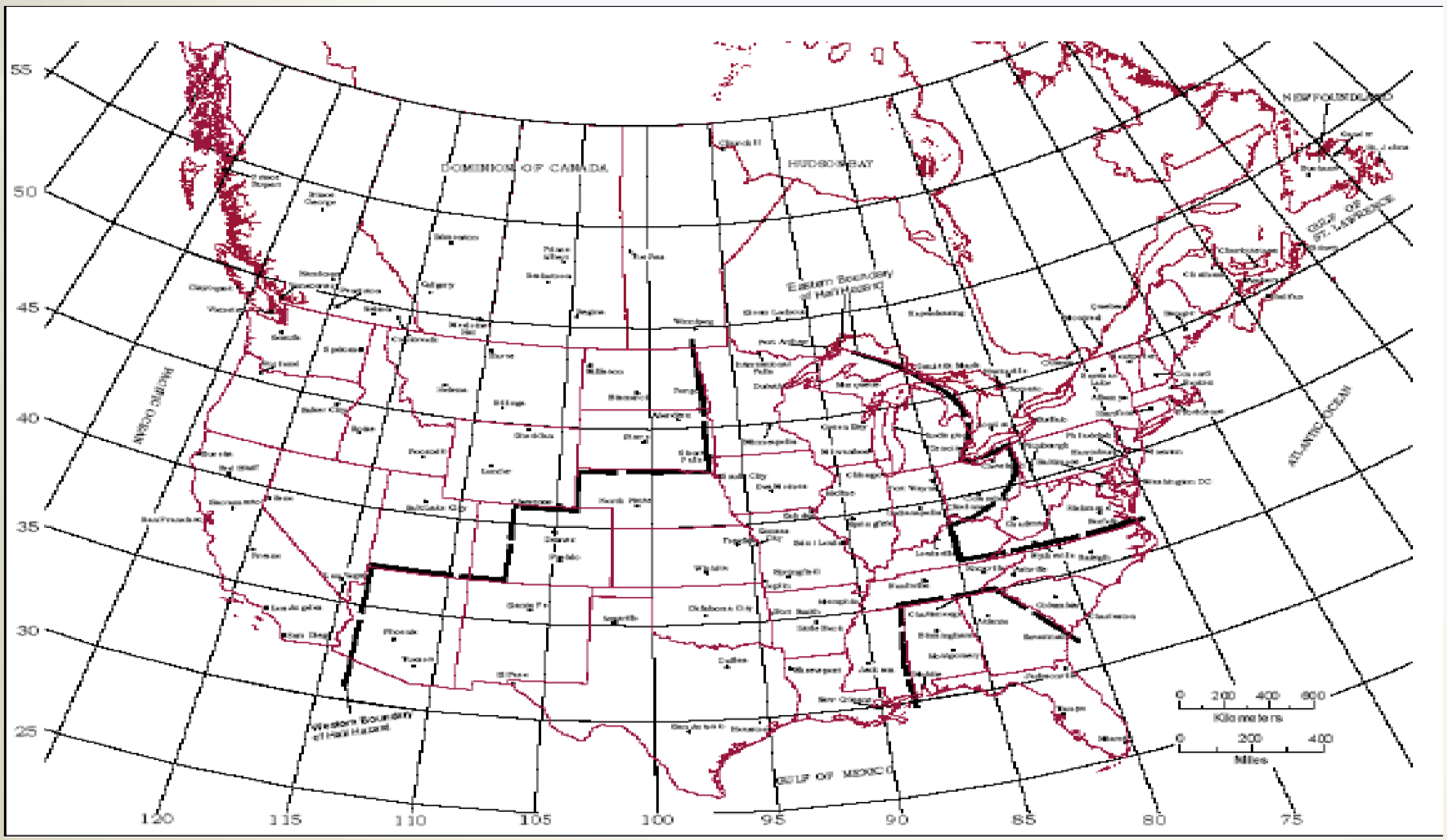
- The most likely single cause of roof damage is hail; the U.S. sees about 4800 hailstorms every year
- Hail accounts for an estimated **1 billion dollars** per year in property damage in the US
- International Building Code (Chapter 38 in NFPA 5000) and FM 4470/4476 address the requirements for roof coverings/BIPV



Hailstorm Hazard Map for United States (ref: FM 4476)

Susceptibility to Hail Damage for BIPV Systems

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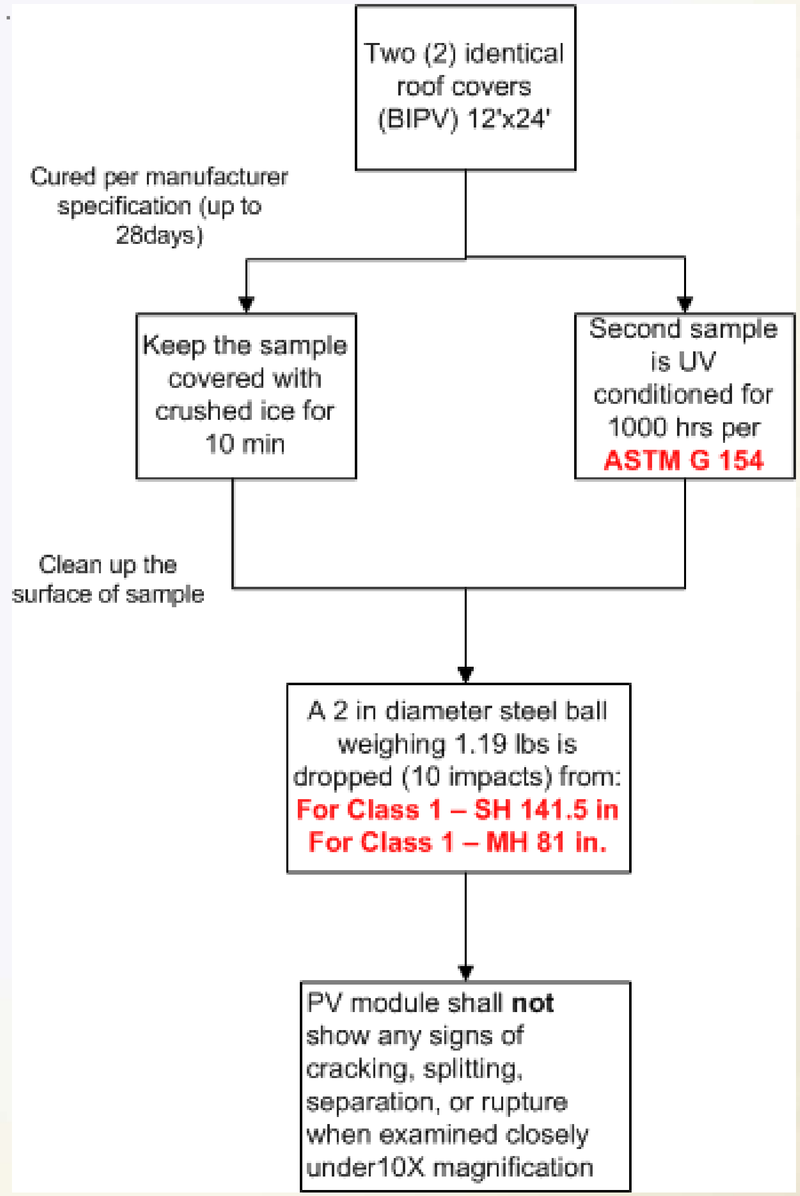
- **FM 4476** (Approval standard for Flexible PV modules) proposes tests to determine the susceptibility to Hail Damage for PV modules:

  Hail damage ratings:

  1. Class 1 – **SH** (Severe), impact energy 14 ft lb acceptable to use in most southern regions
  2. Class 1 – **MH** (Moderate), impact energy 8 ft lb used in rest of the country

- **UL 2218** (Impact Resistance for roof covering materials) provides a method to determine the Impact Resistance, but is not a standard for BIPV!



Retention of Adhesion for BIPV Systems

- BIPV modules can be applied to roofing membranes using an adhesive, so it is critical to have reliable adhesion strength of the membrane to PV module
- ICC –ES AC365 defines the test for Retention of Adhesion after Temperature Cycling
- This test primarily compares the adhesion strength before and after the environmental stress

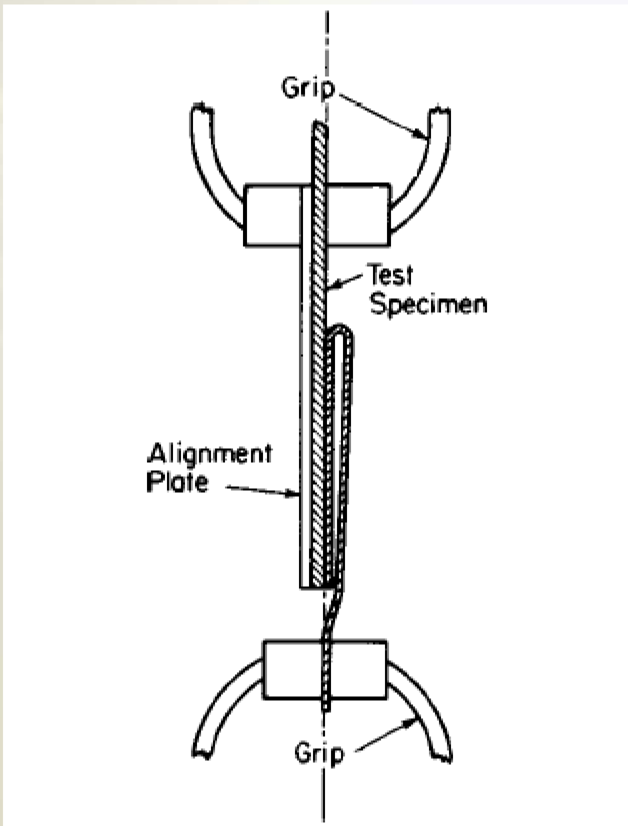
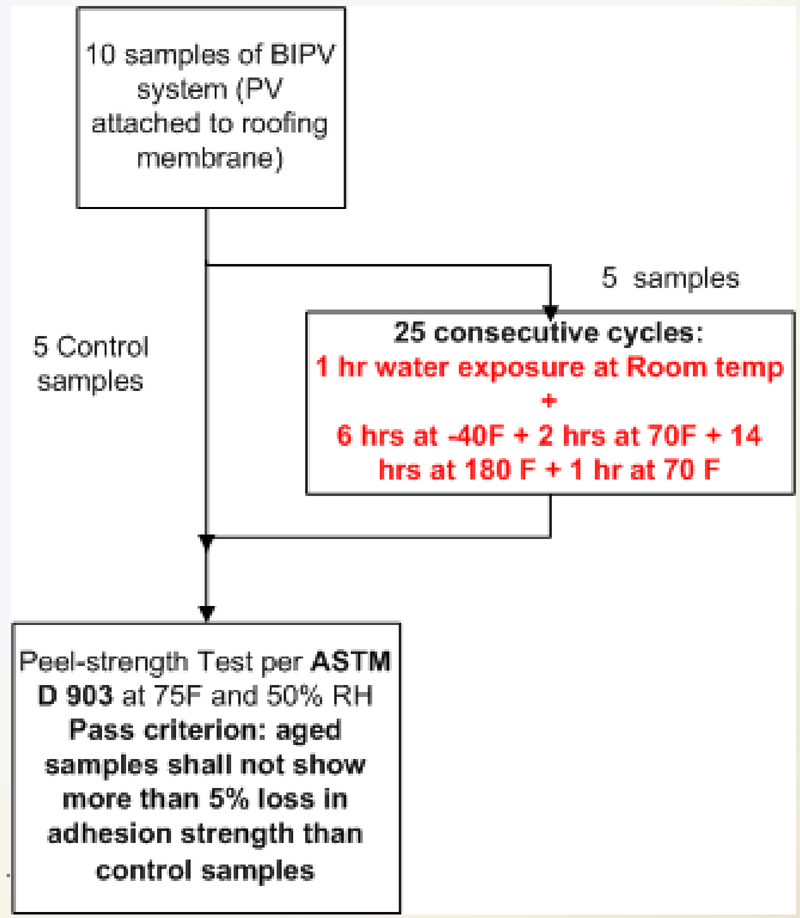


Fig: Specimen under test, per ASTM D 903



Laminate Mechanical Integrity Evaluation

The following tests can be used to evaluate mechanical integrity of the BIPV module with respect of performance of the adhesives and polymer/module interfaces

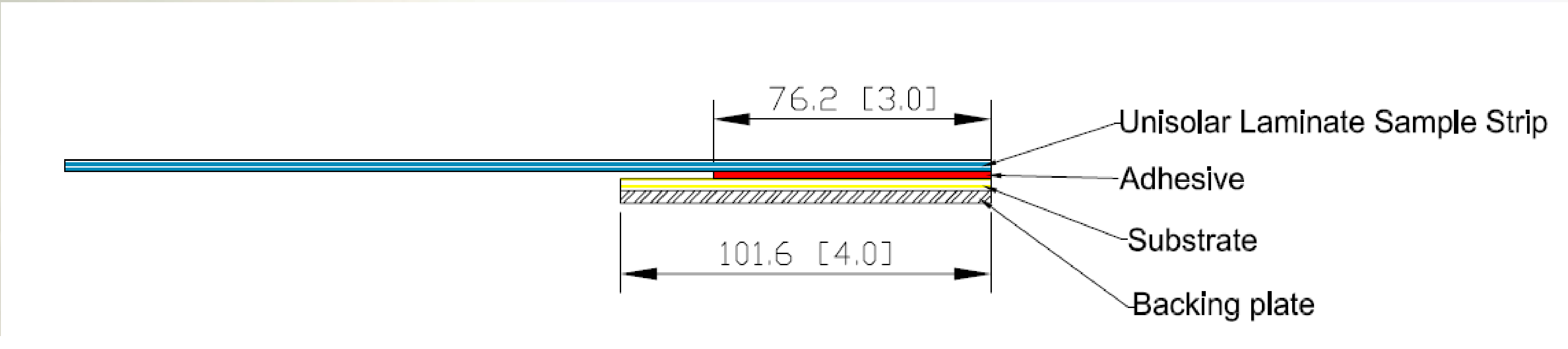
Uni-Solar Test Protocol for substrates

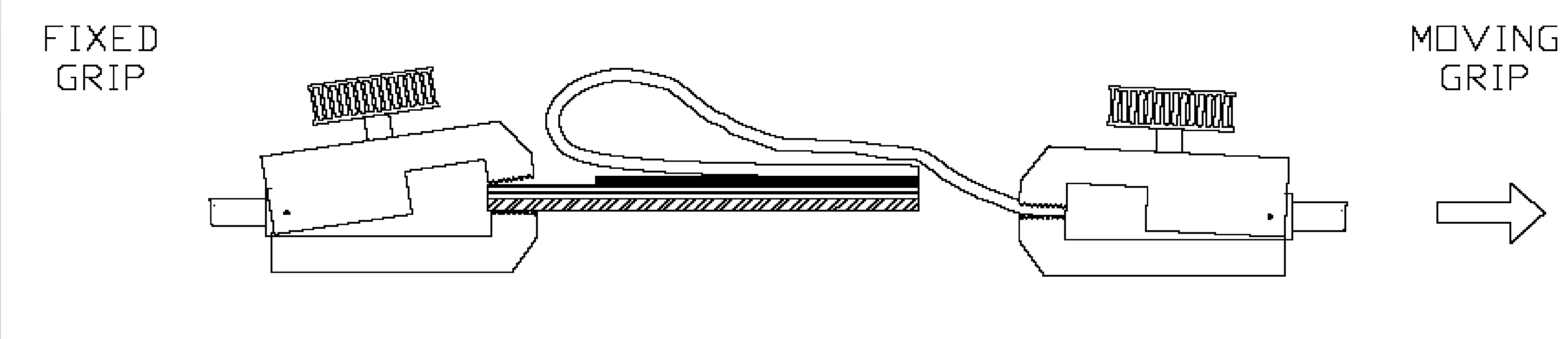
TEST	ASTM Test Protocol
Shear Test	ASTM D1002-05
Peel test	ASTM D 903-98(2004)
Environmental Aging	ASTM E1171 (2004)

TEST PHASES	Pre-Test		Test	Temperature Tested	Sample Size
Initial	Non Aging Test		Peel	- 40°C, RT and 85°C	5 samples/TEMP
			Shear	- 40°C, RT and 85°C	5 samples/TEMP
Final	After Environmental Aging	200 Thermal Cycles (30 days)	Peel	- 40°C, RT and 85°C	5 samples/TEMP
			Shear	- 40°C, RT and 85°C	5 samples/TEMP
		10 Humidity Freeze Cycles (10 days)	Peel	- 40°C, RT and 85°C	5 samples/TEMP
			Shear	- 40°C, RT and 85°C	5 samples/TEMP
		Damp Heat 1000 hrs (42 days)	Peel	- 40°C, RT and 85°C	5 samples/TEMP
			Shear	- 40°C, RT and 85°C	5 samples/TEMP

Laminate Mechanical Integrity Evaluation

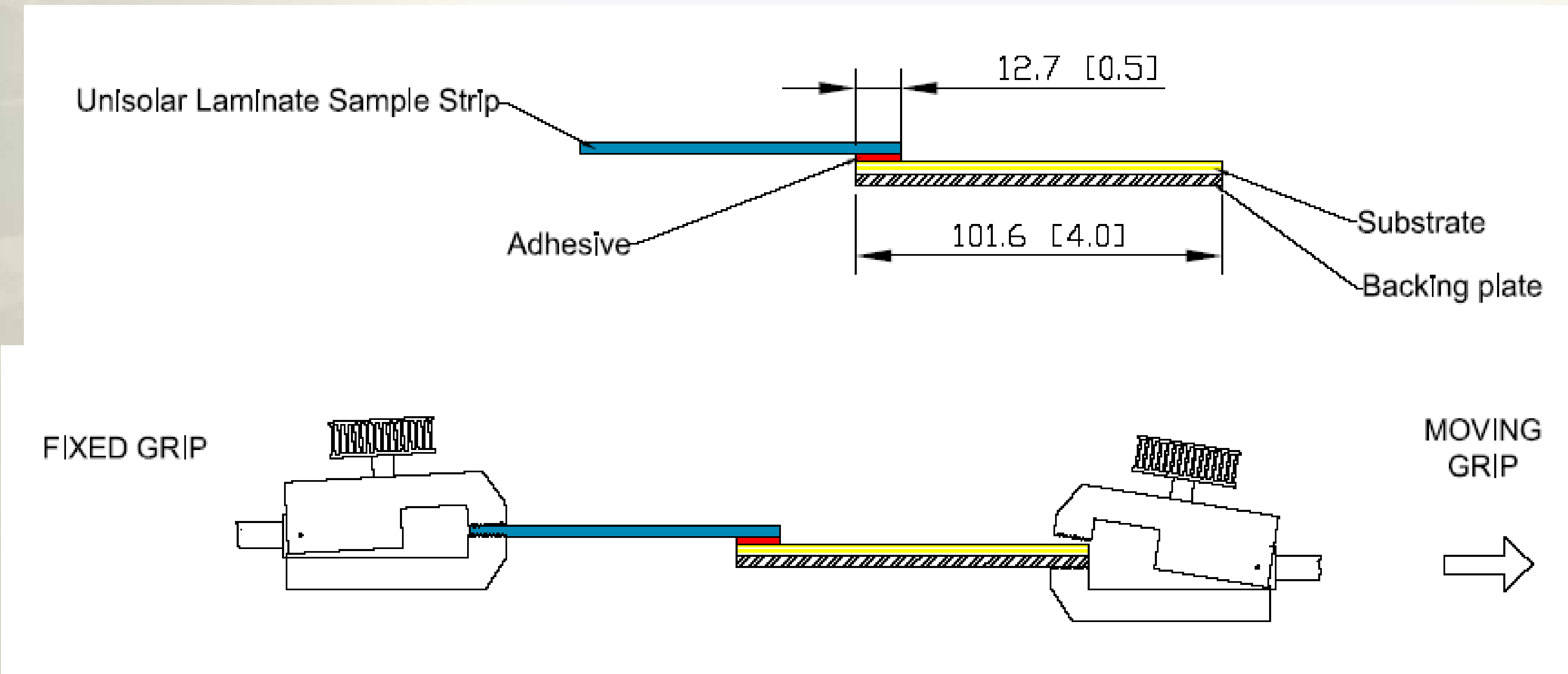
Peel Samples as per ASTM-903





Laminate Mechanical Integrity Evaluation

Shear Test sample and setting as per ASTM D1002-01



Other Requirements for BIPV Systems

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Fire

- Fire test per ASTM E108, Fire test for roof coverings or UL 790 (spread of flame and burning brand test)
- Roof slope dependent BIPV system classifications
- Various regions/states require BIPV systems to have **class A** fire rating

UV Exposure

- BIPV modules/materials are required by IBC to meet 2000 hrs of UV exposure, which is **double** the exposure that's required by UL 746C for **f1 rating** (polymer materials)

Resistance to Foot Traffic

- FM standard for BIPV, FM4470:
  - A simulated test to evaluate the performance of the roof covering when subjected to a 200 pound load a minimum of 5 times over the same area, using a 3 inch (76 mm) square steel plate
  - Sample size 12 inch (305 mm) square horizontal panel
  - Failure results if cracking, puncturing or tearing occurs

Summary

- Reliability evaluation of BIPV product is relatively challenging because of both product design and variety of applications
- Building industry codes are mature, proven and very stringent; matching with building roofing standards is a significant challenge that BIPV manufacturers must deal with and overcome
- Different regions set specific requirements, based on demographic location and environmental conditions
- Long term - Need specific tests and uniform standards for BIPV