

ROOF-MOUNTED SOLAR PHOTOVOLTAIC PANELS

Table of Contents

	Page
1.0 SCOPE	3
1.1 Changes	3
1.2 Hazards	3
1.2.1 Natural Hazards	3
1.2.2 Fire Exposure	3
2.0 RECOMMENDATIONS	4
2.1 Construction and Location	4
2.1.1 Wind	4
2.1.2 Fire Exposure and Classification	8
2.1.3 Gravity Loads and Roof Drainage	10
2.1.4 Hail	10
2.1.5 Earthquake	10
2.2 Electrical	10
2.3 Operation and Maintenance	11
2.4 Human Element	11
3.0 SUPPORT FOR RECOMMENDATIONS	13
3.1 Basic Operation of PV Systems	13
3.1.1 Earthquake Concerns	13
3.2 Wind Resistance	13
3.2.1 Boundary Layer Wind Tunnel (BLWT) Testing and Ballasted PV Systems	13
3.2.2 PV Systems Fastened to Standing Seam Roofs (SSR)	16
3.2.3 Effective Wind Area	17
3.2.4 Avoiding Roof Aggregate	18
3.3 Fires and Electrical Ignition Sources	19
3.3.1 Ground Fault Protection	19
3.3.2 Preventing Fires from DC Ground Fault in PV Arrays	19
3.4 Exterior Fire Spread in Roof-Mounted PV Arrays	19
3.5 Reserved for Future Use	20
3.6 Hail Resistance	20
3.7 Flexible PV Installations	20
3.8 Information Needed for FM Global Plan Review	20
4.0 REFERENCES	21
4.1 FM Global	21
4.2 Other	21
4.3 Bibliography	22
APPENDIX A GLOSSARY OF TERMS	22
APPENDIX B DOCUMENT REVISION HISTORY	24
APPENDIX C SAMPLE PROBLEM: PV MODULES PARALLEL TO ROOF	25
C.1 Example	25
C.2 Solution	25
C.3 Summary	26
C.4 Discussion	28

List of Figures

Fig. 2.1.1.1. Wind deflectors provided on the high sides of panels in each row (closed array)	5
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Fig. 2.1.1.9a and Fig. 2.1.1.9b. Examples of mechanical anchors used to secure equipment to the roof deck or roof framing	6
Fig. 2.1.1.11a. Slotted pedestal	7
Fig. 2.1.1.11b. Flanged pedestal	7
Fig. 2.1.1.12. Wind zones for sloped PV arrays on low-slope roofs per SEAOC-PV2, 2017	8
Fig. 2.1.2.1. Recommended roof expansion joint detail	9
Fig. 2.2.2a. Example of residual current measurements with auxiliary trip (CB = combiner box, RCD = residual current disconnect, GFDI = ground fault detection and interruption)	11
Fig. 2.2.2b. Example of electronic current sensing relay in ground circuit	12
Fig. 2.2.2c. Example of module level power electronics	12
Fig. 3.2.1.1a. Mechanically fastened roof cover billowing when subjected to wind pressure	15
Fig. 3.2.1.1b. Solar panels with steeper slopes or lacking wind deflectors will experience greater wind effects	15
Fig. 3.2.1.1c. Equipment lacking anchorage to roof framing	16
Fig. 3.2.2a. Solar panels secured to standing seam roofs using external seam clamps	17
Fig. 3.2.2b. Unacceptable arrangement unless specifically tested and FM Approved: clamp missing from SSR rib below middle of outer panel edge	17
Fig. C.1-1. Plan view of proposed layout for PV modules and clamps	26
Fig. C.3-1. Wind zones for low-slope roofs ($\leq 7^\circ$) per ASCE 7 and DS 1-28	27
Fig. C.3-2. Various wind zones for proposed PV array in the example	27

List of Tables

Table 2.1.4.1. Minimum Hail Ratings for PV Modules	10
Table 3.8. Coefficients for Velocity Pressure (K_z)	21
Table C.2-1. Values of GC_p per ASCE 7-16 and Data Sheet 1-28	26
Table C.3-2. Preliminary Wind Design Pressures	28
Table C.4-1. Final Wind Design Pressures	29

1.0 SCOPE

This data sheet provides property loss prevention guidance related to fire and natural hazards for the design, installation, and maintenance of all roof-mounted photovoltaic (PV) solar panels used to generate electrical power.

This document does not address solar towers, roof-mounted solar-powered water heaters, PV carports, or ground-mounted solar farms. For guidance on ground-mounted solar farms, and elevated PV (such as carports) see Data Sheet 7-106, *Ground-Mounted Solar Photovoltaic Power*.

1.1 Changes

July 2023. Interim revision. Minor clarifications were made.

1.2 Hazards

1.2.1 Natural Hazards

1.2.1.1 Windstorm

Inadequate windstorm resistance can result in varying degrees of damage to roof-mounted PV solar panels. In a worst-case scenario, they could be dislodged, break, and become windborne debris that damages other panels and roof covers, allowing water to damage the building interior and contents.

1.2.1.2 Hail

Exposure to hail exceeding that which the panels have been tested and Approved for is likely to damage all the panels in the array(s).

1.2.1.3 Snow and Ponding

Excessive loads from snow and rainwater accumulations on a roof in conjunction with the weight of these PV systems can damage or collapse a roof, particularly where the PV systems impede rainwater flow to drains.

PV panels with greater slopes and heights will increase snow accumulations and collapse potential unless the roof can support the extra load.

1.2.1.4 Earthquake

Seismic activity can cause lateral or vertical movement of the panels. This can cause broken glass, damaged electrical components, and an increased potential for ignition.

1.2.2 Fire Exposure

1.2.2.1 Exterior Fire Exposure

Exterior fire exposure due to the ignition of combustible components of the roof assembly below the PV panels (or from adjacent buildings, yard storage, wildland fires and bushfires) can damage PV panels.

PV systems' wiring circuits, combiner boxes, and inverter and control equipment are subject to electrical failure and subsequent fire. The panels themselves create heat that can ignite debris on the roof surface below the panels. Numerous fires started by the PV electrical system have involved combustibles within the roofing assembly and were adversely affected by re-radiation of heat from the rigid PV panels.

Some PV racking systems use plastic frames, which can add significant fuel loading to a roof fire. Also, while the top surfaces of the panels are covered with glass, the undersides of the panels are typically laminated with a weather-resistant, polymeric encapsulant (back-sheet) and combustible adhesives (such as ethylene vinyl acetate or EVA). This will add fuel to a roof-level fire and accelerate lateral fire spread.

The lower the classification (ASTM E108) of the exterior fire exposure of the roof assembly (cover and insulation, C or B vs. A), the greater tendency there is for fire spread.

In extreme cases, if above-deck roof components have low melting temperatures, they can burn and flow; if there is a lack of protection at roof expansion joints, an exterior roof fire could spread into the building and cause extensive interior damage.

2.0 RECOMMENDATIONS

Use FM Approved roof-mounted solar PV assemblies that are tested and rated for exterior fire spread and have a suitable wind and hail rating. Because the roof and PV assembly interact with respect to exterior fire spread and wind, it is critical that all components of the entire roof-PV be installed as FM Approved. For a list of roof-PV assemblies that are FM Approved, see RoofNav, an online resource of FM Approvals. Even if a roof assembly has a Class A exterior fire spread rating when used alone (without PV above), that rating is negated once PV panels are placed above it. FM Approved PV systems can be found in RoofNav as a “surfacing layer”.

Where installations are proposed at FM Global client locations, submit plans, specifications, and calculations to the local FM Global office for review and comment prior to ordering materials. For details on what information is needed, see Section 3.8.

2.1 Construction and Location

2.1.1 Wind

2.1.1.1 Design all roof-mounted, rigid PV solar panels and their securement using basic wind pressures in accordance with Data Sheet 1-28, *Wind Design*. Adhere to the following recommendations except where noted otherwise:

- A. Use the design wind speeds as noted in Data Sheet 1-28, *Wind Design*. Do not further reduce the design wind speed to that of a lower MRI based on assumptions regarding the expected lifespan of the arrays.
- B. Use Exposure C in non-coastal areas unless all conditions for Exposure B are met as outlined in Data Sheet 1-28. Use Exposure D where needed per Data Sheet 1-28.
- C. Use the topographic factor (K_{ZT}) as determined using ASCE 7 or Data Sheet 1-8, *Antenna Towers and Signs*. For locations with relatively flat terrain ($< 6^\circ$ or 10% ground slope), K_{ZT} can be assumed to be 1.0.
- D. Where available, use rigid PV solar panels and roof assemblies that are FM Approved together in accordance with Approval Standard 4478.
- E. Multiply the basic wind pressure (q_h) by the appropriate pressure coefficient, considering the effective wind area (EWA). The EWA will be dependent on whether the array is ballasted or mechanically fastened. Use guidance in 2.1.1.2 through 2.1.1.6. The pressure coefficients used should also reflect whether the PV arrays are open or closed (use wind deflectors). See Figure 2.1.1.1.
- F. An importance factor (IF) of 1.15 is recommended for the wind design.

2.1.1.2 Design wind pressure resistance for PV arrays that are parallel to the surface and whose top edge is within 10 in. (254 mm) of the roof surface using roof pressure coefficients for low-slope roofs per Data Sheet 1-28. An air equalization factor (γ_A) may be applied in accordance with SEAOC PV 2 (2017), depending on the exact distance between the roof surface and top of the PV modules, as well as the gap between modules in both directions.

- Where the distance from the top edge of the PV panel is no more than 10 in. (254 mm) from the flat part of the roof surface, and the horizontal space between panels is at least $\frac{1}{4}$ in. (6 mm) in both directions, use a value of 0.8 for γ_A .
- Where the distance from the top edge of the PV panel is no more than 5 in. (127 mm) from the flat part of the roof surface, and the horizontal space between panels is at least $\frac{3}{4}$ in. (19 mm) in both directions, use a value of 0.6 for γ_A .
- Interpolation is acceptable.

Where the above conditions are met, the edge factor (γ_E) that is applied to the outer panels around the entire perimeter of the array may be reduced to 1.25. Per ASCE 7-22, in that situation, $\gamma_E = 1.5$ only



Fig. 2.1.1.1. Wind deflectors provided on the high sides of panels in each row (closed array)

applies for a distance of $2h_2$ from the panel edge. Since h_2 is ≤ 10 in. (254 mm), $2h_2 \leq 20$ in. (508 mm) and the panel width is typically ≥ 40 in. (1.0 m); only half of the edge panel has a surcharge load due to the edge effect. For simplicity, use $\Upsilon_E = 1.25$ where Υ_A applies.

For an example, see Appendix C.

2.1.1.3 Determine the wind pressure coefficients needed for ballasted or anchored roof-mounted PV panels using **one** of the following options:

- A. Provide wind resistance based on prescriptive calculation methods provided in SEAOC PV2 2017 (see Section 4.2).
- B. Provide wind resistance based on boundary layer wind tunnel (BLWT) data per ASCE 49 (or equivalent international standard). Organizations that are qualified to conduct BLWT tests are noted in Section 3.2.1.
 1. Have a qualified third party conduct a review of the BLWT test report.
 2. Do not use computational fluid dynamics modeling as the primary substantiation for the design of wind resistance.
 3. For large installations ($\geq 10,000$ modules), have a qualified third party review the design for the following:
 - a. The correct interpretation and application of BLWT data (see Section 3.2.1) at the specific site
 - b. The racking system structure to verify the adequacy of the effective wind area (EWA) at the specific site
- C. Use a wind pressure coefficient in the design that reflects the location within the PV array (corner, edge or interior) and the effective wind area (EWA) or load sharing provided by the stiffness of the racking. Conduct a full scale Vertical Load Distribution Test (VLD) to determine the EWA and respective pressure coefficient.

2.1.1.4 Install rigid PV solar panels over metal standing seam roofs (SSR) using external seam clamps (ESC) and PV clamps that are FM Approved as an entire system, and properly fit the specific standing seam rib type at each seam. Torque clamps and PV studs in accordance with the manufacturer's instructions and inspect for tightness.

Where rigid PV panels are installed over insulated metal panel roofs (IMP), connect the PV panel through the IMP and directly into the top flange of the purlin, unless otherwise specifically tested and FM Approved. If connected to the top facer of the IMP, wind uplift may cause the top facer to delaminate from the IMP.

Ensure design wind loads are in accordance with the recommendations in Section 2.1.1.1, 2.1.1.2, or 2.1.1.3, as applicable.

2.1.1.5 Install ballasted rigid PV roof-mounted solar panels roofs with a maximum roof slope of 1/2 in. per ft (2.4°). A higher slope is not recommended for ballasted PV panels as it will decrease frictional resistance to wind forces and increase sliding forces from gravity loads, weakening wind resistance. Use a combined weight of solar panels, associated hardware, and additional concrete paver blocks as needed to meet wind loads per Sections 2.1.1.1, 2.1.1.2, or 2.1.1.3 as applicable.

Use a coefficient of static friction (μ) of 0.4 in the design unless a higher value can be justified (the lesser of the wet or dry value) based on the materials used and testing in accordance with ASTM D1894 (or equivalent standard outside the United States).

2.1.1.6 Install ballasted, rigid roof-mounted PV panels over fully adhered roof covers.

There is no consensus wind design method for installing ballasted PV arrays over mechanically fastened single-ply roof covers.

Where mechanically fastened single-ply roof covers are proposed, use a roof-PV assembly that is FM Approved in which the PV array is secured to the roof cover and the roof cover is mechanically fastened to the roof deck. This allows the wind load to be transferred into the roof deck and limits differential movement between the roof cover and the underside of the PV panels that might otherwise negate BLWT test data. PV arrays that are secured to adhered single-ply roof covers may also be used if FM Approved for that application.

2.1.1.7 Use concrete paver blocks for ballasted PV panels that meet specifications in ASTM C1491 and are tested in accordance with ASTM C1262 (does not include pass/fail criteria) for exposure to freeze-thaw cycles. The cumulative weight loss measured in the test should not exceed 5% of the initial weight of the specimen. (Use comparable standards outside the United States.)

2.1.1.8 Do not install PV modules on roofs with aggregate, including pea gravel or larger stone ballast.

2.1.1.9 Anchor all related equipment, such as combiner/junction boxes and conduits, to the roof deck or roof structural members (or inverters to concrete foundations) as required to provide proper anchorage against expected loads (see Figures 2.1.1.9a, 2.1.1.9b, and 3.2.1.1c). Use mechanical anchors that can be connected to the equipment and to the roof deck or roof framing. The dead weight and resulting frictional resistance for most equipment is not sufficient to resist wind uplift and lateral wind loads.



Fig. 2.1.1.9a and Fig. 2.1.1.9b. Examples of mechanical anchors used to secure equipment to the roof deck or roof framing

2.1.1.10 During installation, complete all required steps for the securement of PV panels before the end of each shift. This includes the mechanical connection to previously installed panels and any needed additional ballast.

2.1.1.11 Provide a positive method of securement between concrete paver blocks and pedestals or paver trays. This could include slotted or flanged pedestals (see Figures 2.1.1.11a and b).



Fig. 2.1.1.11a. Slotted pedestal



Fig. 2.1.1.11b. Flanged pedestal

2.1.1.12 Where wind loads are too high to make ballasting practical throughout, hybrid systems (ballast and anchors) can be used in accordance with **one** of the following:

A. Provide mechanical anchors for the entire array. Design the anchors to resist loads considering their effective wind area and providing a safety factor of 2.0 based on allowable stress design (ASD), or 1.25 times the Load and Resistance Factor Design (LRFD) or Strength Design) load. Have a third-party review performed by a licensed structural engineer.

B. Provide mechanical anchors (designed per item A) for all modules within perimeter zones of the array and provide ballast for interior zones if roof strength is adequate. Have a third-party review performed by a licensed structural engineer.

C. Provide additional setback distance between the roof edges and the edges of the array so that the arrays are in wind zones with lower pressures, and anchor (designed per item A) or ballast accordingly. For example, arrays with a setback distance $\geq 2H$ (where H = roof height) are in Zone 1 or 1', where wind pressures are much less than in Zone 3 or 2 (see Figure 2.1.1.12).

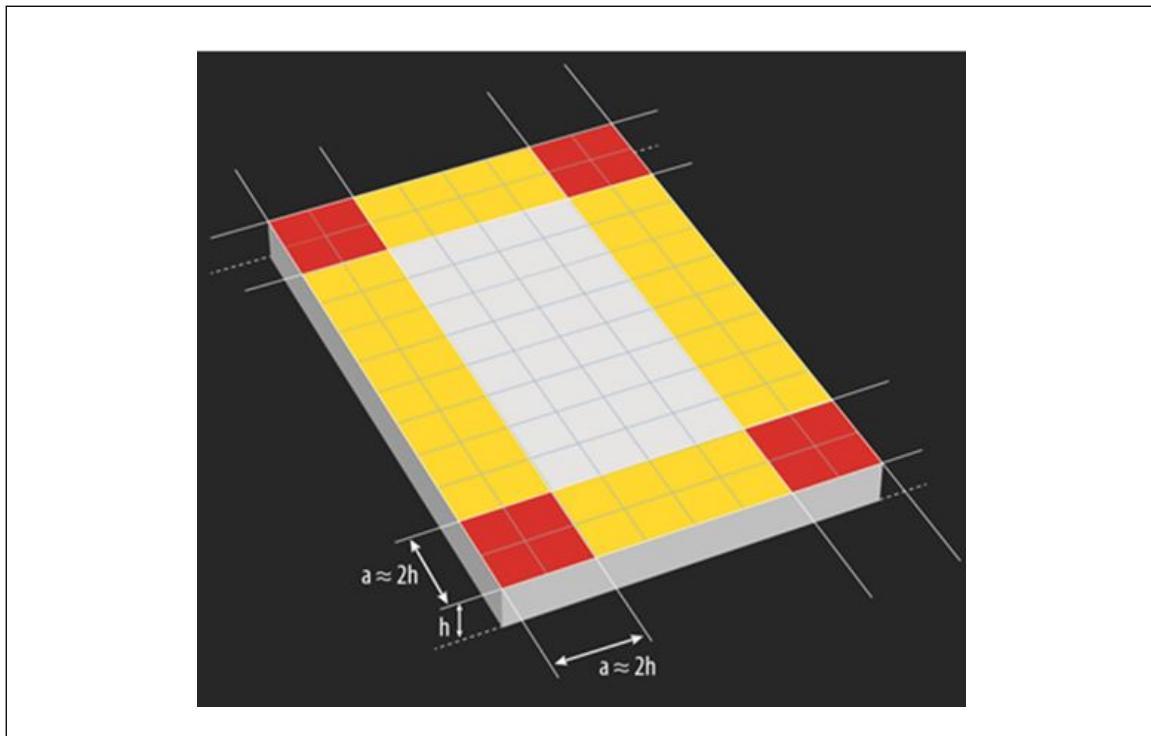


Fig. 2.1.1.12. Wind zones for sloped PV arrays on low-slope roofs per SEAOC-PV2, 2017

Zone 3 (Red): Building Corner, $2h \times 2h$

Zone 2 (Yellow): Building Perimeter, $2h$ wide between corners

Zone 1 (White): Distance greater than $2h$ inward from Zones 3 and 2

Zone 1' (not illustrated above): Exists for relatively wide buildings only $>10h$. Beyond distance of $5h$ from building edges.

2.1.2 Fire Exposure and Classification

2.1.2.1 Provide noncombustible, compressible insulation (such as mineral wool) within roof expansion joints or around other roof penetrations when new PV installations are to be installed on new or existing roof covers. See Figure 2.1.2.1.

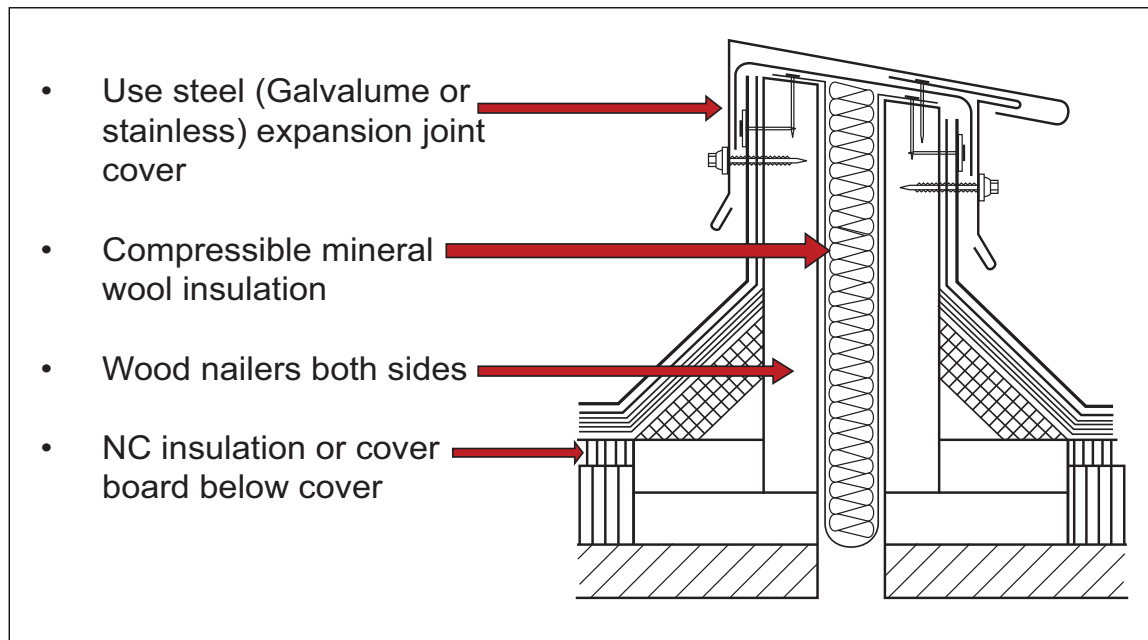


Fig. 2.1.2.1. Recommended roof expansion joint detail

2.1.2.2 When new roofs are to be installed, do one of the following to minimize exterior roof fire spread:

- A. Where a new roof is to be installed first, use PV panels that are FM Approved for the specific roof system per Approval Standard 4478 and RoofNav.
- B. Where there is an existing FM Approved Class 1A rated metal panel roof that is not part of an FM Approved roof-PV assembly, use PV modules with glass back sheets.
- C. Where there is an existing FM Approved Class 1A rated single-ply roof that has a gypsum cover board or mineral wool or expanded glass insulation directly below the roof cover, use PV modules with glass back sheets.
- D. Due to the amount of fuel in the roof cover alone, do not use multi-ply roof covers below PV arrays, regardless of the presence of mineral surfacing, roof gravel or roof coatings, unless specifically FM Approved.
- E. Where the roof deck is wood, install a noncombustible layer directly below the single-ply roof cover. This could be minimum ¼ in. (6.4 mm) gypsum, mineral wool or expanded glass. Provide sprinkler protection in the building as outlined in Data Sheet 2-0, *Installation Guidelines for Automatic Sprinklers*.

Use PV modules with glass back sheets and install roof assemblies that are FM Approved Class A rated single-ply membrane systems that use a layer of FM Approved gypsum cover board (min. 1/4 in. [6 mm]), mineral wool, or expanded glass (coverboard or insulation) directly below the cover.

For existing installations where combustible construction is unavoidable, consider the installation of FM Approved, linear heat detection on top of the roof cover and below the PV modules. One line of heat detection can be placed within each sun-facing or east-west facing row of PV panels.

2.1.2.3 Do not use PV panel systems that contain thermoplastic foam, such as extruded or expanded polystyrene. The roof assembly should maintain a Class 1 or noncombustible fire rating for underside fire exposure.

2.1.2.4 Do not install PV arrays within 50 ft (15 m) of maximum foreseeable loss (MFL) walls (see DS 1-42, *MFL Limiting Factors*).

2.1.2.5 Provide sufficient aisle spaces between adjacent PV arrays, adjacent rooftop equipment or penetrations, and between PV panels and expansion or control joints on each side. Submit the proposed

layout to the fire service for review and acceptance. Minimum 4 ft (1.2 m) wide aisles at a maximum of 150 ft (46 m) in each direction are recommended; some jurisdictions may require wider or more frequent aisles.

2.1.2.6 Provide adequate space separation between combustible yard storage and exterior walls in accordance with FM Global Data Sheet 1-20, *Protection Against Exterior Fire Exposure*.

2.1.2.7 Break the continuity of roof covers at parapet walls, roof expansion joints or roof area dividers. Use metal cap flashings as recommended in Section 2.1.2.1. The exterior fire exposure rating of the roof assembly is negated once the roof cover is in a vertical position.

2.1.2.8 For new construction where skylights are required by code use tempered glass skylights.

2.1.3 Gravity Loads and Roof Drainage

2.1.3.1 Install PV systems on roofs with minimum slopes of 1/4 in. per ft (1.2°), but not greater than that noted in Section 2.1.1.5.

2.1.3.2 Design the PV modules and the roof supporting them to resist design snow loads, including potential drifting, in accordance with DS 1-54. FM Approved PV modules are evaluated for gravity load resistance.

2.1.3.3 When PV systems are proposed for existing roofs, ensure the dead weight of the proposed PV system does not reduce the roof resistance recommended in DS 1-54 for snow, rain, and other live loads to below acceptable levels. Consider 2 to 3 psf (0.10 to 0.14 kPa) for the PV modules and hardware plus additional recommended ballast weight.

2.1.3.4 Ensure the path for rainwater flowing to roof drains is unobstructed for all PV arrays. Analyze in accordance with DS 1-54, *Roof Loads and Drainage*.

2.1.4 Hail

2.1.4.1 Use PV modules that have hail ratings (established in accordance with FM Approval Standard 4478 or 4476) as recommended for hail-prone regions as defined by DS 1-34. See Table 2.1.4.1.

Table 2.1.4.1. Minimum Hail Ratings for PV Modules

<i>Hail-Prone Region</i>	<i>Rigid FM 4478</i>	<i>Flexible FM 4476</i>
Moderate hail	Class 2	MH
Severe hail	Class 3 or Class 4	SH
Very severe hail	Not available	Not available

2.1.5 Earthquake

2.1.5.1 Design rigid PV solar panels located in seismic zones 50 through 500 years to prevent lateral movement during a design seismic event. (For determination of seismic zones and other details, see DS 1-2.) This should be done by providing anchorage to the roof deck or framing around the entire perimeter of each array. The design of the anchors should consider not only the strength of the anchors but the transfer of loads directly to secondary roof framing or through the deck and the deck securement into the secondary roof framing.

Use bolted or other positive fastening methods as required by Chapter 13 of ASCE 7. Do not consider frictional resistance dependent on gravity. Use PV modules that have been FM Approved in accordance with Approval Standard 4478, where available.

See Section 3.1.1 for additional information.

2.2 Electrical

2.2.1 Install new PV electrical energy systems, including the array circuit(s), inverter(s), and controller(s) for these systems, in accordance with Article 690 of the 2017 version of NFPA 70, National Electrical Code (or equivalent international standard). Provide Module Level Power Electronics (such as DC optimizers and microinverters) that sense and isolate faults and deenergize the array at the module level, and alarm such faults. The system should report the alarm condition to remote network monitoring software, enabling rapid shutdown of PV systems on buildings as defined in NEC 2017. See Figure 2.2.2C.

For more information, see Section 3.3.

2.2.2 Do not install electrical wiring within the rib opening of steel decking or otherwise within the plane of the above-deck components. Besides serving as a possible ignition source, it would also inhibit access for maintenance and repair and be subject to damage from mechanical fasteners used to secure above-deck roof components.

2.2.3 Ensure adequate provision is made for expansion and contraction due to extreme temperature fluctuations during the year. This includes wiring, as well as the interface between the PV panels and the roof cover.

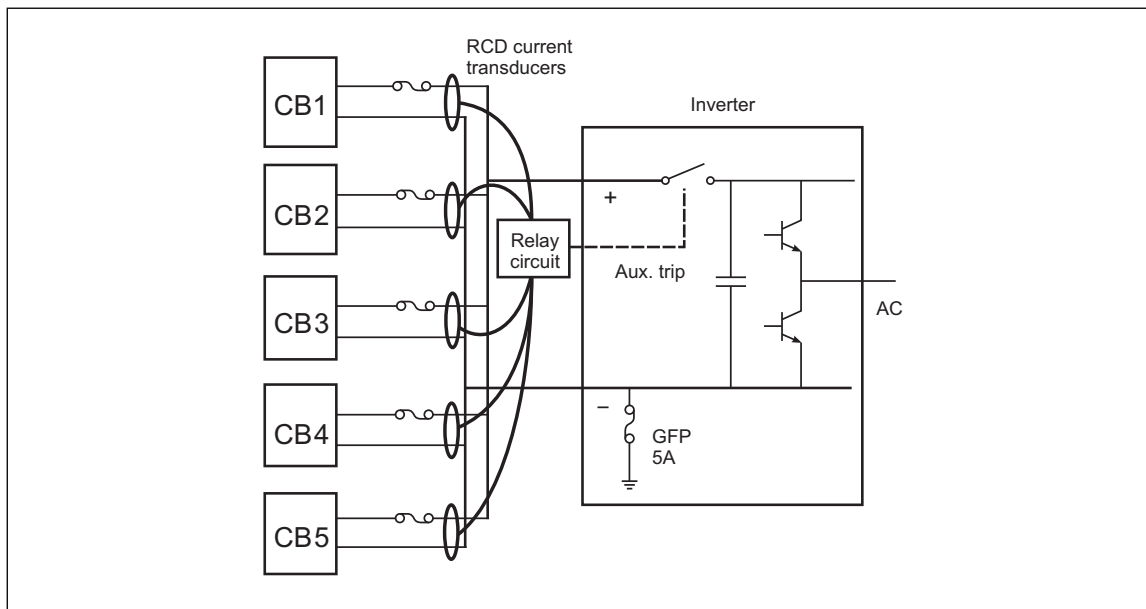


Fig. 2.2.2a. Example of residual current measurements with auxiliary trip (CB = combiner box, RCD = residual current disconnect, GFP = ground fault detection and interruption)

2.2.4 Design and install interior cables and bus-bars in accordance with DS 5-31.

2.2.5 Use rigid PV panels that meet electrical performance criteria per IEC/EN 61215-1, 61215-1-1, and 61215-2.

2.2.6 Use rigid PV panels that comply with criteria for electrical safety per IEC/EN 61730-2, *Photovoltaic (PV) Module Safety Qualifications, Part 2: Requirements for Testing*, or ANSI/UL 1703, *Flat Plate Photovoltaic Modules and Panels*.

2.3 Operation and Maintenance

2.3.1 Check all equipment for damage or required maintenance after seismic or severe weather events, including windstorm, lightning, hail, and snow storms.

2.3.2 Inspect the sealing of roof penetrations for water-tightness annually, and repair or replace as needed.

2.3.3 Have routine inspection, testing, and maintenance of the PV arrays and related equipment performed by qualified personnel and in accordance with the manufacturers' guidelines.

2.4 Human Element

2.4.1 Arrange pre-fire planning with the fire service. Ensure they are familiar with ground access, stairs to the roof, PV array aisles, the location of combiner boxes and inverters, and all related fuses and disconnects.

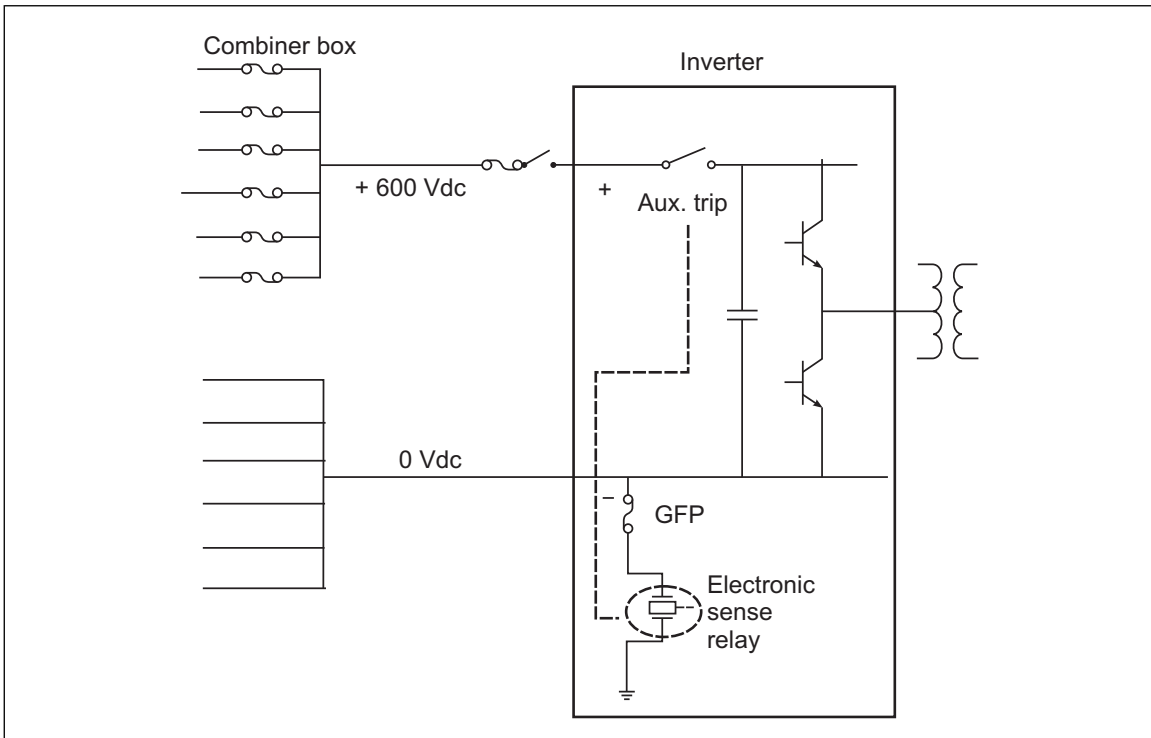


Fig. 2.2.2b. Example of electronic current sensing relay in ground circuit

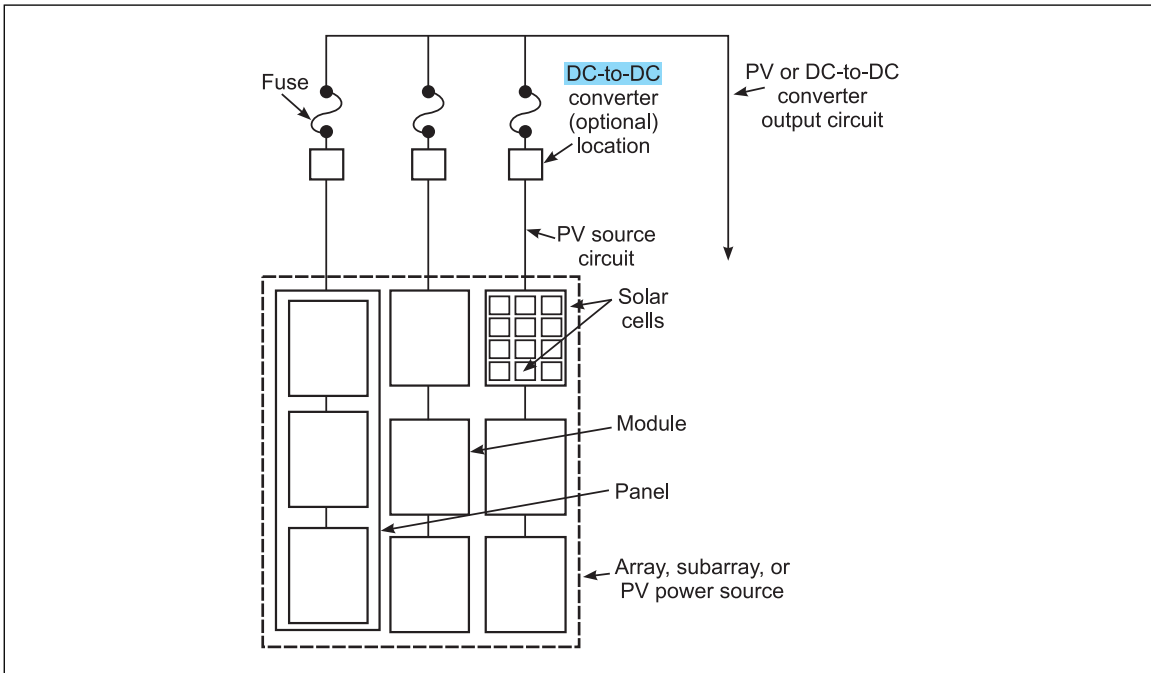


Fig. 2.2.2c. Example of module level power electronics (courtesy of the National Fire Protection Association)

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Basic Operation of PV Systems

Rigid PV solar panels are made of semiconductors in the form of individual silicon cells wired in series, and usually protected above by tempered glass and on the bottom by a polymeric encapsulant (back-sheet). Back-sheets are laminated in up to 3 layers and can consist of almost any combination of ethylene vinyl acetate (EVA), polyethylene terephthalate (PET), Kynar, or Tedlar. An anti-reflective coating is provided on the top surface. Modules are linked together in series to form strings, and then individual strings are connected within a combiner box to form an array. The modules within the array convert energy from sunlight into direct current (DC) electrical power. This power can be stored as DC, but more commonly it is converted to AC using an inverter, and then fed into a large electrical grid, or in some cases used directly on-site. Usually one or more arrays/combiner boxes are connected to an inverter when the electric power is converted from DC to AC.

Common sites for PV panels are roofs of warehouses and other facilities that do not require extensive rooftop equipment that would shadow the PV panels. Aisles are often provided within or between arrays to allow access for maintenance of rooftop equipment and manual firefighting, as well as to prevent the panels being shadowed by other equipment, higher roofs, or other obstructions to sunlight. For additional information on rigid PV panels, see DS 7-106.

3.1.1 Earthquake Concerns

Seismic load concerns are somewhat different from wind load concerns. In seismic design, greater emphasis is placed on lateral forces. Some lateral movement may be tolerable from a life safety perspective, and therefore acceptable per building codes. Significant lateral movement can result in considerable damage to PV modules.

PV arrays may be provided with sufficient ballast to resist vertical wind loads, which are a greater concern with wind than lateral loads. While frictional resistance caused by gravity loads (combined weight of PV modules, racking, and added ballast) can help resist lateral forces due to seismic acceleration, that lateral force is a function of dead weight. Thus, increasing the ballast beyond what is needed for wind design also increases lateral seismic loads.

Lateral loads distribute more efficiently within a PV array, whereas vertical load distribution is very localized. Providing mechanical anchorage around the entire perimeter of a PV array is a preferred method to reduce PV module damage during seismic events.

3.2 Wind Resistance

3.2.1 Boundary Layer Wind Tunnel (BLWT) Testing and Ballasted PV Systems

Testing in a boundary layer wind tunnel (BLWT) is conducted to determine wind loads and resistance for roof-mounted PV panels. It is important that the scaled models used to replicate the proposed roof-mounted panels be as representative as possible, particularly with ballasted arrays. This includes the sizes of individual panels, the weights of the panels and ballast, the PV panel slope (see Figure 3.2.1.1b), the coefficient of friction (μ) between the roof surface and the underside of the panel pedestals or paver trays, and the size of the array. Tests should replicate the minimum array size to be used, regarding the number of interconnected panels within a given array and the minimum number of panels within a row or column.

To allow the test data to be used for a variety of combinations of roof cover types and pedestal pads/paver trays, separate testing may be needed to quantify the coefficient of friction between the two surfaces. Testing should reflect any slip sheets that may be used. Since movement of any panel defines failure, the use of the static coefficient of friction may be used in lieu of the dynamic value. While often the wet coefficient of friction yields a lower value, test data reflects that in some cases the dry value is lower.

Testing needs to be conducted in a boundary layer wind tunnel (BLWT) rather than an aerospace wind tunnel (AWT). While there are some similarities between the two types, the BLWT simulates wind flow toward a building by providing obstructions between the entrance of the wind into the tunnel and the scaled building model. Typically, an open terrain or Exposure C is simulated. The simulated building is often a flat rigid object. This allows the wind to hit the wall of the model, flow over it, and create turbulence and vortices that cause higher uplift pressures above the roof, particularly at the perimeter and corner areas. Such a realistic effect is not provided when using an aerospace wind tunnel.

Even in a BLWT, internal building pressure effects and potential vertical movement of the roof cover are not simulated. The building models used in a BLWT test are very rigid and do not represent the behavior of a mechanically fastened roof cover (see Figure 3.2.1.1a), which may billow when exposed to wind pressure. Such vertical movement of the roof cover can increase the drag and lift coefficients for the PV modules, and can make the results of the BLWT invalid. The results of the BLWT test are more applicable to a fully adhered roof cover. PV panels used over mechanically fastened roof cover should be mechanically fastened.

While there are numerous aerospace wind tunnels, a limited number of BLWTs exist. The following locations have BLWTs:

- Colorado State University (CSU)
- Western University (formerly the University of Western Ontario or UWO), Ontario, Canada
- Cermak, Peterka and Peterson (CPP) in Colorado and Australia
- Rowan, Williams, Davies and Irwin, Inc. (RWDI), Canada
- I.F.I. Institute, Germany
- Force Technology, Europe
- University of California, Davis
- University of Maryland
- University of Minnesota
- Concordia University, Montreal, Quebec, Canada
- Peutz Ltd, Mook, The Netherlands

A. Experimental wind load estimates on roof-mounted solar panels can be inaccurate for the following reasons:

1. The experiments were conducted without considering the effect of the building on the solar panels. This includes experiments that were conducted in an aerospace wind tunnel, which is used for testing cars and aircraft. These types of wind tunnels produce smooth wind at a constant speed, and at very low turbulence intensity ($\leq 0.5\%$). To study the wind load on roof-mounted solar panels, experiments must be conducted in a BLWT, where the wind is turbulent and gusty with high turbulence intensity ($\leq 10\%$). The wind tunnel experiments also must be conducted in accordance with the ASCE's Wind Tunnel Studies of Buildings and Other Structures.
2. The experiments were conducted only for a single wind direction. Just like the roof itself, the tilted solar panels can experience substantial wind loads from cornering winds.

B. Wind load estimates obtained using only computational fluid dynamics simulations on roof-mounted solar panels are not recommended by ASCE and may be inaccurate for the following reasons:

1. The simulations were performed without considering the effect of the building on the solar panels.
2. Validation of the computational fluid dynamics simulations with existing literature or with BLWT experiments were not performed.

3.2.1.1 Increased Ballast or Securement Around Openings and Aisle Spaces

Often, there will be aisle spaces around other roof-mounted equipment, or between arrays that provide fire fighter or maintenance access, that break the continuity of the interconnection between panels. This reduces the wind load distribution, as well as the shielding affect against wind that the outer panels in the array provide for those panels farther in from the aisles. To account for this, additional ballast or securement (typically 50% more) should be provided for the panels immediately around the openings.



Fig. 3.2.1.1a. Mechanically fastened roof cover billowing when subjected to wind pressure



Fig. 3.2.1.1b. Solar panels with steeper slopes or lacking wind deflectors will experience greater wind effects



Fig. 3.2.1.1c. Equipment lacking anchorage to roof framing

3.2.2 PV Systems Fastened to Standing Seam Roofs (SSR)

Rigid PV panels can be mechanically fastened to SSRs and can be FM Approved in accordance with Approval Standard 4478. For more information on SSRs, see DS 1-31. SSR panels are seamed to the internal clips, which are pre-fastened at each deck rib to each steel purlin or a continuous substrate. The wind design for SSR assumes the wind load is distributed evenly to each internal clip. An external seam clamp, like those used to enhance the wind resistance of SSRs, is used to connect PV panels to the SSR deck ribs (see Figures 3.2.2a and 3.2.2b). These clamps do not penetrate the seam. One clamp should be provided at each standing seam rib near the down-slope and up-slope edges of the PV panels. Otherwise, the wind load transferred from the PV modules may 1) buckle the deck ribs or 2) fail the internal SSR clip and screws securing the clip to the top flanges purlin. The spacing between clamps may vary from about 3 to 10 ft² (0.3 to 1.0 m²) per clamp, depending on the SSR rib spacing and the distance between internal clips along the deck seams. It is important that the individual clamp be designed to fit the specific seam of the SSR. For an example problem, see Appendix C.



Fig. 3.2.2a. Solar panels secured to standing seam roofs using external seam clamps



Fig. 3.2.2b. Unacceptable arrangement unless specifically tested and FM Approved: clamp missing from SSR rib below middle of outer panel edge

3.2.3 Effective Wind Area

The effective wind area (EWA) reflects the area of a given component of an assembly to which the wind load is distributed or shared. For a fastener, the EWA can be assumed to be the area supported by the fastener.

For ballasted PV arrays, determining the EWA for wind uplift can be complicated. It is critical that the EWA be accurate. As the EWA increases, the wind pressure coefficient decreases. Using an unrealistically large EWA in the design calculations will result in wind resistance that is too low. The EWA for a ballasted array varies depending on the location of the module within the array (i.e., corner, edge, or interior) as well as the rigidity of the hardware or racking that connects the modules. The EWA can be determined using one of the following methods:

- A. Finite Element Analysis (FEA) of the hardware or racking assembly (see 3.2.3.1)
- B. A full scale vertical load distribution (VLD) test as outlined below

Racking members for roof mounted PV arrays vary in stiffness. To quantify the array's ability to share wind uplift loads, VLD testing is needed. In these tests, the results should consider both a) when failure or permanent deformation occurs, and b) when the vertical displacement becomes excessive. If displacement is excessive, the PV array may no longer be represented by the wind tunnel model and the respective pressure coefficients. It may also negate the positive effects of wind deflectors in reducing uplift forces. Displacement must not exceed 3 to 6 in. (75 to 150 mm) in the VLD. The EWA should not exceed 1.5 PV modules for the corner, 2.7 for the edges and 9.6 for interior areas.

Two alternative methods are:

1. Bi-linear Method, and
2. Displacement Ratio Limit method (DRL)

A VLD test should be done on a full-scale mock-up of an array. A crane or hoist, load cell and means to measure vertical deflection are needed. The following criteria should be met:

- A. The array should be tested 1) without any additional ballast other than the dead weight of the PV modules and associated hardware or racking, and 2) with the maximum ballast that could be used.
- B. The vertical load should be applied at various areas of the array including corner, edge and interior.
- C. The vertical load should be applied to at least two points along the long edge of the PV panel.
- D. The applied vertical load cannot cause permanent deformation or cracking of any components anywhere within the array and the maximum vertical deflection must be limited.

3.2.3.1 Finite Element Analysis (FEA)

Finite element analysis can be used by the structural design engineer to establish structural capacity curves for the ballasted PV array for a range of applicable ballast weights (for which the PV array is typically designed). Tributary area can be determined from the intersection of the structural capacity curve and the design wind load (which can be calculated using SEAOC PV 2). Effective wind area is assumed to be the same as the tributary area. The following steps explain the procedure to calculate the structural capacity curve.

Step 1: Identify governing loading areas (i.e. corner, edge and interior area of the PV array).

Step 2: For each loading area, define governing loading scenarios that can result in the least resistance or structural capacity (i.e., one panel loaded, two panels loaded, three panels loaded etc.).

Step 3: For each loading area, perform nonlinear finite element analysis of the PV array for each loading scenario and ballast weight, considering uniform wind load on each panel and applicable boundary conditions and materials of the PV array as built. During the analysis, increase the wind load until the system reaches any failure criterion such as permanent deformation or maximum uplift displacement of a portion of the PV array.

Step 4: For each loading area, plot the wind loads (from the analysis) of different loading scenarios (number of panels loaded) for each ballast weight. Repeat this and add the curves for all other ballast weights to the same plot. The resulting plot is the capacity curve for the applicable loading area.

Step 5: Repeat Steps 2 to 5 and obtain the structural capacity curves for all the governing loading areas.

The above information is intended for use by the structural design engineer, who should verify that this procedure was followed. Detailed review by field engineering is not practical.

3.2.4 Avoiding Roof Aggregate

The presence of roof aggregate where there are roof-mounted PV modules could result in windborne debris damage to the PV panels. If ballasted PV pedestals or paver trays are installed directly on top of roofing aggregate, it can adversely affect the arrays' resistance to sliding. Roof cover ballast that is continuous over the entire roof cover and consists of concrete paver blocks designed in accordance with DS 1-29, *Roof Deck Securement and Above-Deck Roof Components*, are acceptable if a sufficient weight of concrete paver blocks is provided above the solar panel pedestals or paver trays to provide the needed wind resistance for the solar panels.

3.3 Fires and Electrical Ignition Sources

3.3.1 Ground Fault Protection

Numerous fires have started in U.S. installations of roof-mounted PV arrays due to inadequate ground fault protection. Such installations in the United States typically include conductors that are intentionally grounded, but have ground fault detection designed for ungrounded conductor faults. This design is based on conservative assumptions of leakage current to avoid nuisance trips. However, the present ground fault detection uses fuses that are not sensitive enough, resulting in undetected ground faults. Such systems have become more prevalent in recent years and, as they continue to age, the frequency of such fires could increase.

Fires of electrical origin are common in roof-mounted solar arrays. There are sufficient combustibles present in the form of roof coverings and insulation, which are more likely to become ignited with the PV system there. Also, the redirection of flames and re-radiation of heat by the PV panels from a roof fire tend to create more fire spread than if the panels were not there. Following the electrical guidance in this document will reduce, but not eliminate, the potential for a fire.

The goal is to identify an initial ground fault prior to the second ground fault. Recent losses have shown that traditional ground fault protection (GFP) using fuses per older versions of Article 690 of the NEC was not sufficiently sensitive and allowed “blind spots” with an undetected initial ground fault. Given a second ground fault, this can result in enough energy to start a roof-top fire.

Included in NEC 2017 is a requirement to reduce voltage within the array, also commonly referred to “module-level rapid shutdown.” This is done to reduce voltage in the array during emergency situations or general maintenance. The most widely implemented solution is using module-level rapid shutdown electronics such as DC optimizers.

In addition to ground faults, module-level power electronics can provide arc fault circuit interruption (AFCI) and monitoring for these conditions as well. Module-level power electronics do not rely on fuses for ground fault protection.

3.3.2 Preventing Fires from DC Ground Fault in PV Arrays

A ground fault in a PV array is an accidental electrical short circuit involving ground and one or more normally designated current-carrying conductors. Ground faults in PV arrays are safety concerns because they may generate DC arcs at the fault point on the ground fault path, damage surrounding insulation, and create fire hazards. The risk of fire is escalated substantially if a second ground fault is developed. A DC ground fault is common in PV systems and can result from the following causes:

- A. Insulation failure of cables (e.g., an animal chewing through cable insulation and causing a ground fault)
- B. Incidental short-circuit between the normal conductor and ground (e.g., a cable in a PV junction box incidentally contacting a grounded conductor)
- C. Ground faults within PV modules (e.g., a solar cell short-circuiting to grounded module frames due to deteriorating encapsulation, impact damage, or water corrosion in the PV panel)
- D. Abraded wire insulation caused during installation or from thermal movement of the components

To properly protect PV arrays from ground fault damage and ensuing fire, NFPA 70, National Electrical Code, Article 690.5(A), specifies the ground fault protection device (GFPD) or system must be capable of detecting a ground-fault current, interrupting the flow of fault current, and providing an indication of the fault. Per past industry experience, there are some cases in which the first ground fault could not be detected by the currently designed GFPD (such as applying a fuse in the grounding electrode). A second ground fault made the fault current flow in the array, leading to fire.

3.4 Exterior Fire Spread in Roof-Mounted PV Arrays

Where roof-mounted PV arrays are present, the risk of exterior fire spread is much greater than it would be for the roof assembly alone. This would be the case even if the solar panels had no combustible components. A typical fire scenario is the electrical wiring associated with the solar PV array causing ignition of the roof assembly. The potential flame height is largely a function of the type of roof cover and insulation

immediately below the array. While the presence of solar panels may affect combustion air being drawn to the fire, it otherwise does not reduce, but redirects the flames from the roof fire.

Solar panels containing foam plastic are not common, and will not alter the noncombustible (underside fire exposure) rating of concrete, gypsum, lightweight insulating concrete decks, or Class 1 steel deck assemblies with a thermal barrier, such as gypsum board. If it is not obvious that the integrity of an existing Class 1 steel deck has been maintained, assume it is Class 2 for the purposes of determining the need for sprinklers below the deck, or the MFL. There may still be a concern about exterior fire exposure.

PV panels that contain no foam plastic will not alter the existing Class 1 underside fire exposure rating for steel deck but will affect resistance to exterior fire exposure.

Components of more common types of rigid PV panels (such as plastic frames and back-sheets and adhesives) can ignite and radiate heat back to the roof cover and insulation, resulting in much greater exterior fire spread than would be expected with the roof assembly itself. Consequently, only specific roof assemblies are acceptable regarding fire spread with roof-mounted PV panels present.

Aisle spaces between PV arrays can be used by the fire service to ventilate a fire within the building. The fire service may also use manually operated mechanical exhaust fans to vent an occupancy fire. Aisles have been used by the fire service in their efforts to limit fire spread across the top of the roof by cutting trenches in the above-deck components down to the top of the roof deck, breaking the continuity of combustibles within the above-deck roof components.

3.5 Reserved for Future Use

3.6 Hail Resistance

Hail resistance of rigid PV panels should be determined by ice ball testing in accordance with Approval Standard 4478. Hail resistance of flexible PV panels should be determined by steel ball testing in accordance with Approval Standard 4476.

Impact from hail larger than that for which the panels were successfully tested could cause severe damage to the PV panels.

3.7 Flexible PV Installations

Adhered, flexible solar panels have been FM Approved in the past. They were required to be adhered across their entire underside. Flexible solar panels that are only secured around their edges will not uniformly distribute the wind load to the roof cover they are adhered to.

3.8 Information Needed for FM Global Plan Review

The following information is needed for an FM Global plan review:

- A. Will the existing roof cover remain? If yes, indicate the type of roof cover, type of insulation or cover board immediately below the roof cover, and whether the roof cover is fully adhered to it. Provide a sketch of the roof expansion joint, including the type of insulation within it, considering Recommendation 2.1.2.1.
- B. If a new roof cover is proposed, submit complete details for the roof cover, insulation and cover boards, securement methods, and expansion joint description considering Recommendations 2.1.2.1 and 2.1.2.2.
- C. Submit the calculation for basic wind pressure (q_h) including the design wind speed, related coefficients for velocity pressure (see Table 3.8), directionality, topography, etc.
- D. The submittal should verify that the wind pressure coefficients used are based on the effective wind area (EWA, see Section 3.2.3) and the location of the modules within the array. The EWA for vertical load distribution for ballasted PV arrays is typically limited to the area of a few modules. Usually the EWA will be the area of 1 to 9 modules depending on the location of the module within the array (corner, edge, or shielded/interior). PV racking that uses rigid framing will have larger EWAs than arrays that have less rigidity.

Table 3.8. Coefficients for Velocity Pressure (K_z)

Height above ground level, z		Exposure		
		B	C	D
ft	m			
0-15	0-4.6	0.57	0.85	1.03
20	6.1	0.62	0.90	1.08
25	7.6	0.76	0.94	1.12
30	9.1	0.70	0.98	1.16
40	12.2	0.76	1.04	1.22
50	15.2	0.81	1.09	1.27
60	18	0.85	1.13	1.31
70	21.3	0.89	1.17	1.34
80	24.4	0.93	1.21	1.38
90	27.4	0.96	1.24	1.40
120	36.6	1.04	1.31	1.48
140	42.7	1.09	1.36	1.52
160	48.8	1.13	1.39	1.55
180	54.9	1.17	1.43	1.58
200	61	1.20	1.46	1.61
250	76.2	1.28	1.53	1.68
300	91.4	1.35	1.59	1.73
400	121.9	1.47	1.69	1.82
450	137.2	1.52	1.73	1.86
500	152.4	1.56	1.77	1.89

4.0 REFERENCES

4.1 FM Global

Data Sheet 1-2, *Earthquakes*

Data Sheet 1-20, *Protection Against Exterior Fire Exposure*

Data Sheet 1-28, *Wind Design*

Data Sheet 1-29, *Roof Deck Securement and Above-Deck Roof Components*

Data Sheet 1-31, *Panel Roof Systems*

Data Sheet 1-34, *Hail Damage*

Data Sheet 1-42, *MFL Limiting Factors*

Data Sheet 1-54, *Design Loads and Drainage*

Data Sheet 5-11, *Lightning Protection*

Data Sheet 5-19, *Switchgear and Circuit Breakers*

Data Sheet 5-20, *Electrical Testing*

Data Sheet 5-23, *Design and Protection for Emergency and Standby Power Systems*

Data Sheet 7-106, *Ground-Mounted Solar Photovoltaic Power*

FM 4476, *Approval Standard for Flexible Photovoltaic Modules*

FM 4478, *Approval Standard for Rigid Photovoltaic Modules*, December 2016

ANSI/FM 4473, *Test Standard for Impact Testing of Rigid Roofing Material by Impact Testing with Freezer Ice Balls*

Approval Guide, Building Materials section, an online resource of FM Approvals

RoofNav, an online resource of FM Approvals for roofing professionals

4.2 Other

American Society of Civil Engineers (ASCE). *Minimum Design Loads for Buildings and Associated Criteria*. ASCE 7, 2022.

American Society of Civil Engineers (ASCE). *Wind Tunnel Studies of Buildings and Other Structures. Manual of Practice 67*.

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International Electrotechnical Commission (IEC). *Grid Connected Photovoltaic Systems: Minimum Requirements for System Documentation, Commissioning Tests and Inspection*. IEC 62446.

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Los Angeles City Fire Department Requirement. *Solar Photovoltaic System*. FPB Requirement No. 96, 12/14.

Pagnamenta, R. "BP Solar Panel Blaze Raises Concerns Over Alternative Energy." The Times, Monday June 29, 2009.

APPENDIX A GLOSSARY OF TERMS

Aerospace wind tunnel: A wind tunnel that simulates horizontal wind forces acting directly on an object. It does not simulate conditions between the fans and the object within the lower portion of the boundary layer, which is required to replicate the surface roughness exposure related to wind design of the building and rooftop equipment. Neither does it replicate wind flow over a wall of a modeled structure below the rooftop equipment that would be required to simulate actual suction effects in addition to the horizontal forces.

Allowable stress design (ASD): A structural design method in which the allowable stresses contain a safety factor because the design is to stress levels that are only a percentage of the failure stresses.

Arc-fault circuit interrupter (AFCI): A device intended to provide protection from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to deenergize the circuit when an arc fault is detected.

Arc prevention: Technology that uses advanced arc prevention techniques to prevent arcs from forming. This exceeds the minimal requirements stated in NEC 2017 and UL 1699B, but these technologies are used by some manufacturers of module level power electronics today. Limits low energy level (200 Joules).

Array size: The number of interconnected PV panels (the minimum number of panels within each row and each column) and the gross plan area occupied within a given array. There is usually a slight (fraction of an inch) separation between panels in the east-west direction and sufficient separation (depending on panel

slope) between rows to prevent shadowing. Wind tunnel or field model tests should replicate the minimum array size required. Data for a larger array does not justify the design for a smaller array.

Automatic module-level DC shutdown: Systems that have built-in module-level power electronics and safety features that deenergize the PV array at the module level. These systems may be automatically triggered by a loss of grid power, high temperatures, ground faults, arc faults, faulty connectors, faulty wiring, rodent damage, etc. This is sometimes referred to as “safe DC.”

Ballasted: Not adhered to the roof cover below, nor fastened to the roof deck or structure. Resistance to wind loads is provided by the weight of the panels, mounting equipment, and any additional ballast. (Same as “loose laid.”)

Boundary layer wind tunnel: A wind tunnel with a long transition between the fans and the object, and that has obstructions to replicate the lower portion of the boundary layer and the surface roughness exposure related to wind design of the building and rooftop equipment. Testing is done with scaled models of rooftop equipment and the building upon which it is installed.

Closed mounting system: A PV mounting system that has a wind deflector on the high side (north side in northern hemisphere and south side in southern hemisphere) of each row of panels, but may or may not have one on the east and west ends of each row.

Coefficient of friction (μ): A dimensionless coefficient used to quantify resistance to lateral movement (in this case, between the undersides of the panel mounts and the top surface of the roof cover). It is equal to the lateral load resistance divided by the force normal to the two mating surfaces. This will vary depending on the construction of the underside of the panel mount and the type of roof cover. Such construction includes, but is not limited to, stainless steel, aluminum, coated metal, or metal with a pad (such as a piece of single-ply roof cover material or rubber) adhered to its underside.

Computational fluid dynamics (CFD): A form of computer modeling that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of fluids with surfaces defined by boundary conditions. Validation of such software is performed using a wind tunnel.

DC-to-DC converter: A device installed in the PV source circuit or PV output circuit that can provide an output dc voltage and current at a higher or lower value than the input dc voltage and current.

DC-to-DC converter output circuit: Circuit conductors between the dc-to-dc converter source circuit(s) and the inverter or dc utilization equipment.

DC-to-DC converter source circuit: Circuits between dc-to-dc converters and from dc-to-dc converters to the common connection point(s) of the dc system.

FM Approved: Products or services that have satisfied the criteria for Approval by FM Approvals. Refer to RoofNav, an online resource of FM Approvals, for a complete list of roofing products and services that are FM Approved.

Inverter: An electrical device used to convert direct current (DC) electrical power to alternating current (AC) electrical power.

Load and resistance factor design: Also known as “strength design” or “ultimate design,” it is a structural design method that provides a safety factor by applying factors to the loads, and in some cases a lesser safety factor to the resistance of the materials.

Loose Laid: not adhered to the roof cover below, nor fastened to the roof deck or structure. Resistance to wind loads is provided by the weight of the panels, mounting equipment, and any additional ballast. (Same as “ballasted.”)

Moderate hail hazard area: Area in which the hail size does not exceed 1.75 in. (44 mm) for the 15-year mean recurrence interval (MRI).

Non-sheltered PV panels: PV panels located on the exterior side of an array in the perimeter row(s) of PV panels, and that are not sheltered from the wind load from other panels, and for which the wind load may be greater than that of the interior, sheltered panels.

Open mounting system: A PV-mounting system that does not have a wind deflector on the high side (north side in northern hemisphere and south side in southern hemisphere) of each row of panels.

Photovoltaic (PV) system: A system that uses solar panels to convert sunlight into electricity. It consists of PV panels, support framework, and electrical connections and equipment to allow regulating and converting the electrical output from DC to AC.

PV panel: An individual unit consisting of numerous cells, usually 60 or 72. It is usually about 39.4 in. (1 m) in the north-south direction and 65 to 77 in. (1.65 to 2.0 m) in the east-west direction. In most cases it is bounded by edge framing. In some cases panels are also referred to as modules, particularly for ballasted situations. For anchored installations, three or four modules connected together may be considered a panel.

Rapid shutdown of PV systems on buildings: PV system circuits installed on or in buildings that include a rapid shutdown function to reduce shock hazard for emergency responders.

Roof control joint: A construction joint that provides a break in the continuity of above-deck roof components to prevent damage to the roof cover from thermal movement. This joint does not provide a break in the roof deck.

Roof expansion joint: A construction joint that provides a break in the continuity of the building framing, roof deck, and above-deck roof components to prevent damage to the building components from thermal movement.

Setback: The distance between the outside edge of a roof supporting solar panels and the outer edge of the solar array.

Severe hail hazard area: Area in which the hail size exceeds 1.75 in. (44 mm) but does not exceed 2 in. (51 mm) for the 15-year mean recurrence interval (MRI).

Shadowing: Shade created by neighboring objects that necessitate relocation of solar panels and sometimes openings within the array. This can create wind forces on solar panels immediately adjacent to the opening that are higher than the forces on the interior of the array.

Sheltered PV panels: PV panels located on the interior side of the perimeter row(s) of PV panels that are somewhat sheltered by the perimeter panels and for which the wind load is somewhat less than for the perimeter panels.

Very severe hail hazard areas: Areas in the United States designated as such on the Hailstorm Hazard Map in DS 1-34.

APPENDIX B DOCUMENT REVISION HISTORY

The purpose of this appendix is to capture the changes that were made to this document each time it was published. Please note that section numbers refer specifically to those in the version published on the date shown (i.e., the section numbers are not always the same from version to version).

July 2023. Interim revision. Minor clarifications were made.

January 2023. The following significant changes were made:

- A. Additional guidance related to the recommended wind Importance Factor (IF) was added.
- B. Guidance related to minimum and maximum roof slopes has been clarified.
- C. Recommendations related to fire concerns were added, as supported by loss experience.
- D. The example problem in Appendix C was modified.

January 2021. Interim Revision. Minor editorial changes were made.

October 2020. Interim revision. Minor editorial changes were made.

July 2020. Interim revision. Minor editorial changes were made.

February 2020. Interim revision. The following changes were made:

- A. Simplified the electrical recommendations section and added references to the 2017 edition of the *National Electrical Code*.
- B. Simplified wind design guidance for PV arrays that are parallel to and within 5 to 10 in. (125 to 250 mm) of the roof surface.

C. Expanded wind design guidance for sun-facing, sloped PV arrays.

October 2014. Interim revision. Added additional diagram (Figure 12B, *One-line example diagram to a PV system with ground faults*).

July 2014. This is the first publication of this document.

APPENDIX C SAMPLE PROBLEM: PV MODULES PARALLEL TO ROOF

C.1 Example

A proposed PV array is to be secured to an existing 24 in. (610 mm) wide, metal standing seam roof (SSR) using extruded aluminum external seam clamps (ESC). The roof slope is ¼ in. per ft (1.2°). The PV modules will be parallel to the roof surface. The distance between the flat part of the roof deck and the top edge of the integral aluminum frame of the PV module is to be 5 in. (127 mm). The PV modules are 60 cell and are 39 in. (1 m) wide and 66 in. (1.68 m) long. The long dimension of the PV modules will run across the deck ribs. Three ESC will be used to secure each long edge of the PV module to the roof deck ribs in accordance with Figure C.1-1. The horizontal space between modules will be 6 in. (152 mm) in their longitudinal direction and 1 in. (52 mm) in the opposite direction. A minimum of 800 modules must be installed to provide the required electrical output. The building is just slightly above sea level. Other details are as follows:

H = 33 ft (10 m), Wind Exposure Category C, $K_z = 1.0$ per Table 3.8

$W_L = 246$ ft (75 m), $W_S = 140$ ft (42.7 m)

V = 110 mph (49 m/s) allowable wind speed per Data Sheet 1-28

$K_{zT} = 1.0$ $K_D = 0.85$ per Data Sheet 1-28

$K_e = 1.0$ per Data Sheet 1-28

With ESC installed at each deck rib, the wind load from the PV modules follows the same wind load path as for the design of the SSR. The wind load path goes from the deck ribs to an internal clip, then through self-drilling screws securing the internal clips into the top flange of steel purlins.

The fire service requires a minimum 6 ft (1.8 m) wide aisle every 100 ft (30.5 m). The goal is to minimize the wind load transferred to the existing roof.

C.2 Solution

STEP 1: Since the PV modules are parallel to the roof surface, and within 10 in. of the flat part of the roof deck, per ASCE 7-16 and SEAOC PV2, the wind design load may be based on that used for a low slope ($\leq 7^\circ$) gable roof. The value for GC_p is determined from Figure 30.3-2A of ASCE 7-16 and Data Sheet 1-28. (See Table C.2.1)

STEP 2: As explained in Section 2.0 of this document, an edge factor (Υ_E) = 1.25 must be applied to the exposed PV modules located along each outer row closest to the roof edge and adjacent to aisles between arrays of all widths. Since the largest area supported by any ESC is between 6.50 and 8.53 ft² (0.6 and 0.8 m²) the GC_p will be based on an **effective wind area (EWA) ≤ 10 ft² (1 m²)**.

STEP 3: Since the top edge of the module is ≤ 5 in. (127 mm) from the flat part of the roof surface ($h_1 = h_2$), and the minimum gap (G) between modules in each direction is $\geq 3/4$ in. (19 mm), for an EWA ≤ 10 ft² (1 m²), $\Upsilon_A = 0.6$. The unfactored loads are as follows:

$$q_H = 0.00256 K_z K_{zT} K_D K_e V^2 = 0.00256 (1.0) (1.0) (0.85) (1.0) (110)^2 = 26.3 \text{ psf}$$

$$p = q_H (GC_p) \Upsilon_E \Upsilon_A$$

The dimensions of the individual roof zones are noted in Figures C.3-1 and C.3-2.

Zone 3:

$$p = (26.3) (-3.2) (1.25) (0.6) = -63.2 \text{ psf for the first row of exposed modules}$$

$$p = (26.3) (-3.2) (1.0) (0.6) = -50.6 \text{ psf for the interior rows of modules}$$

Zone 2:

$$p = (26.3) (-2.3) (1.25) (0.6) = -45.4 \text{ psf for the first row of exposed modules}$$

$$p = (26.3) (-2.3) (1.0) (0.6) = -36.3 \text{ psf for the interior rows of modules}$$

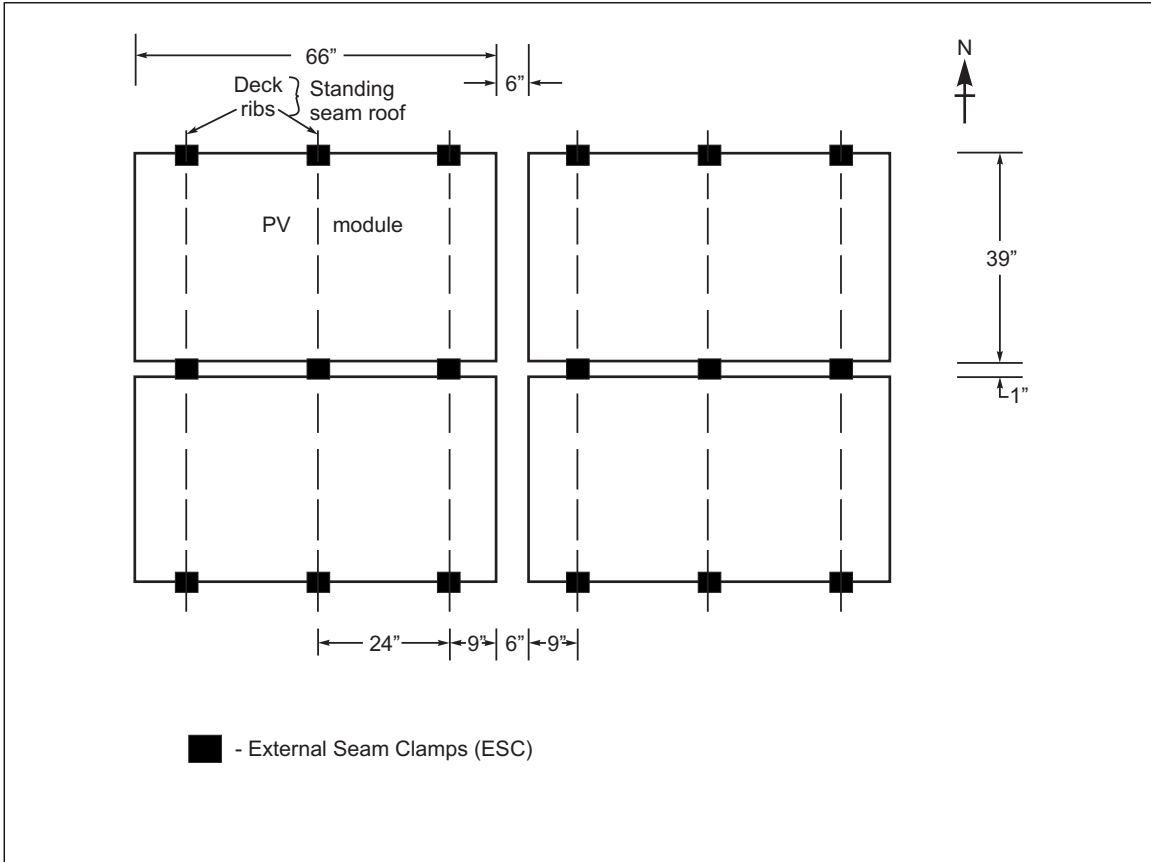


Fig. C.1-1. Plan view of proposed layout for PV modules and clamps

Zone 1:

$p = (26.3) (-1.7) (1.25) (0.6) = -33.5$ psf for the first row of exposed modules

$p = (26.3) (-1.7) (1.0) (0.6) = -26.8$ psf for the interior rows of modules

Zone 1':

$p = (26.3) (-0.9) (1.25) (0.6) = -17.8$ psf for the first row of exposed modules

$p = (26.3) (-0.9) (1.0) (0.6) = -14.2$ psf for the interior rows of modules

Allowable or design Wind pressures are summarized in Table C.3-2.

Table C.2-1. Values of GC_p per ASCE 7-16 and Data Sheet 1-28

Roof Slope $\leq 7^\circ$	
GC_p per ASCE 7-16	
Zone	GC_p
1	3.2
2	2.3
1	1.7
1'	0.9

Note: All values of GC_p are based on an effective wind area (EWA) of 10 ft² (1 m²)

C.3 Summary

A. Wind design pressures shown in Table C.3.-2 should be used.

B. The following modules located in an outer row or column are considered “exposed” and should be designed using the higher wind loads that include an edge factor = 1.25:

1. The north and south edges of Arrays 1 and 2.
2. The west edge of Array 1 and the east edge of Array 2.
3. Also, the east edge of Array 1 and the west edge of Array 2 require an edge factor = 1.25.

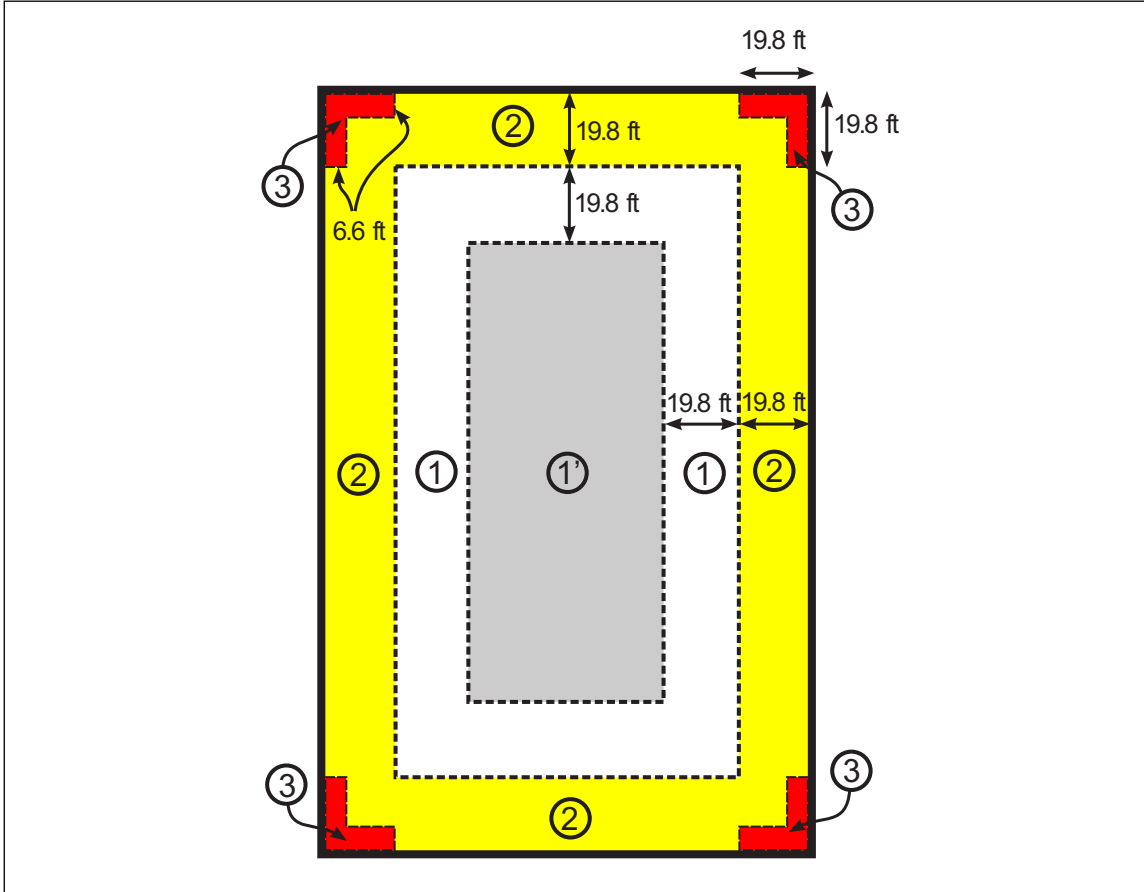


Fig. C.3-1. Wind zones for low-slope roofs ($\leq 7^\circ$) per ASCE 7 and DS 1-28

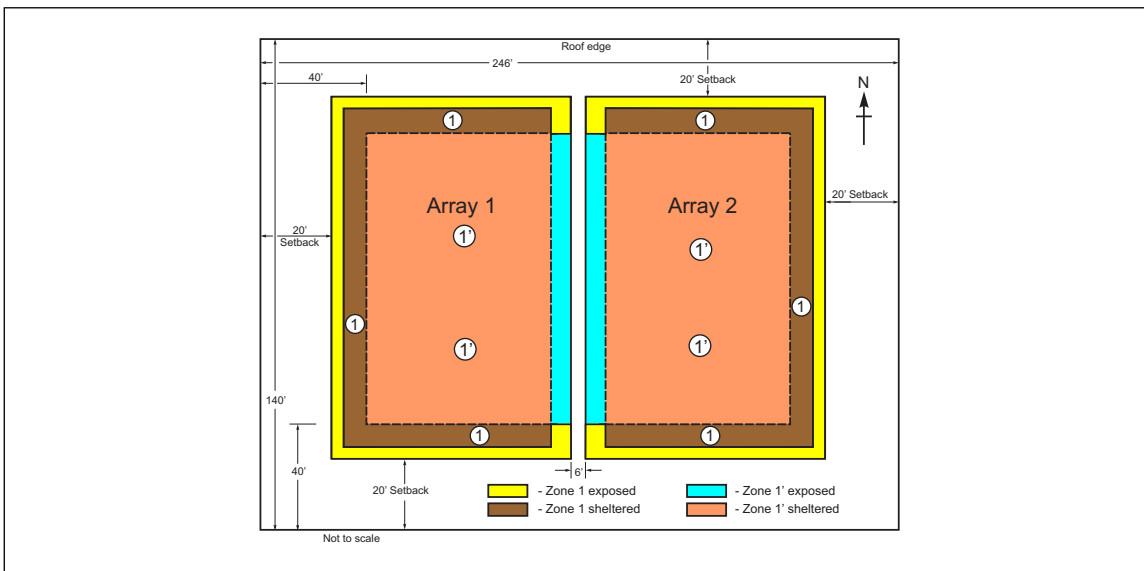


Fig. C.3-2. Various wind zones for proposed PV array in the example

C. The tempered glass for the proposed solar panel is 3.2 mm (1/8 in.) thick. Per ASTM E 1300, the allowable wind pressure (short duration) is only 102 psf. A test of the PV module indicated that the aluminum frame failed catastrophically at 105 psf (5.0 kPa). That is equivalent to an allowable load of only 65.6 psf (3.1 kPa) with a factor of 1.6 applied. Given that there is sufficient room on the roof, providing a minimum setback of 20 ft (6.1 m) for the PV modules installed per Figure C.3-2, is a preferred solution.

Table C.3-2. Preliminary Wind Design Pressures

Zone	GCP	ESC Location	Edge Factor (E)	Zone Dimensions*, ft (m)	Allowable Wind Uplift Pressure, Psf (kPa)	Ultimate Resistance with SF = 1.6 for PV Modules	Ultimate Resistance with SF = 2.0 for Clamps	Ultimate Load on at Each PV Connection lbs (kN)
3	-3.2	Outer Edge/ Exposed	1.25	L-shaped, 6.6 (2.0) Perpendicular to roof edges, by 19.8 (6.0) parallel to roof edges	- 63.2 (3.0)	- 101 (4.8)	- 126.4 (6.1)	822 (3.66) ¹
		Shielded	1.0		-50.6 (2.4)	- 80.9 (3.9)	- 101.2 (4.8)	658 (2.93)
2	-2.3	Outer Edge/ Exposed	1.25	Between roof edge, Zone 3 and a point 19.8 (6.0) perpendicular to roof edges	- 45.4 (2.2)	72.6 (3.5)	- 90.8 (4.3)	590 (2.63)
		Shielded	1.0		- 36.3 (1.7)	-58.1 (2.8)	-72.6 (3.5)	472 (2.10)
1	-1.7	Outer Edge/ Exposed	1.25	Between 19.8(6.0) and 39.6 (12.1) in from roof edges	- 33.5 (1.6)	- 53.6 (2.6)	- 67.0 (3.2)	436 (1.94)
		Shielded	1.0		-26.8 (1.3)	-42.9 (2.1)	-53.6 (2.6)	348 (1.55)
1'	-0.9	Outer Edge/ Exposed	1.25	Beyond 39.6 (12.1) in from the roof edges	-17.8 (0.9)	- 28.5 (1.4)	- 35.6 (1.7)	231 (1.03)
		Shielded	1.0		-14.2 (0.7)	-22.7 (1.1)	-28.4 (1.4)	185 (0.82)

Note 1. Maximum area of the PV clamp 6.5 ft² (24 x 39 in.)/(144 in.²/ft²).

The ultimate load transferred to the deck ribs with PV connections at each rib is (6.5 ft²) (126.4 psf.) = 822 pounds per PV connection. If the purlin spacing is ≤ 40 in. (1.0 m), assume that load is transferred to the internal clip. If the purlin spacing is 60 in. (1.5 m), the maximum load on the internal clip would be 822 lb (1.67) = 1372 pounds (620 kg). That is because one PV connection is directly over a purlin connection, it will also pick up one-third of the load from each of the PV connections on either side.

This analysis is not required if the PV-roof assembly has been FM Approved for the needed PV wind pressure.

C.4 Discussion

Several options were considered to provide the required number of modules, but minimize wind forces applied to the roof. Limiting the distance between the modules and the roof surface to 5 in. (635 mm), and providing a minimum gap of ¾ in (19 mm). between modules provides a significant reduction in the wind uplift design pressure as γ_A is reduced to 0.6. Note that this is allowed per SEAOC PV2-2017 and ASCE 7-22.

Another factor is the setback distance from the edge of the roof to the first row of PV modules, which often is 10 ft (3.05 m) to 15 ft (4.6 m) on all 4 sides of the building. In reviewing Table C.3-1, it can be noted that the wind pressure has been further reduced considerably by **increasing the setback distance to 20 ft** (6.1 m) on all sides and placing the modules in Zone 1 and 1', and not in Zone 2 or 3.

As the local fire service required a minimum 6 ft (1.8 m) wide access aisles at maximum distances of 100 ft (30.5 m), the modules along each side of the aisle must use an edge factor = 1.25 since the aisle is > 4 ft (1.2 m) wide.

This will still allow enough room for the required minimum of 800 modules by installing the modules in two - approximate 100 by 100 ft (30.5 by 30.5 m) arrays. Within each array 14 modules in each of 30 rows are used (see Figure C.3-2). This allows for up to 840 modules total. It also simplifies the allowable wind design, which is now summarized in Table C.4-1.

Table C.4-1. Final Wind Design Pressures

Zone*	GC_p	ESC Location	Edge Factor (E)	Zone Dimensions, ft (m)	Allowable Wind Uplift Pressure, Psf (kPa) *
1	-1.7	Outer Edge/ Exposed	1.25	Between 19.8 (6.0) and 39.6 (12.1) in from roof edges	-33.6 (1.6)
		Shielded	1.0		-26.9 (1.3)
1'	-0.9	Outer Edge /Exposed	1.25	Beyond 39.6 (12.1) in from the roof edges	-17.8 (0.85)
		Shielded	1.0		-14.2 (0.7)

* See Table C.3-2 for factored pressures.