Characterization of Photovoltaic Materials – Critical Flux for Ignition / Propagation Phase 3

Project Number: 11 CA43479
File Number: SV19060
Date: January 16, 2012

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EXECUTIVE SUMMARY

This report is a third phase continuation of a research project conducted to determine the effect of rack mounted photovoltaic (PV) systems on the flammability classification rating of roofing materials. The original project (Phase 1) was conducted in response to fire and building code officials' interest in determining if a Class C rated module would reduce the fire resistance performance and/or fire rating of some Class A rated roof systems. And if so, which roof systems are impacted and to what extent. Results of that activity were documented in a report titled "Effect of Rack Mounted Photovoltaic Modules on the Fire Classification Rating of Roofing Assemblies" dated September 30, 2009, revised November 30, 2010. The research was expanded in a second phase to arrays mounted at various angles to a roof and a comparison of standard ignition brands to wood excelsior and leaf debris. These results were published in a report titled "Effect of Rack Mounted Photovoltaic Modules on the Fire Classification Rating of Roofing Assemblies Phase 2" dated January 30, 2012.

Phase 1 - An analysis of the data generated by the experiments carried out in the first study [1] pointed to the following key findings:

- The presence of a rack mounted PV module on a roof has an adverse effect on the fire performance of the roof regardless of the fire rating of the roof or the Class rating of the PV panel based on Spread of Flame test method described in UL 790 *Standard for Safety for Standard Test Methods for Fire Tests of Roof Coverings*, Eighth Edition, Dated April 22, 2004 and UL 1703 *Standard for Safety for Flat Plate Photovoltaic Modules and Panels*, Third Edition, Dated March 15, 2002.
- The extent of the degradation on fire performance with respect to flame spread of a roof depends upon PV installation parameters such as setback distance and separation gap between roof and PV module.
- The presence of a rack mounted PV module on a roof could adversely affect the fire performance of the roof when subjected to burning brands placed on the roof based on the Burning Brand test method described in UL 790.

Phase 2 - An analysis of the data generated by the experiments carried out in the second study [2] pointed to the following key findings:

- Some PV modules mounted at angles (positive and negative) to steep and low sloped roofs impacted the fire classification rating of the supporting roof assembly. The extent of the impact was dependent on the angle of the module relative to the roof and the type of roofing system.
- PV modules mounted at zero clearance to the roof surface demonstrated no impact to the fire rating of the roof when the ignition source flame was directed to the front vertical surface of the module or when the ignition source flame was directed along the horizontal face of the module.
- The heat release rate and heat transfer to the roof surface of Class A and Class C brands did not demonstrate a direct correlation to common materials that may collect between PV modules and the roof surface, such as leaf debris and excelsior (wood wool). The Class A brand yielded results significantly greater than the leaf debris and

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[1] Effect of Rack Mounted Photovoltaic Modules on the Flammability of Roofing Assemblies, Date: September 30, 2009, Revised March 5, 2010
[2] Effect of Rack Mounted Photovoltaic Modules on the Flammability of Roofing Assemblies, Date: September 30, 2009, Revised March 5, 2010

wood excelsior while the Class C brand yielded results significantly less than the leaf debris and wood excelsior. While the Class B brand was not included in the experiments, the deduction of these experiments is that the representation of common materials is closest to the Class B brand in terms of heat release and heat transfer to the roof surface. .

As an extension of the above work, a broad stakeholder group to the Solar ABC's projects held meetings to discuss the project results and what actions should be taken. The group consensus was that work should be initiated toward revisions to the fire tests in UL 1703, *Standard for Safety for Flat-Plate Photovoltaic Modules and Panels*. To satisfy this objective, the matter was brought to the UL 1703 Standards Technical Panel (STP). A task group was convened under the STP to develop a proposal to modify the current flame spread test and burning brand test to more appropriately evaluate the flame spread and burning brand resistance of roof mounted PV modules as an assembly, i.e. the PV modules in conjunction with the intended roof structure. The proposed approach addresses the research findings that evaluating the fire performance of PV modules and roofs independently does not indicate performance of the combination.

However, during discussions, attendees at stakeholder meetings as well as members of the STP expressed concerns regarding the number of tests that would be required to evaluate multiple combinations of PV and roofing systems. It was acknowledged that although roofing systems may be generally grouped into low and steep sloped roofs, the number of manufacturers and types of roofing products within this two groups were thought to be in excess of what could be reasonably evaluated by a PV manufacturer. The Phase 3 study reported herein was commissioned to determine possible similarities of roofing materials in a an effort to optimize the coverage of a PV / roofing system evaluation to a large number of roofing types while minimizing the amount of testing required.

Summary of Findings

An analysis of the data generated by the experiments in this Phase 3 point to the following key findings:

- The critical flux values for most of the roofing products was determined to be greater than the 15 kW/m^2 exposure measured on the surface of a noncombustible deck without a PV (see Table 1, Assembly 1). Exceptions being one architectural shingle, one membrane and two insulation boards with critical heat flux values of 14, 14, 13, 14 kW/m^2 respectfully.
- The critical flux values for all of the roofing products was determined to be less than the 41 kW/m^2 exposure measured on the surface of a noncombustible deck with a PV installed with a gap of 5" (see Table 1, Assembly 34).
- The critical flux for ignition of low slope roof products was found to be generally consistent as were the critical flux for ignition of high slope roof products.

Continuation of Fire Safety Research Project

This project was conducted to expand on previously collected empirical data for consideration by manufacturers of PV and roofing products, regulatory officials such as Authorities Having Jurisdiction, and code and standards development organizations. It is anticipated that the results of these experiments will lead to potential code and standards revisions.

Acknowledgments

The authors would like to acknowledge the following individuals for their contributions including guidance and support for this project:

Bill Brooks of Brooks Engineering
Larry Sherwood of Sherwood Associates
Kevin Lynn of the Department of Energy (DOE)
Andy Rosenthal of New Mexico State University

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Introduction

This research project described herein expands on work conducted in Phases 1 and 2. Phase 1 of this project sought to address regulatory concerns over the installation of Class C fire rated PV modules over Class A fire rated roofs. Results of that activity have been documented in a report titled “Effect of Rack Mounted Photovoltaic Modules on the Fire Classification Rating of Roofing Assemblies” dated September 30, 2009, revised November 30, 2010. Phase 2 sought to address questions regarding 1) fire spread of along modules mounted at 0 in. clearance installation height above the roof, 2) arrays installed at various angles to the roof, and 3) comparison of Class A and Class C burning brands and common materials that may collect between PV modules and the roof surface, represented by leaf debris and excelsior (wood wool). The results were published in a report titled “Effect of Rack Mounted Photovoltaic Modules on the Fire Classification Rating of Roofing Assemblies Phase 2” dated January 30, 2012.

As an outgrowth of the above work, a broad stakeholder group to the Solar ABCs projects held meetings to discuss the project results and what actions should be taken. The group consensus was that work should be initiated towards revisions to the fire tests in UL 1703, “Flat-Plate Photovoltaic Modules and Panels”. To satisfy this objective, the matter was brought to the UL 1703 Standards Technical Panel (STP). A task group was convened under the STP to develop a draft proposal to modify the current test flame spread and burning brand test to more appropriately evaluate the flame spread and burning brand resistance of roof mounted PV modules as an assembly - the PV modules in conjunction with the intended roof structure. This proposed approach more closely aligns with the research findings.

However, during discussions, attendees at stakeholder meetings as well as members of the STP expressed concerns regarding the number of tests that would be required to evaluate multiple combinations of PV and roofing systems. It was acknowledged that although roofing systems may be generally grouped into low and steep sloped roofs, the number of manufacturers and types of roofing products within this two groups were thought to be in excess of what could be evaluated by a PV manufacturer. This study, Phase 3, was commissioned to determine possible similarities of roofing materials in an effort to optimize the coverage of a PV / roofing system evaluation to a large number of roofing types and while minimizing the amount of testing required.

Critical Flux

Critical flux is a fundamental fire property of a material and can be defined as the minimum level of incident radiant flux energy required for ignition, expressed as energy per unit area (kW/m^2 or W/cm^2). In some model building code applications such as floor covering materials [3], the critical flux required to propagate a flame along a surface is used to regulate the permissible materials.

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[3] International Fire Code, 2012 Edition - Interior floor finish and floor covering materials required by Section 804.3.3.2 to be of Class I or II materials shall be classified in accordance with NFPA 253. The classification referred to herein corresponds to the classifications determined by NFPA 253 as follows: Class I, 0.45 watts/cm^2 or greater; Class II, 0.22 watts/cm^2 or greater.

For a sense of scale and comparative purposes, values for critical flux of some common materials are given below:

- Wood, newspaper – 9 to 12 kW/m^2 [4]
- Asphalt – 22 to 27 kW/m^2 [5]
- Polyisocyanurate foam – 17 kW/m^2 [6]

Determination of Critical Flux for Ignition / Propagation

Objectives and Technical Plan

The objective of this phase was to assess a material flammability parameter (critical flux) of materials used in the construction of PV modules and representative roofing products. This data would be used to:

1. document relative fire performance to better understand the contribution of materials to the flame spread of PV module and roofing assemblies,
2. provide quantitative data to support generic Type classifications of PV module construction,
3. develop a data baseline for future use in reviewing proposed materials in third party listed products.

The technical plan consisted of conducting experiments on a variety of common roofing and PV products to determine the critical flux for ignition or propagation.

Experiments were conducted following the test protocols outlined in:

- ASTM E 648, "Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source, also known as the Floor and Radiant Panel Apparatus (FARP)",
- ASTM E1321, "Standard Test Method for Determining Material Ignition and Flame Spread Properties, also known as the Lateral Ignition and Flame Travel apparatus (LIFT)" and,
- ASTM E1354, "Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter", also known as the cone calorimeter apparatus.

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[4] Spearpoint M J, Quintiere J G. Predicting the ignition of wood in the Cone Calorimeter - effect of species, grain orientation and heat flux. Fire Safety Journal, Vol 36/4, pp. 391-415, 2001.

[5] Colwell – Test Methodologies for reaction to fire of pavement materials, Sustainable & Advanced Materials for Road Infracsture, SAM-04-B20, 2005

[6] Quintiere and Harkleroad – New Concepts for Measuring Flame Spread Properties, National Bureau of Standards, NBSIR 84-2943, 1984

Photographs of each of the test fixtures are shown in Figures 1, 2 and 3.

Figure 1 – Figure Illustrates ASTM E648 FARP Test Apparatus

Figure 2 – Figure Illustrates ASTM E1321 LIFT Test Apparatus

Figure 3 – Figure Illustrating ASTM E1354 Cone Calorimeter Test Apparatus

Background - Heat Flux Measurements from Phase 1 Project:

Phase 1 of the Project included measurements of the heat flux exposure of the UL 790 / UL 1703 flame spread test. Experiments were conducted on noncombustible deck with and without a noncombustible surrogate of a PV module. These heat flux measurements provide an opportunity for comparison of critical flux of roofing and PV materials to the spread of flame exposure.

The temperature and heat flux data from those fire tests are reprinted here and summarized in Table 1 for twelve experiments. For a complete review of this data, please reference the original project report ("Effect of Rack Mounted Photovoltaic Modules on the Flammability of Roofing Assemblies", Date: September 30, 2009, Revised March 5, 2010).

Table 1 - Results for Spread of Flame test on simulated PV module and roof

Assembly ID	Gap (in)	Setback (in)	Rail	Temperature @ 5 mins			Average Temp Rise (last 30 sec)			Heat Flux Max	
				1	3	4	1	3	4	1	2
				(°F)	(°F)	(°F)	(°F)	(°F)	(°F)	(kW/m^2)	(kW/m^2)
1	N/A	N/A	N/A	502	177	151	371	93	65	15	3
7	2 1/2	0	N/A	948	465	362	859	355	260	23	9
9	2 12	12	N/A	747	384	292	679	313	211	16	8
11	2 1/2	24	N/A	457	294	232	261	175	135	7	6
12	5	0	Vertical	974	768	562	-	-	-	29	22
17	5	0	Horiz.	1008	751	604	909	688	513	34	17
22	10	0	N/A	630	373	327	-	-	-	19	9
24	10	12	N/A	551	374	332	458	292	246	17	7
26	10	24	N/A	490	317	280	381	223	183	11	7
34	5	0	N/A	1066	719	576	939	637	508	41	25
35	5	24	N/A	600	430	369	499	334	279	12	9
36	5	12	N/A	865	518	406	703	428	316	23	12

Samples

PV modules and roofing products samples used in these Phase 3 experiments were either donated by industry or purchased from local retailers. The PV modules were a metal framed glass on polymer design, representative of Class C fire classification rating. The roofing products consisted of Class A steep slope 3 tab and architectural roof shingles, base and cap sheets, EPDM and FR EPDM membranes, and polyisocyanurate insulation boards:

- Composite or 'stacks' cut from PV modules consisting of glass, encapsulant and cell and backplane layers (3 manufactures)
- 3 tab shingles (3 manufactures)
- Architectural shingles (3 manufacturers)
- Base sheet (1 manufacturer)
- Cap sheet (2 manufacturers)
- EPDM membrane (1 manufacturer)
- FR EPDM membrane (1 manufacturer)
- Insulation board (1 manufacturer)
- FR insulation board.(1 manufacturer)

Specimens for each experiment were prepared in accordance with the respective test protocol.

Experimental Plan

The experimental plan to obtain critical flux for ignition was to obtain the values using the FARP apparatus, followed by the LIFT apparatus and finally the Cone apparatus. The plan was to then to compare measured values from the different test methods for the same roofing or PV product to gain an understanding on the influence of the test method and fixture on critical flux values.

Critical flux measurements are obtained directly from the FARP and LIFT experiments using the ASTM E648 and E1321 test protocols. In both of these test protocols the flame front or propagation along the sample surface is directly related to the incident radiant flux exposure during the test. A calibration is conducted to establish the heat flux / distance relationship. The critical flux is then determined from the point at which the flame front progresses.

The cone calorimeter protocol using the ASTM E1354 procedure does not determine critical flux directly as a reported result from the test protocol. Rather, the test apparatus may be used to conduct experiments at multiple heat flux exposures in order to derive the critical flux by plotting heat flux vs. ignition times. The technique is described in National Institute of Standards and Technology publication titled "Predicting the Ignition Time and Burning Rate of Thermoplastics in the Cone Calorimeter".[7] Three experiments were conducted on each material at three heat flux exposures - To determine the critical flux for ignition, the reciprocal of the time to ignition (1/

[7] Hopkins, Predicting the Igntion Time and Burning Rate of Thermoplastics in the Cone Calorimeter", NIST-GCR-95-677, September 1995

t_{ign}) was plotted vs heat flux for each sample. A linear best fit equation was fitted to the data. The x axis intercept (heat flux) indicated the critical flux.

For the membrane and insulation board samples, experiments were conducted at 25, 50, and 70 kW/m^2. For the granulated roofing products and PV module 'stack' samples, experiments were conducted at 35, 50 and 70 kW/m^2.

All roofing materials samples were specimens cut from the individual product (shingle, sheet or membrane). The PV module stack specimens were cut from full modules. The PV modules were Class C, metal framed, and glass on polymer construction.

ASTM E648 Results

Experiments were conducted on two shingles using the FARP (ASTM E648) apparatus. Additional experiments on other materials were not conducted as the flame front did not propagate beyond the ignition source impingement zone. These results indicate the critical flux of the roofing product was greater than that generated in the apparatus which is 10 kW/m^2.

Figure 4 – Figure Illustrating Sample After Exposure in the ASTM E1321 Test Apparatus

ASTM E1321 Results

Experiments using the LIFT (ASTM E1321) were also inconclusive. During the conduct of the initial experiments with samples in a horizontal configuration, the test fixture became overheated resulting in damage to the equipment. Additional experiments were not attempted.

ASTM E1354 Results

Critical flux values determined from cone calorimeter measurements are tabulated in Table 2; individual test results for the various materials are plotted in Figures 5 through 21. The following is a summary of the experiment results:

- The critical flux for the three PV module stacks ranged from 31 to 34 kW/m^2
- The critical flux for the three tab shingles ranged from 18 to 22 kW/m^2
- The critical flux for the architectural shingles ranged from 14 to 26 kW/m^2
- The critical flux for the base and cap sheets ranged from 15 to 18 kW/m^2
- The critical flux for the two non-fire retardant membranes were 14 and 18 kW/m^2, whereas the fire retardant product was 19 kW/m^2
- The critical flux for the non-fire retardant and fire retardant insulation boards was 13 and 14 kW/m^2 respectfully

Table 2 Summary of Cone Calorimeter measured Critical Flux Results

Product	Critical Flux (kW/m^2)
PV Module Stack #1	32
PV Module Stack #2	34
PV Module Stack #3	31
Shingle - 3 tab #1	18
Shingle - 3 tab #2	22
Shingle - 3 tab #3	21
Shingle – architectural #1	21
Shingle – architectural #2	26
Shingle – architectural #3	14
Base Sheet #1	17
Cap Sheet #1	18
Cap Sheet #2	15
Membrane – EPDM #1	14
Membrane - FR EPDM #1	19
Membrane –TPO #1	18
Insulation Board #1	13
FR Insulation Board #1	14

Plots of 1/ t_{ign} vs time – 3 Tab Shingles:

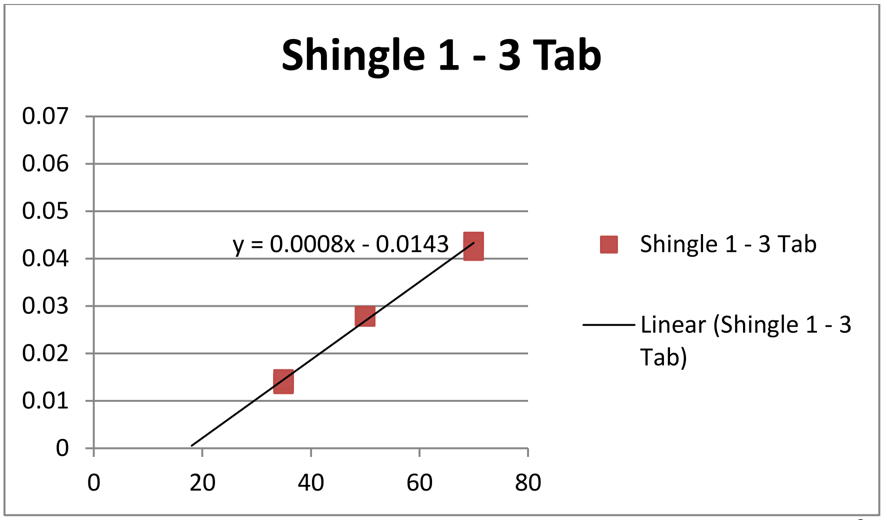

Figure 5 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

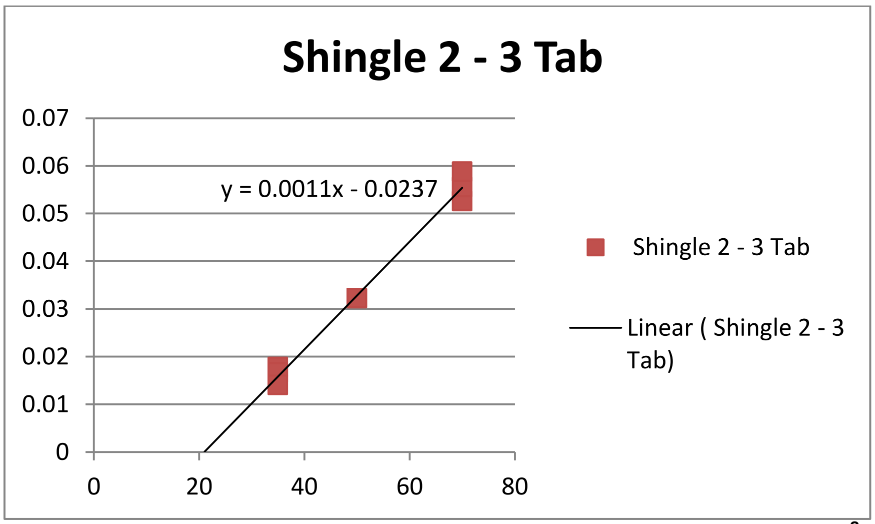

Figure 6 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

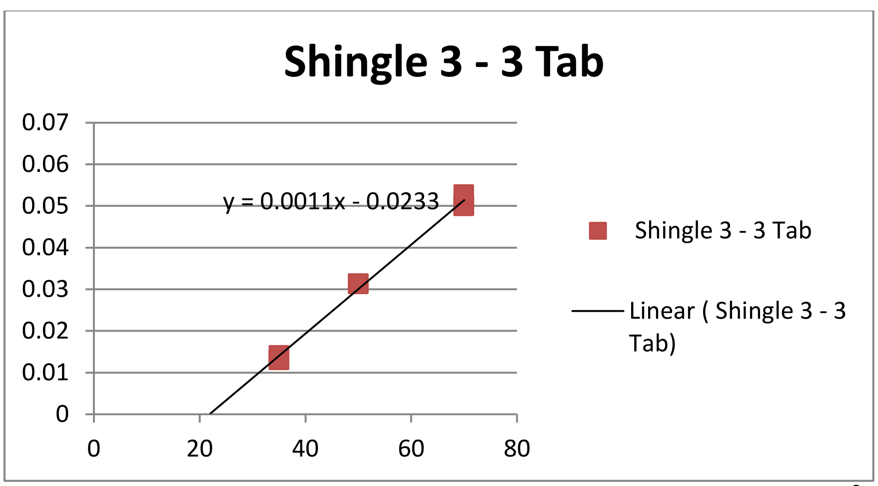

Figure 7 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

Plots of 1/ t_{ign} vs time – Architectural Shingles:

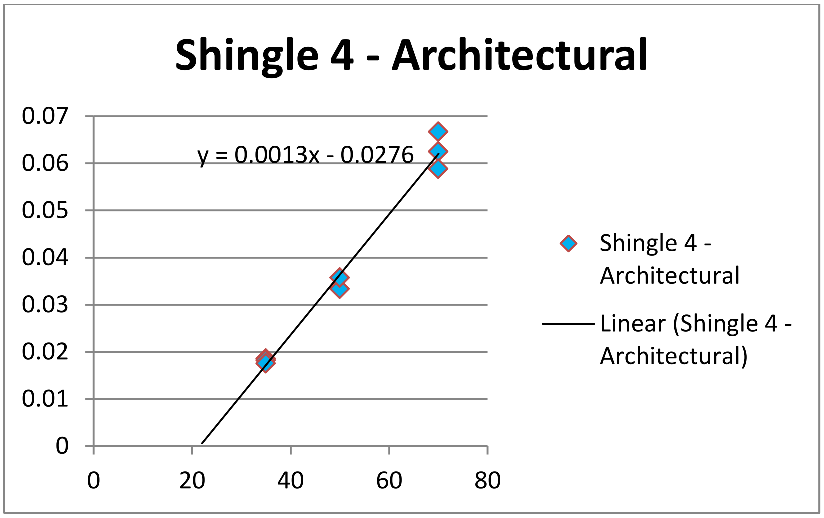

Figure 8 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

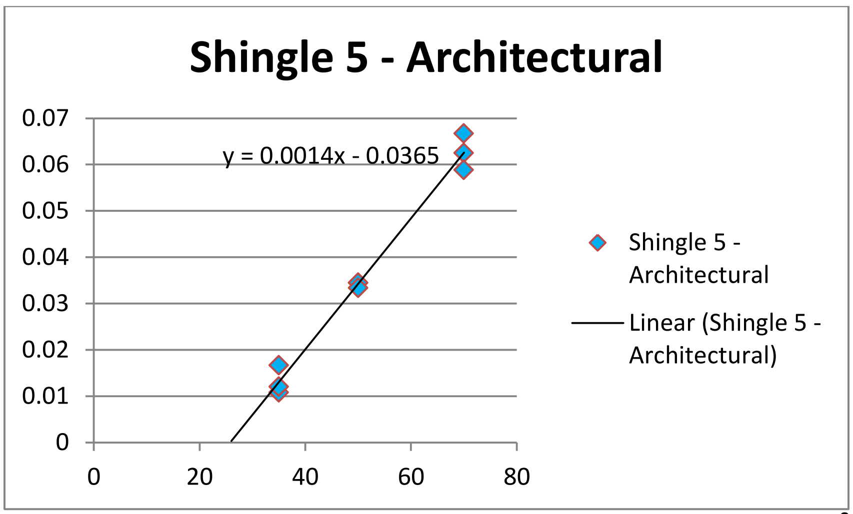

Figure 9 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

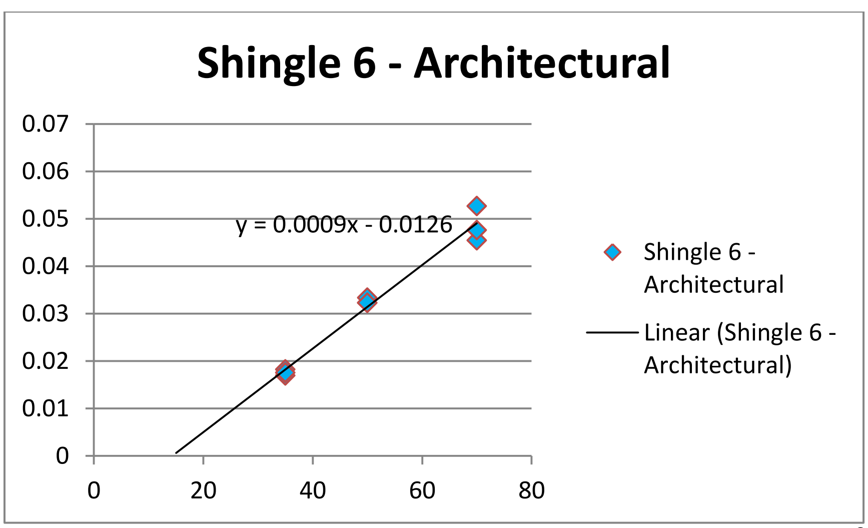

Figure 10 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

Plots of $1/t_{ign}$ vs time – Base & Cap Sheets:

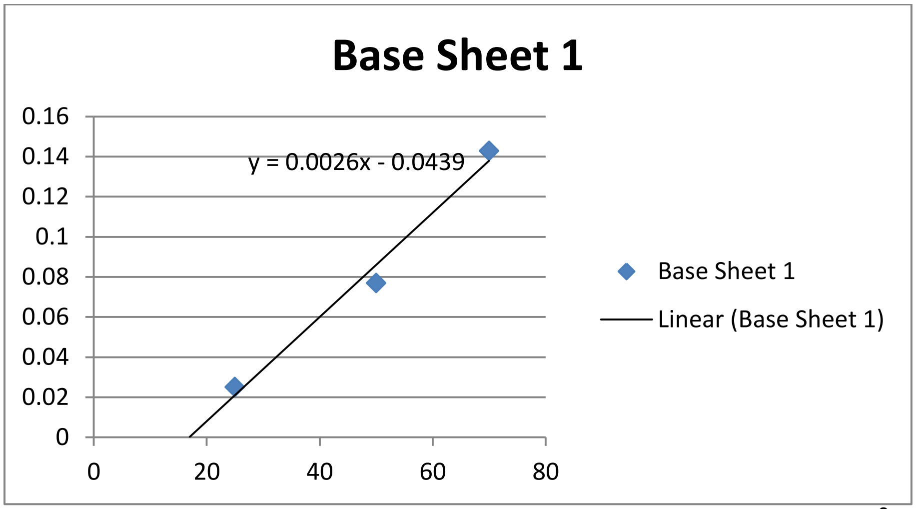

Figure 11 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

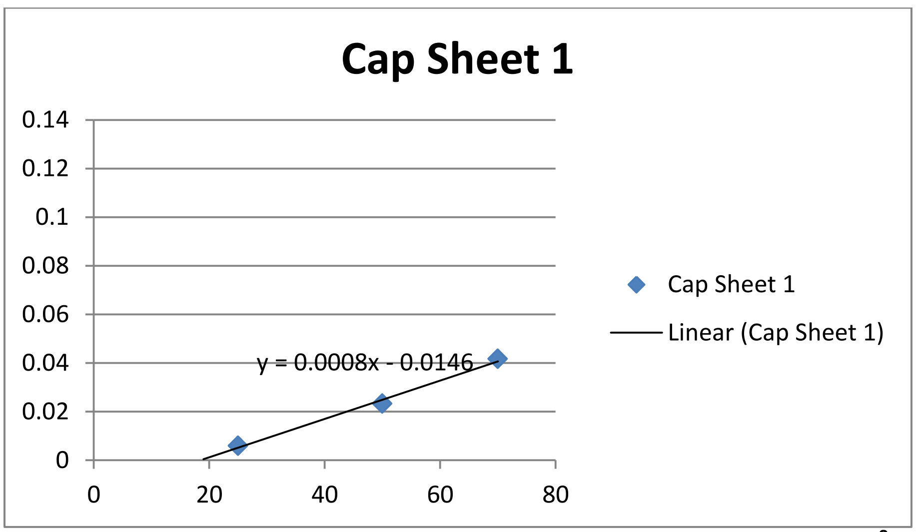

Figure 12 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

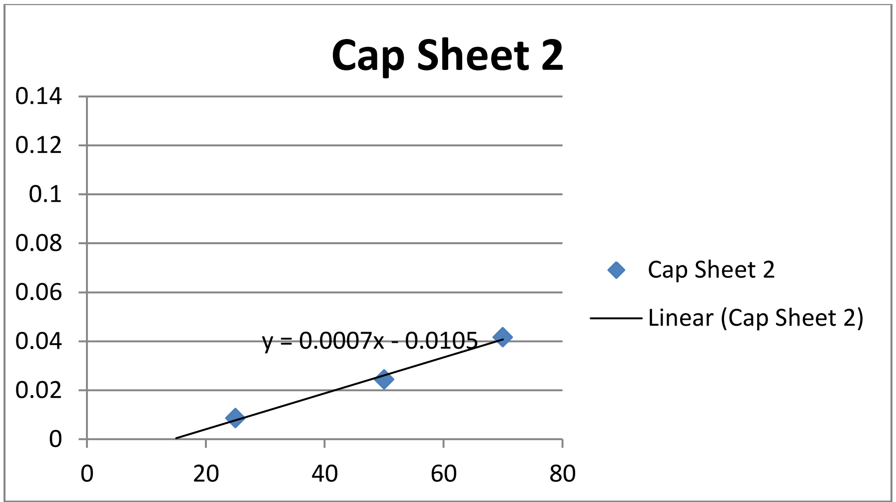

Figure 13 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

Plots of 1/ t_{ign} vs time – Low Slope Membranes:

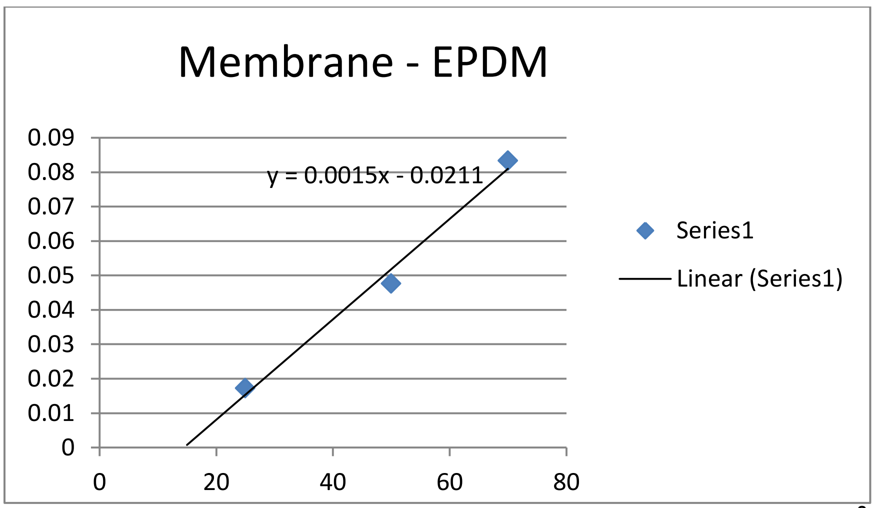

Figure 14 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

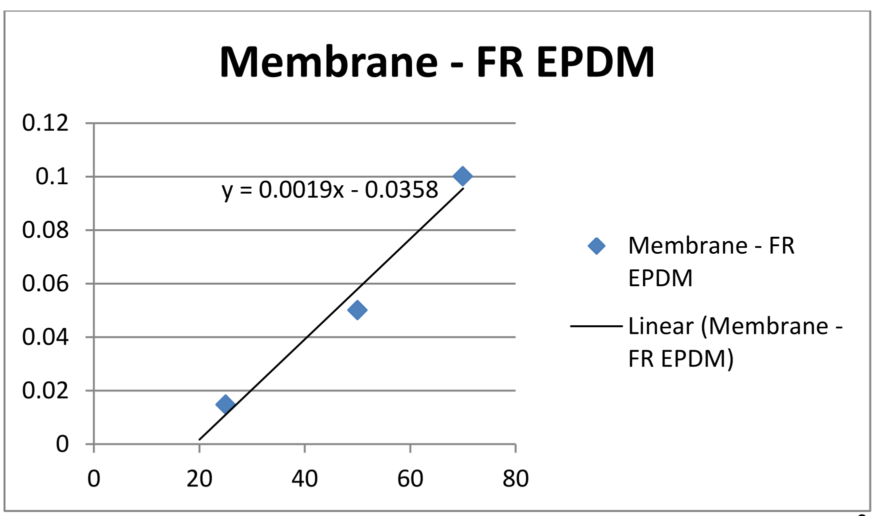

Figure 15 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

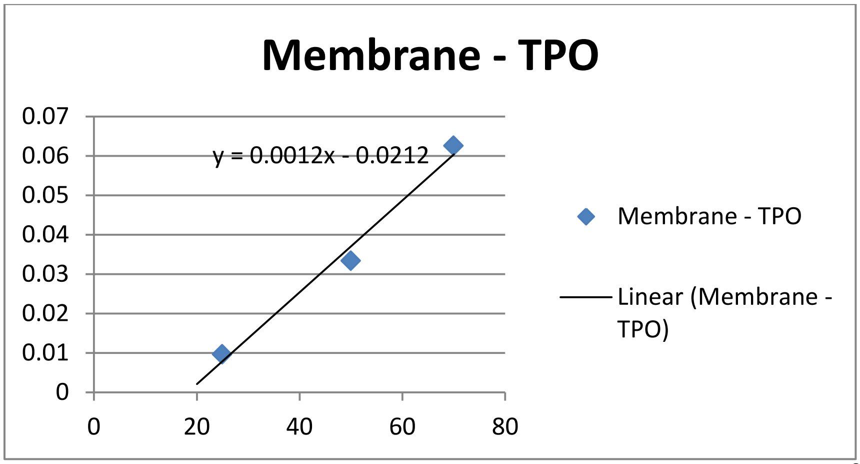

Figure 16 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

Plots of 1/ t_{ign} vs time – Low Slope Insulation Board:

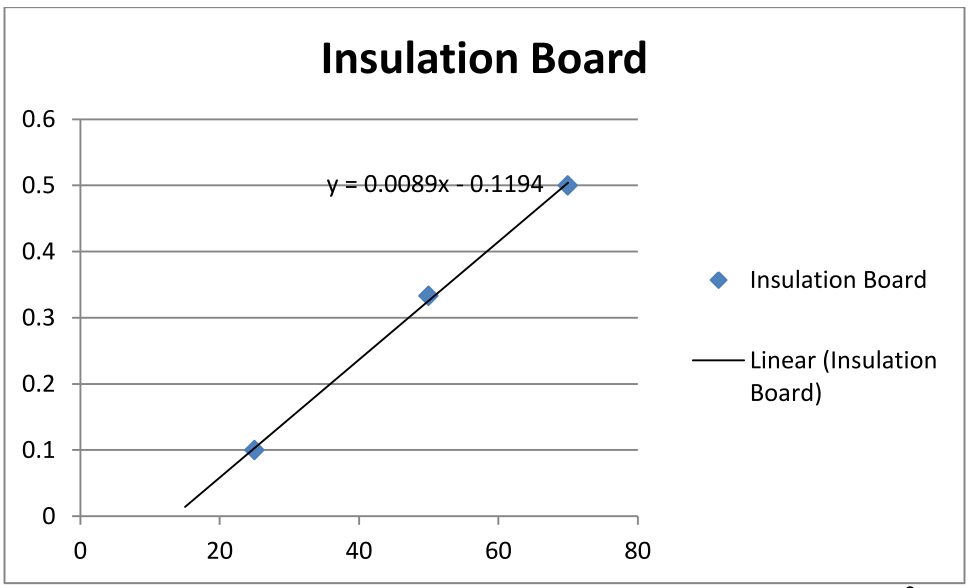

Figure 17 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

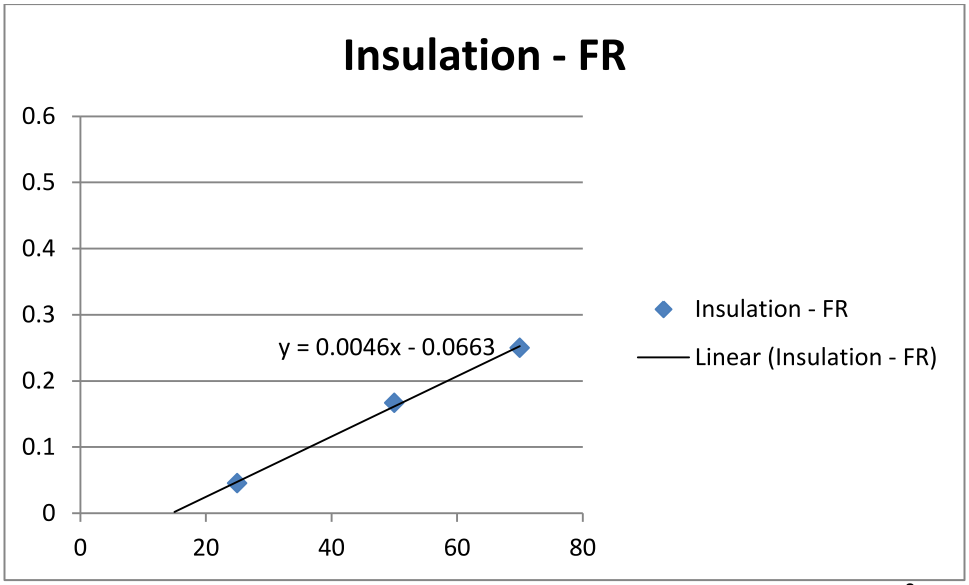

Figure 18 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m^2

Plots of 1/ t_{ign} vs time – PV Module Stacks:

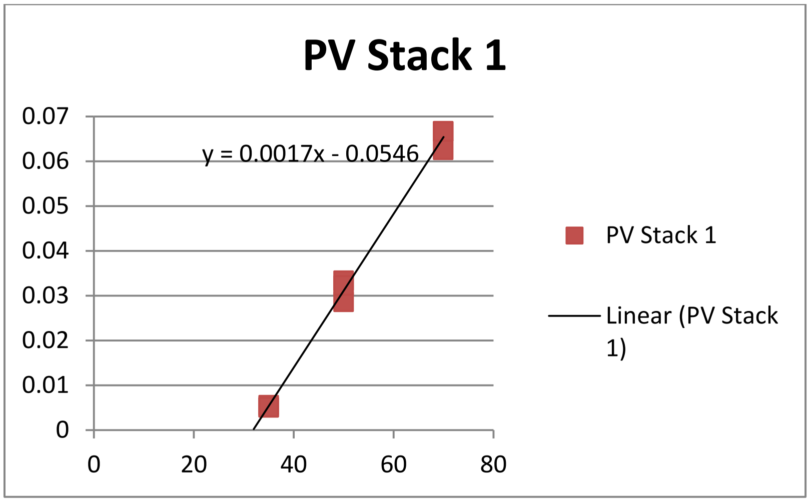

Figure 19 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m²

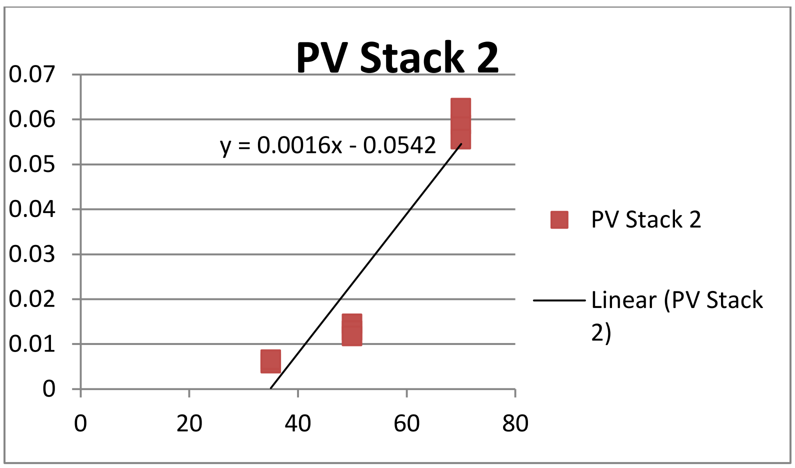

Figure 20 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m²

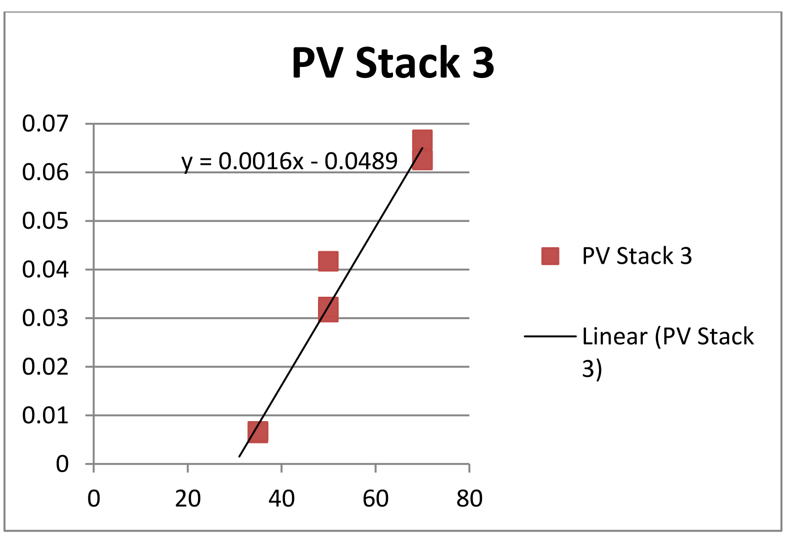

Figure 21 - Graph of 1 / Time to Ignition Vs Heat Flux in kilowatts/m²

SUMMARY AND RECOMMENDATIONS

SUMMARY OF FINDINGS

An analysis of the data generated by the experiments carried out in this study point to the following key findings:

- The critical flux values for most of the roofing products was determined to be greater than the 15 kW/m^2 exposure measured on the surface of a noncombustible deck without a PV (see Table 1, Assembly 1). Exceptions being one architectural shingle, one membrane and two insulation boards with critical heat flux values of 14, 14, 13, 14 kW/m^2 respectfully.
- The critical flux values for all of the roofing products was determined to be less than the 41 kW/m^2 exposure measured on the surface of a noncombustible deck with a PV installed with a gap of 5" (see Table 1, Assembly 34).
- The critical flux for ignition of low slope roof products was found to be generally consistent as were the critical flux for ignition of high slope roof products.

It should be noted that the roofing products had been evaluated by UL 1703 and have attained a Class A rating either a product in the case of a shingle or as a component of a system in the case of the low slope materials (sheets, insulation, membrane). As such a degree of fire performance would be expected.

RECOMMENDATIONS

Based on the research study findings, the Research Team would like to make the following recommendations and suggestions:

- Conduct additional experiments on other low slope membranes such as TPO and PVC materials to gain a better understanding of the critical flux for ignition of other technologies.
- Conduct additional ASTM E1354 cone calorimeter tests to determine other properties which have an effect on fire performance such as time to ignition, peak heat rate and effective heat of combustion. These characteristics can be determined on individual materials/products and combinations of products such as membrane-insulation systems.
- Continue research in this area to evaluate the sensitivity of the fire performance of roofing systems to the various PV installation methodologies. As a matter of practicality, it is unlikely that a manufacturer would submit every possible PV and roofing product installation configuration for fire test evaluation. Further work is needed to determine a generic roofing material which can be utilized as a worst case representative for testing of PV modules.
- This research should be shared with the PV and roofing industries as well as external fire community (firefighters, fire marshals, and authorities having jurisdiction - AHJs).
- Conceptually, the critical flux for ignition can be used to quantify a material or combination of materials propensity to ignite and spread flame. This parameter should be used by the UL 1703 Standards Technical Process (STP) fire test working group for defining generic categories of PV modules and roofing materials.

- Propose to the UL 1703 STP a requirement that for PV modules comprised of a glass superstrate; polymeric encapsulant; polymeric substrate with metal framing the laminate matrix or stack shall have a critical radiant flux no lower than 25 kW/m^2.
- Propose to the UL 1703 STP a requirement that for PV installations over steep slope roofs, a Class A three tab shingle shall be used in the evaluation of PV modules and have a critical flux of no higher than 25 kW/m^2.
- Propose to the UL 1703 STP a requirement that for PV installations over low slope roofs, a Class A single-ply EPDM rubber membrane shall be used in the evaluation of the PV module and have a critical radiant flux no higher than 20 kW/m^2.