Characterizing Fire Danger from Low-Power Photovoltaic Arc-Faults

Kenneth M. Armijo, Jay Johnson, Michael Hibbs and Armando Fresquez

Sandia National Laboratories, Albuquerque, NM, 87185, USA

Abstract — While arc-faults are rare in photovoltaic installations, more than a dozen documented arc-faults have led to fires and resulted in significant damage to the PV system and surrounding structures. In the United States, National Electrical Code® (NEC) 690.11 requires a listed arc fault protection device on new PV systems. In order to list new arc-fault circuit interrupters (AFCIs), Underwriters Laboratories created the certification outline of investigation UL 1699B. The outline only requires AFCI devices to be tested at arc powers between 300-900 W; however, arcs of much less power are capable of creating fires in PV systems. In this work we investigate the characteristics of low power (100-300 W) arc-faults to determine the potential for fires, appropriate AFCI trip times, and the characteristics of the pyrolyzation process. This analysis was performed with experimental tests of arc-faults in close proximity to three polymer materials common in PV systems, e.g., polycarbonate, PET, and nylon 6,6. Two polymer geometries were tested to vary the presence of oxygen in the DC arc plasma. The samples were also exposed to arcs generated with different material geometries, arc power levels, and discharge times to identify ignition times. To better understand the burn characteristics of different polymers in PV systems, thermal decomposition of the sheath materials was performed using infrared spectra analysis. Overall a trip time of less than 2 seconds is recommended for the suppression of fire ignition during arc-fault events.

Index Terms — Arc-Fault, PV Fire, Characterization, and Modeling.

I. INTRODUCTION

As the worldwide installed capacity of photovoltaic systems continues to grow and age, the number of arc-faults in PV systems is expected to increase. Even without external damage or defects, wiring and busbars are subjected to high thermal stresses when current is at or above the conductor rating, especially when the conductor is in conduit or surrounded by other thermal insulation [1]. PV Brandsicherheit, a joint German program investigating fires in PV systems, found there were 14 cases of PV systems starting the surroundings on fire [2]. In the US, there have also been a number of high profile fires caused by arcing in PV systems [3-5].

To address the danger associated with arcing in PV systems, the US National Electrical Code® (NEC) [6] has required arc-fault circuit interrupters (AFCIs) on rooftop systems since 2011 and all systems since 2014. Underwriters Laboratories created the Outline of Investigation for listing AFCIs, UL 1699B [7], which requires AFCIs to detect arc-faults between 300-900W. In previous studies at Sandia National Laboratories, arc-faults have been sustained well below these values [8-9], and series arc-faults on a single PV string are

likely to be below 300 W. Therefore it is recommended that UL consider incorporating a low power (100 W) arc-fault test for residential AFCIs since these are also capable of establishing fires. It should also be noted that many AFCIs use the noise on the DC system to determine when there is an arc [8-10]; and while the noise characteristics of the lower power arc-faults are similar—if not slightly higher than high power arc-fault signatures [11]—if the AFCI uses any time domain techniques (e.g., current or voltage changes/transients), low power arcs could go undetected. Therefore, it is important to add a new UL 1699B test at lower arc power levels. In this paper, we consider obstacles to adding such a test.

Each arc power level in UL 1699B has a required AFCI trip time based on burn tests performed by UL [12] and Hastings, et al. [13]. UL 1699B states an AFCI must trip in the lesser of 2 seconds or 750 joules divided by the arc-power. To verify this trip time calculation is valid for the newly proposed 100 W low power arc-fault, extensive experimental analysis was conducted. PV fires are caused by high-temperature plasma discharged during an arc-fault event, so this study specifically investigated the time to polymer ignition as a proxy for evaluating fire danger. Important factors in determining the time to ignition, defined by either producing smoke or fire, were arc power and material combustion threshold. Three common PV system polymers (polycarbonate, nylon 6,6, and PET) with varying combustion ignition potentials were evaluated. The gap between the electrodes did not contain pure air when a sheath material was included [14] and therefore the arc plasma was composed of a combination of air and outgassed organics (e.g. hydrocarbons), which resulted in different dielectric strengths, varied the arc gap potentials, and material ignition times.

To better understand the influence of atmospheric chemistry on plasma behavior, the burned polymer samples were measured with IR spectroscopy to compare the degree of thermal decomposition. The samples had varying exposure times, arc powers, and geometries but the primary difference in samples was those with holes in the sleeve. This allowed oxygen replenishment which improved the sustainability of the arc.

II. ARC-FAULT EXPERIMENTATION

A. Electrical Testing Setup

A PV simulator at Sandia National Laboratories was programmed to represent a constant power I-V curve from a

set of 1024 points, shown in Fig. 1. Regardless of the electrode gap spacing, the arc power would be nearly constant for a given curve. In this investigation, 100 W and 300 W constant power curves were used for the experimental studies. As a safety precaution, the PV simulator power was provided to the arc-fault generator through a power resistor so the simulator was never shorted. Additionally, the curves programmed into the PV simulator were limited to 600 V and 15 A.
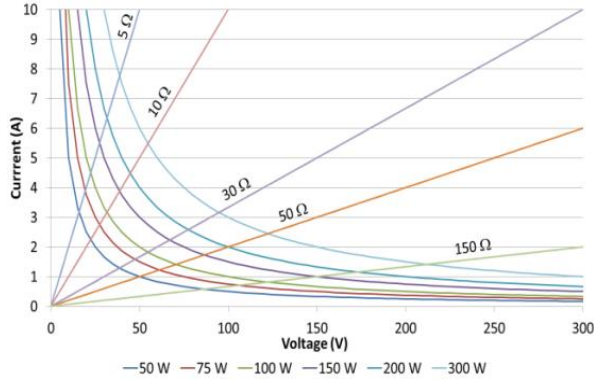

Fig. 1.   Constant Power Arc-Fault IV Test Curves.

A. Experimental configuration and data acquisition system.
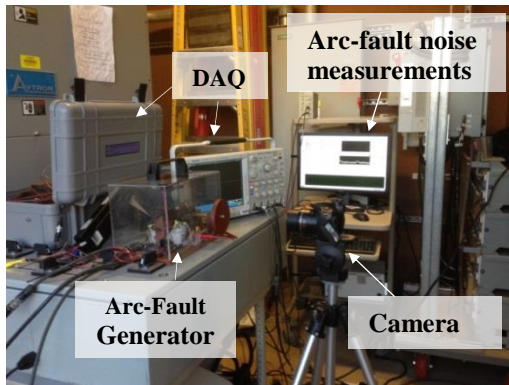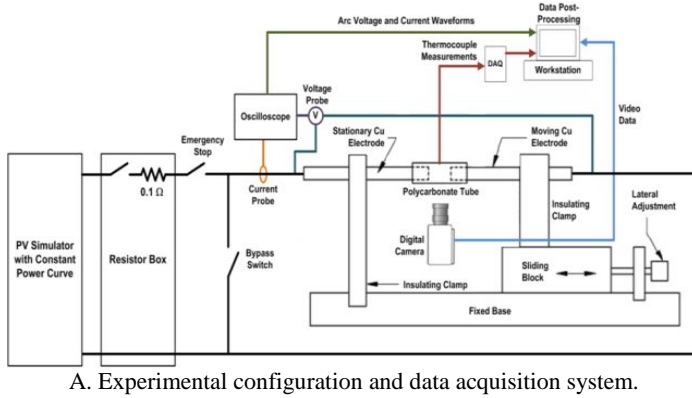

B. Photograph of the arc-fault test bed.

Fig. 2.   Arc-Fault Experimental Setup.

As shown in Fig. 2, the experimental setup consisted of an arc-fault generator, current and voltage probes, and a k-type thermocouple attached to the top of each respective polymer test sheath. The full parametric test matrix included 17 permutations of electrode geometries, sheath polymers/ geometries, and arc power levels [11]. For test purposes, each annulus test piece (sheath), with a 0.125 inch wall thickness and 0.75 inch length, was inserted over the two electrodes. The inner diameters were either 0.25 or 0.125 inches. For this apparatus, the electrodes—one moveable (anode) and one stationary (cathode)—were made of solid copper. The electrodes were separated using a lateral adjustment of the moveable electrode to the desired gap spacing.

In addition, a set of test specimens were machined with a small centralized hole to assess combustion rates with an increased presence of oxygen. The hole simulated an arc-fault open to the atmosphere versus an arc-fault contained in the module, connector, or other self-contained area within the array. The polymer specimens were placed halfway over the stationary electrode and the moveable electrode was then adjusted to the appropriate gap distance from the stationary electrode. During each respective test, PV power was applied until the sample pyrolyzed by quickly setting the electrode gap to sustain the arc. A UL-listed smoke detector was also installed just above the arc-fault generator and video recordings were taken to evaluate the first instance of smoke and subsequent combustion of the sheath material.

B. Arc Degradation Results

Exemplary results can be seen in Fig. 3 for a 100 W arc with a 0.25 inch polycarbonate sheath, containing a 0.125 inch hole for air ingress. The data indicates the temperature increases steadily as the polycarbonate sheath undergoes phase change due to the DC-DC discharge plasma arc.
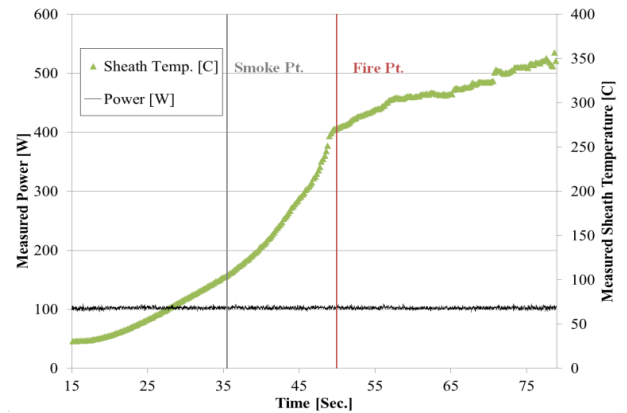

Fig. 3.   100W Arc-fault test results using a 0.25 inch polycarbonate sheath that includes a 0.125 inch hole. The arc-fault was established at time = 0 seconds.

Respective arc-fault videos obtained from the digital camera were converted into a series of individual frames so the time fire ignition could be determined, as well as to validate other thermal measurements. The smoke ignition times were determined by connecting the smoke detector alarm speaker circuit to the data acquisition system.

TABLE I

POLYMER IGNITION TIME SUMMARY OF ARC-FAULT EXPERIMENTS WITH A PV SIMULATOR AND ARC-FAULT GENERATOR

Arc Power	Polymer Type	Electrode Diameter	Electrode Tip Type	Contains Oxygen Ingress Hole	Contains Steel Tuff	Avgerage Smoke Ignition Time [Sec.]	Standard Deviation Smoke Ignition Time[Sec.]	Minimum Smoke Ignition Time [Sec.]	Avgerage Fire Ignition Time [Sec.]	Standard Deviation Fire Ignition Time [Sec.]	Minimum Fire Ignition Time [Sec.]	% of Samples Reaching Fire Ignition
300 W	Polycarbonate	1/4"	Flat	No	Yes	11.5	3.2	7.0	14.6	10.7	11.0	100%
300 W	Polycarbonate	1/4"	Flat	Yes	Yes	10.7	4.6	8.1	10.3	7.5	4.0	100%
300 W	Polycarbonate	1/4"	Flat	No	No	14.2	6.7	6.3	14.1	9.0	6.0	100%
300 W	Polycarbonate	1/4"	Flat	Yes	No	11.0	3.5	6.5	11.8	5.9	11.0	100%
300 W	PET	1/4"	Flat	Yes	No	13.2	3.6	8.51	14.3	1.9	13.0	100%
300 W	Nylon 6,6	1/4"	Flat	Yes	No	12.2	0.9	11.4	14.3	16.5	14.0	100%
100 W	Polycarbonate	1/4"	Flat	No	No	28.0	6.6	19.4	69.0	41.4	39.0	100%
100 W	Polycarbonate	1/4"	Flat	Yes	No	23.5	3.8	19.2	22.0	12.7	13.0	60%
100 W	Nylon 6,6	1/4"	Flat	No	No	45.6	6.6	19.8	106.0	2.8	104.0	22%
100 W	Nylon 6,6	1/4"	Flat	Yes	No	25.9	5.6	19.7	88.5	6.4	84.0	14%
100 W	PET	1/4"	Flat	No	No	37.6	4.6	22.1	120.9	14.4	108.5	63%
100 W	PET	1/4"	Flat	Yes	No	27.5	6.0	16.5	75.3	38.6	21.0	86%
100 W	Polycarbonate	1/4"	Round	Yes	No	19.4	12.5	6.5	107.0	17.0	95.0	40%
100 W	Polycarbonate	1/8"	Flat	Yes	No	23.1	3.0	20.0	21.7	4.5	17.0	100%
100 W	PET	1/8"	Flat	Yes	No	15.0	4.6	9.0	14.0	3.5	10.0	100%
100 W	Nylon 6,6	1/8"	Flat	Yes	No	20.4	5.4	12.1	86.5	21.9	71.0	100%
300 W	Polycarbonate	1/8"	Flat	Yes	No	10.5	6.8	2.5	10.3	4.0	3.0	100%

While in some cases the polymers did not reached the fire ignition point, it is clear that 100-300 W arc-faults are capable of causing fires in PV systems. As shown in Table 1, the majority of the 100 W arc-fault tests reached smoke and fire ignition in greater than 20 seconds. The average minimum time to detect smoke was approximately 13 seconds with a minimum value of 2.5 seconds. In situations where the polymer did not combust, the sheath and electrodes heated up to the point that the sheath transitioned from the crystalized state and melted off the hot electrodes, as shown in Fig. 4. The minimum time to visually identify flames in the video frames was 3.0 seconds. Based on flame times and the 2.5 second minimum smoke detection time, it is suggested UL 1699B include a two second trip time requirement for 100 W arcs to ensure the AFCIs can detect low power arc-faults and the AFCI certification standard provides a sufficient safety factor to ensure the arc is de-energized prior to any fire.

Evaluation of the three different polymers, presented in Fig. 5, suggest a negative trend between input arc power and smoke ignition time. The rates for both 100 W and 300 W input power loads were found to be respectively longer for nylon by an average of 10.2% and 36.9%, compared with polycarbonate and PET materials respectively. According to Gilman and Kashiwagi [15], highly effective fire retardant materials such as nylon are able to more effectively reduce polymer flammability over other materials by their ability to form gaseous intermediates which scavenge flame propagation free radicals (e.g. OH and H) thereby inhibiting complete combustion to CO_2 [15]. The result facilitates a reduction in the polymer heat removal rate (HRR) and can raise the level of CO and smoke generation.

The results in Fig. 6 indicate that although the nylon had the highest smoke ignition times for an electrode diameter of 0.25 inches, the use of 0.125 inch electrodes reduced this time below the nylon and polycarbonate polymers by 26.5% and 35.1% respectively. Further, little change was found in smoke ignition times between the two polycarbonate sheath diameters. Reducing the electrode diameter constrains the air volume for plasma discharge, which impacts off-gas concentrations of reactive species, surface chemical reactivity [16], as well as the respective ionization potential [17] to initiate the arc.

(A) melting polycarbonate

(B) igniting polycarbonate

(C) melting nylon

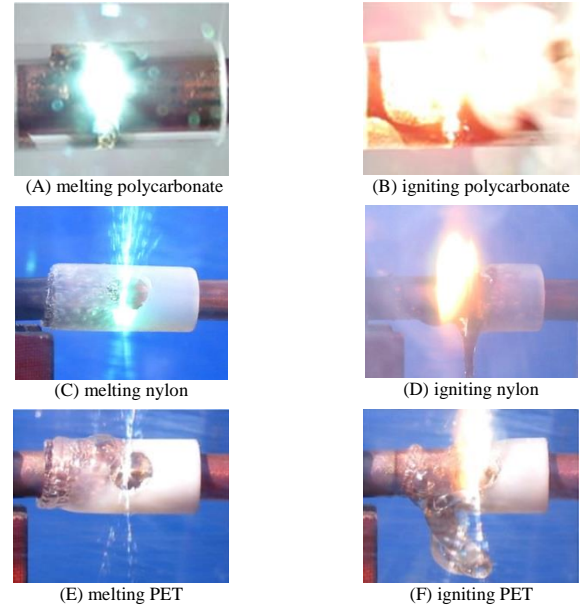(D) igniting nylon

(E) melting PET

(F) igniting PET

Fig. 4. Melt and burn behavior for polycarbonate, PET, and nylon. For all the polymers, the cathode heats up quickly [18] and the polymer sheath melts to the electrode, shown in (A), (C), and (E). In some cases, the polymer transitions to a liquid state and melts off the electrodes without catching fire; otherwise, the polymer visually combusts, e.g., (B), (D), and (F).
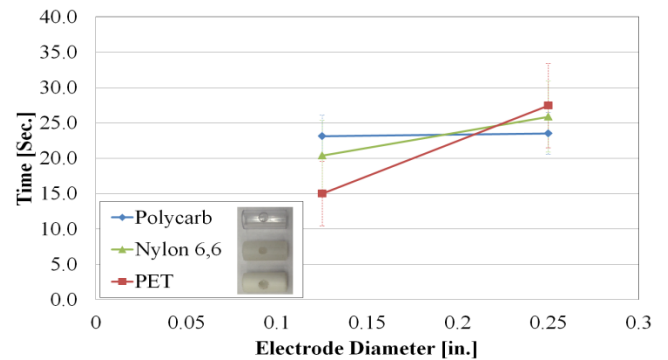

Fig. 5. Smoke ignition time for arc tests using 0.25 inch diameter copper electrodes, with polycarbonate, nylon and PET sheath materials, for 100 W and 300 W power input levels.

Previous research by Pandiyaraj et. al. [19] found increased oxygen levels increased plasma/surface interfacial reactivity potentials, which may influence discharge potentials and the potential for ignition [20]. Thus, for this study, a small 0.125 inch hole (Fig. 5 inset picture) was also included to improve the oxidation and arc sustainability for both 100 W and 300 W power levels. The results showed a 16.1% and 22.9% decrease in ignition times for the respective 100 W and 300 W polycarbonate tests with the inclusion of the hole. However, the results for the nylon and PET tests at 100 W showed a 43.2% and 26.9% reduction in combustion times, respectively. This indicates the presence of oxygen is only a factor in burn time for certain polymers.

UL 1699B requires small tuffs of steel wool mesh to help initiate the arc discharge at a pre-selected arc gap. To evaluate the impact of the small strands of wire for arc initiation and fire onset for the varying sheath materials, wire mesh was inserted between the electrodes, according to UL 1699B guidelines [7]. Arc-faults were created at input powers of 300 W for the 0.25 inch polycarbonate material. The results of these tests suggest a 19.0% and 2.7% reduction in smoke ignition time when a tuff of steel wool was included for an electrode system having a sheath with and without a hole respectively. Therefore, steel wool or aerobic vapor acts as a catalyst for the polymer combustion process, which is also thermally sensitive to changes in the size or path of the arc plasma volume.

It should be noted that originally there were additional testing permutations using 100 W arc-faults with steel wool, but these test cases were very difficult to establish clean-burning arc-faults. Thus, it is recommended that UL 1699B adopt a 100 W arc-fault test with an allowance for using the 'pull-apart' arc-generation method because it provides better testing repeatability. Unfortunately, the pull-apart test does not control the arc-fault power level to a tolerance as tight as the steel wool method, so the UL standard must provide a wider target for the 100 W test, e.g., ±30% of the arc power. By multiplying the arc current and arc voltage and dividing by arc duration, the average arc power can be shown to exist within the 70-130 W tolerance band during post-processing.

For DC-DC arc discharges at 1 atm in air, the current density and extent of the arc stability can be determined by the electrode geometry [21, 22]. In this investigation, two types of electrode tip geometries were evaluated to determine ignition characteristics of a 0.25 inch polycarbonate sheath. In Fig. 7, rounded-tip electrodes found decreased sheath temperatures and delayed flame ignition.

The results between the flat and rounded-tip electrodes found a 17.4% reduction in smoke ignition time, as well as a 26.6% decrease in measured smoke ignition sheath temperatures, respectively. An example arc-fault test with thermocouple data is shown in Fig. 8. The rounded-tip increased arc stability because the plasma stream remained at the minimum gap distance at the center of the electrodes; whereas with the flat electrodes the arc would jump to

different locations on the coplanar electrode faces. This effect was associated with an increase in the visible ignition time by as much as 35.5% and average ignition temperature as high as 260.6°C, shown in Fig. 8. It is postulated that the rounded-tip electrodes constrain the arc plasma stream to the radial center of the electrode cavity and therefore the polymer is exposed to lower initial temperatures during arc-fault tests due to reduced contact with the plasma stream. These type of electrodes were found to have more uniformly distributed heating of the electrodes and polymer material, which would eventually melt into the arc gap and induce fire ignition. For flat electrodes, the arc was often found to be located against the surface of the polymer which intensified localized heating and polymer degradation, often with higher temperatures.
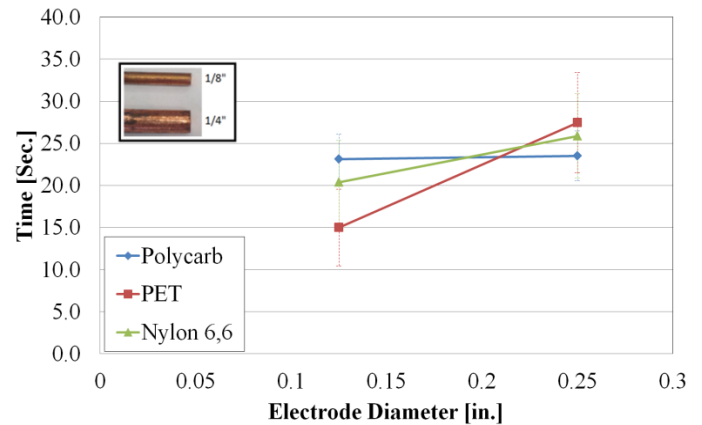

Fig. 6.   Smoke detection times for parametric 100 W arc-fault tests using 0.25 and 0.125 inch diameter copper electrodes, with polycarbonate, nylon, and PET sheaths.
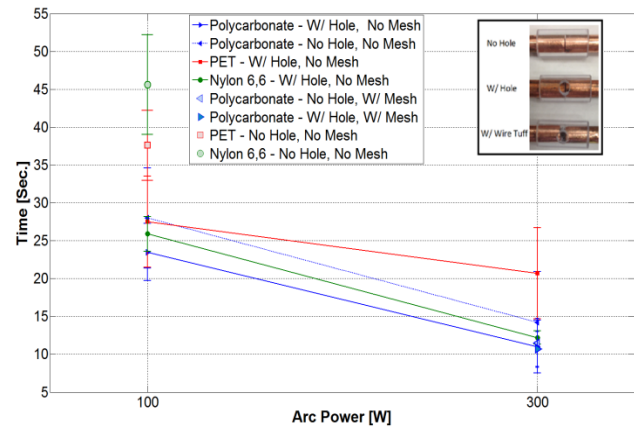

Fig. 7.   Parametric arc-fault Tests using 0.25 inch diameter copper electrodes, with polycarbonate, nylon and PET sheath materials, for 100 W and 300 W arc discharges, with and without oxidation holes and wire mesh.

For UL 1699B, use of rounded-tip electrodes would provide more repeatability in the tests, but the additional machining requirement was determined to be onerous on the test operator.
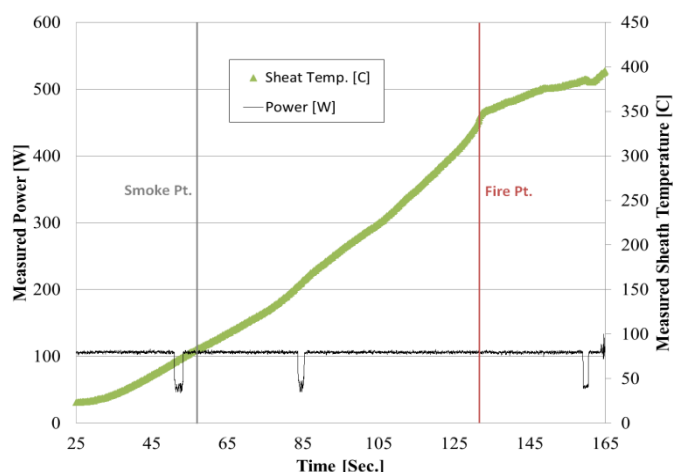
Fig. 8. Rounded-tip electrodes 100 W arc-fault test using a polycarbonate sheath with a 0.125 inch hole and no wire mesh. The arc-fault was established at time = 0 seconds.
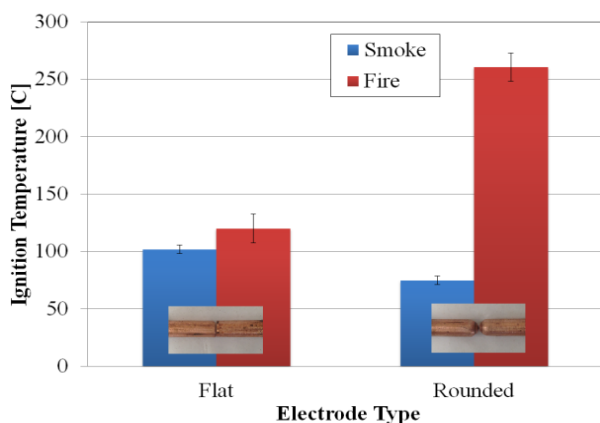

Fig. 9. 100 W rounded-tip electrodes arc-fault test with a polycarbonate sheath, with a 0.125 inch hole, and no steel wool tuff.

III. CHEMICAL DEGRADATION ANALYSIS

The burn resistance of various PV cable insulations against arcing events depends heavily on the chemical structure of the materials. Previous work by Meckler [23] has shown that particular classes of polymers such as polyimides (e.g., KAPTON[®]) buildup carbonizing deposits with thermal destruction which easily leads to arching. However, other materials such as Polytetrafluoroethylene (PTFE) or Fluorinated Ethlenepropylene Copolymer (TEFLON[®]) are resistant against arc tracking [23]. The thermal oxidative degradation of polymers can lead to a variety of products, some of which are volatile while others remain as end groups of cleaved polymer chains. In order to study the surface chemistry of the polymer sheaths exposed to the arc plasma, the samples were cut open and subjected to Attenuated Total Reflection Fourier Transform Infrared Spectroscopy (ATR FTIR) analysis.

ATR FTIR experimental results of samples of the three polymers exposed to arc-faults each showed markers in the IR

spectra, identified as indicators of thermal decomposition of the polymers. These markers were specific peaks in the spectra that either corresponded to diminishment of a functional group in the control polymer, or the appearance of new functional groups found in well-established decomposition products.

IR spectra were taken at several special positions on the samples with varying discoloration in order to determine the extent of the thermal oxidation reactions. Fig. 10 shows IR spectra from an unburned polycarbonate control sample and a polycarbonate sample exposed to an arc-fault. The two most obvious changes in these samples are:

1. the appearance of a broad peak between 3100 and 3500 cm^{-1}, and
2. the diminishment of the sharp peak at 1772 cm^{-1}.

The former is indicative of O-H stretching and the latter is due to (loss of) C=O stretching in a carbonate group. Both of these peaks are consistent with the decomposition reactions illustrated in Fig. 11. In the top reaction, polycarbonate is oxidized to give a phenol and a methyl ketone as products. In the bottom reaction, polycarbonate undergoes a loss of carbon dioxide to give an aryl ether product [24].
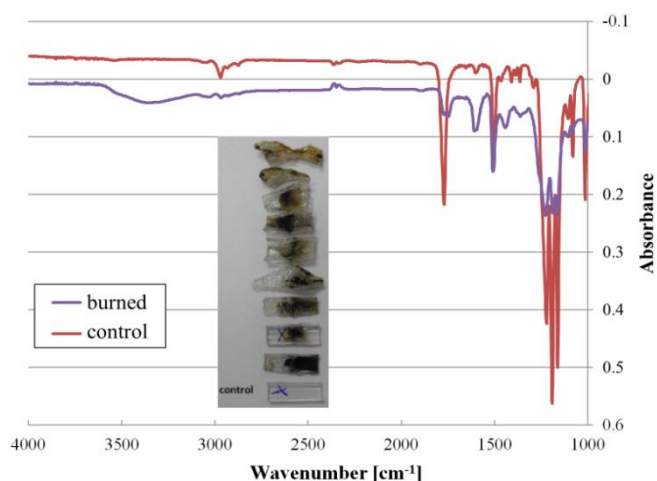

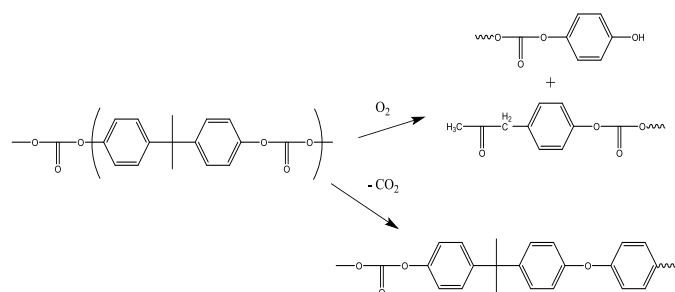Fig. 10. IR spectral analysis of polycarbonate (PC) experimental and control sheaths.

Fig. 11. Thermal decomposition pathways for polycarbonate.

This chemical analysis shows that oxidation reactions (combustion) occur during the arc fault tests and that changes in the appearance of the polymers are not just due to melting.

Fig. 12 shows IR spectra from the analysis of a PET sheath exposed to arc-fault plasma. The two most obvious changes in these samples are:

1. the appearance of a broad peak between 2500 and 3100 cm^{-1}, and
2. the appearance of a sharp peak at 1706 cm^{-1}.

Like polycarbonate, the former is indicative of O-H stretching and the latter is due to C=O stretching in a carboxylic acid. Both of these peaks are consistent with the decomposition reaction illustrated in Fig. 13 (the vinyl ester byproduct undergoes a rapid, subsequent oxidation to give another carboxylic acid).
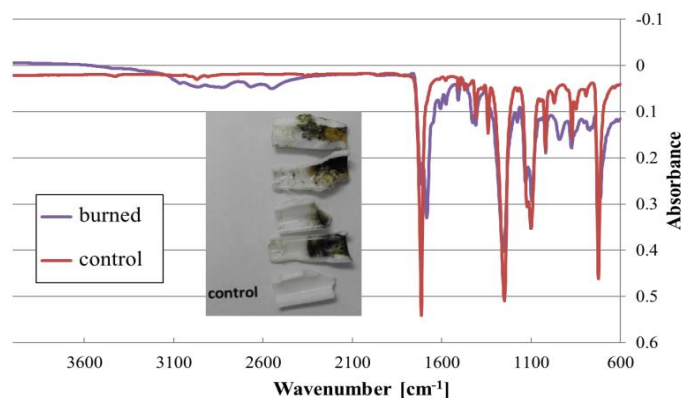

Fig. 12. IR spectral analysis of PET experimental and control sheaths.
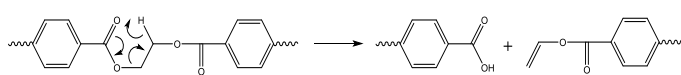

Fig. 13. Thermal decomposition pathway for PET with carboxylic acid byproduct.

Fig. 14 shows IR spectra from nylon 6,6 exposed to an arc-fault plasma. The two most obvious changes in these samples are

1. the appearance of a sharp peak at 1724 cm^{-1}, and
2. the appearance of a peak at 1267 cm^{-1}.

Both of these peaks are indicative of the formation of carboxylic acid groups. The former is due to C=O stretching and the latter is due to the stretching of the C-O single bond in an acid group.

The formation of carboxylic acids requires water, as illustrated in Fig. 15. Water could be present as vapor in the air or it could also be formed by other reactions such as the combustion of the aliphatic hydrocarbon portions of nylon 6,6 which would not leave any other obvious markers in the IR spectra.

Based on the differences in the chemical breakdown of the different polymers when exposed to arc-fault plasmas, the variability in burn and smoke times is expected. This analysis was performed to assess the chemical decomposition mechanisms on the breakdown of materials susceptible to heating from arc-fault plasmas. Each of these mechanisms are however sensitive to environmental factors such as water vapor (i.e., PET), and can vary from the tests performed in this research under dry, moderate (~20°C) temperature conditions. Overall, the results found similar spectral decomposition between respective grouped samples that experienced fire ignition. However, some spectral evidence of increased oxidation of the polycarbonate sheaths over the PET and nylon samples were found. This excessive degradation may explain lower ignition times found by polycarbonate sheath materials. However, due to particular evidence of char and its chemical structure, longer ignition times suggest that PET may have enhanced fire suppression over polycarbonate and even the Nylon 6,6 polymer, which is traditionally used in high temperature applications [19].
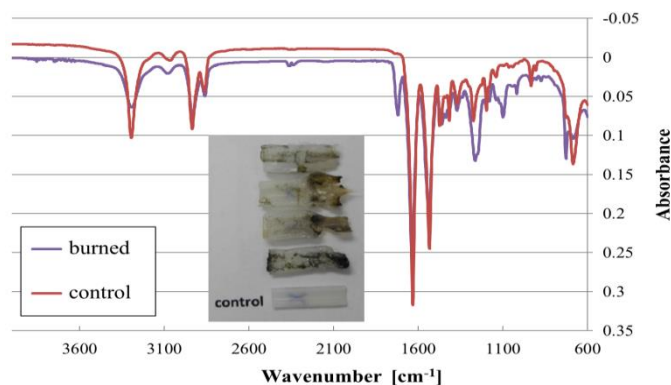

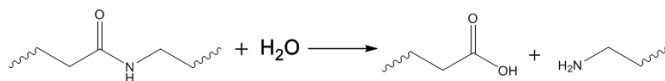Fig. 14. Thermal decomposition pathway for nylon 6,6 with carboxylic acid byproduct

Fig. 15. Thermal decomposition pathway for nylon 6,6 with carboxylic acid byproduct.

IV. CONCLUSIONS

A parametric investigation of three common PV materials, PET, polycarbonate and nylon 6,6 was performed for 100 W and 300 W arc discharges. The results suggest that PET had the highest smoke ignition times for 0.25 inch electrodes and the use of a 0.125 inch electrodes reduced this time below the nylon and polycarbonate polymers by 26.5% and 35.1% respectively. The results also suggest a 16.1% and 22.9% decrease in combustion times for the 100 W and 300 W polycarbonate tests with the inclusion of an oxygen-ingress hole. However, the results for the nylon and PET tests at 100 W were more significant with a 43.2% and 26.9% reduction in ignition times respectively. Overall, increased arc stability was observed with sheaths that contained a hole as well with electrodes that had a rounded-tip. Rounded-tip electrode tests also found longer ignition times compared to the flat-tip tests. Finally, the inclusion of a wire tuff between the electrodes, as opposed to the "pull-apart" method, suggests a 19.0% and 2.7% reduction in smoke ignition time for an electrode system having a sheath, with and without a hole respectively.

Based on these experiments Sandia National Laboratories, in collaboration with the UL 1699B Standards Technical Panel Arc-Fault Generation Task Group, has recommended a 100 W low power arc-fault test be added to the UL 1699B standard because:

1. low power arcs cause fires in polymers common to PV systems,
2. there are no tests that capture this scenario in UL 1699B outline of investigation, and
3. although the noise signatures for low power arcs are slightly higher in amplitude compared to higher power arcs [11], if the AFCI uses time-domain techniques these faults may go undetected.

In addition, a trip time of less than 2 seconds is recommended for the suppression of fire ignition during arc-fault events. Furthermore, the Arc-Fault Generation Task Group recognized the practical challenges in creating and maintaining low power arcs in PV systems for a certification test, therefore the group recommended allowing the "pull-apart" method and a large ±30% arc power tolerance.

V. ACKNOWLEDGEMENT

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