Arc Fault Risk Assessment and Degradation Model Development for Photovoltaic Connectors

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***Abstract* — This work investigates balance of systems (BOS) connector reliability from the perspective of arc fault risk. Accelerated tests were performed on connectors for future development of a reliability model. Thousands of hours of damp heat and atmospheric corrosion tests found BOS connectors to be resilient to corrosion-related degradation. A procedure was also developed to evaluate new and aged connectors for arc fault risk. The measurements show that arc fault risk is dependent on a combination of materials composition as well as design geometry. Thermal measurements as well as optical emission spectroscopy were also performed to further characterize the arc plasma. Together, the degradation model, arc fault risk assessment technique, and characterization methods can provide operators of photovoltaic installations information necessary to develop a data-driven plan for BOS connector maintenance as well as identify opportunities for arc fault prognostics.**

***Index Terms* — connector, arc fault, reliability**

I. INTRODUCTION

As the reliability of traditional photovoltaic (PV) modules becomes better characterized, the focus has gradually expanded to the balance of systems (BOS) components. Increasing emphasis is being placed on inverters, junction boxes, and interconnects [1]. Of these components, the reliability of BOS connectors has been relatively uncharacterized beyond qualification tests, which do not offer a prediction of lifetime. The annual potential power loss observed in one study due to increased contact resistance of a particular connector was estimated to be 140 Watt-hours per string [2]. These losses quickly add up over multiple connectors and strings.

Beyond the obvious, though possibly acceptable, costs of Ohmic power loss, there is the potential cost burden due to arc fault hazards. Although series arc faults that result from BOS connectors are low-probability they can have highly damaging consequences, with visible events that are difficult to quantify if industry-wide public perception costs to PV are included. There have been instances where arc faults related to BOS connectors have been documented with its prevention being identified as a critical knowledge gap [3, 4].

Physically, there are situations where overheated wiring can lead to arcing events and conversely, where arcing can lead to overheating with subsequent combustion of connectors or wire insulation [5]. In most electrical and PV applications, series arc faults, which occur when there the connection failure is in series with the load, are typically more common than parallel arc faults [6]. This type of fault can generally produce high current [5] with a magnitude that depends on the faulted circuit. Research by Shea [5] on residential wire-related arc faults found that, even without defects, wiring can be subjected to high thermal stresses because of currents at or above the conductor or thermal insulation ratings. His results found conductor wire and insulation material ratings can be exceeded when conducting rated current and currents at 110% of the wire ratings. The results found that this type of thermal stress can increase wire aging, especially in the presence of humidity [7] and can accelerate material degradation that increases brittleness of connector insulating materials and crack formation of the conductor wires [5]. Further research by Armijo *et. al.* [8] also found that geometrical variations in wire electrodes can have a significant impact on facilitating and sustaining arcing. In their study they found that a 50% reduction in the geometry of current conducting electrodes resulted in a reduction as high as 45% in arc discharge ignition time. In this investigation, connectors of varying geometries will be examined under a 300W, series-connected arc fault configuration. Accelerated aging of these connectors will also be performed to determine the arc fault hazard potential against a pristine-condition control group.

In addition, current progress towards developing a degradation model for BOS connectors has been limited. To date, there has also not been research that relates any degradation model predictions to the likelihood of arc fault event. This work also seeks to address this issue by utilizing accelerated test and field test results for future development of a degradation model for BOS connectors. An arc fault generator and test methodology has been developed and applied on new and aged connectors to evaluate arc fault risk on various common connectors used within industry. Characterization techniques to better understand the arc fault process has also been developed.

II. APPROACH AND METHODS

The experimental approach for this paper is summarized in the flowchart in Fig. 1. There are two primary project objectives: 1) development of a degradation model for BOS connectors, and 2) evaluation of new and aged connectors for arc fault risk. The results will be used to complete the degradation model with a figure of merit for part failure. The degradation model alone will provide the PV industry with information necessary for a cost-benefit analysis on energy loss versus replacement costs for the respective connectors.

Current accelerated test results, however, suggest that it is more likely that the cost of a catastrophic arc fault event is likely to overshadow the penalty of resistive energy lost. Therefore, the connection between arc fault risk and degradation must be made in order to properly assess the cost effectiveness of BOS connector maintenance.

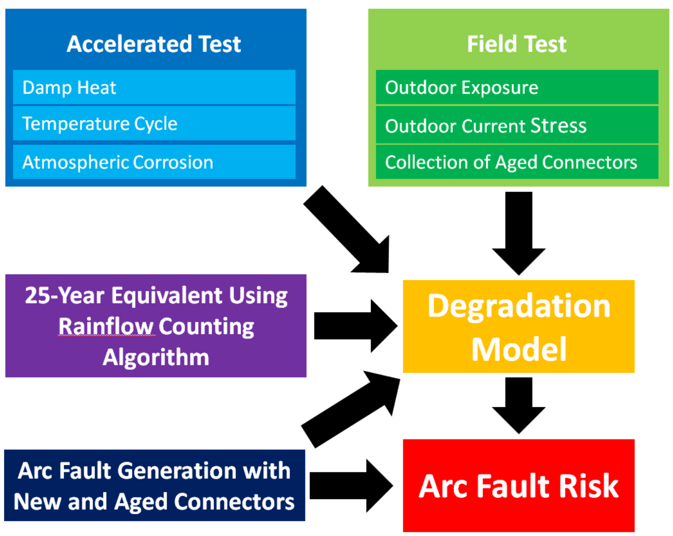

Fig. 1. Overview of the BOS connector arc fault research approach. Accelerated tests are used to generate measureable degradation in a reduced amount of time. These results are correlated with field data through the addition of field tests and a rainflow counting algorithm to develop a degradation model. Arc fault generation experiments with new and aged connectors are then used to determine the amount of degradation necessary for arc fault risk, which provides a failure criterion for the degradation model.

The degradation model requires inputs from four different resources. First, accelerated tests are performed in a laboratory setting to induce degradation and characterize the effects of various stress factors. These accelerated tests are necessary due to the slow degradation of BOS connectors that are in the field. In addition, it will result in an improved understanding on the impacts of various stress factors, which enables the degradation model to be adjusted for different environments without the aid of individual outdoor tests for each climate condition. The laboratory portion of the study consists of three accelerated tests: damp heat (85^{o}C/85% relative humidity), temperature cycling (-45^{o}C to 110^{o}C), and atmospheric corrosion. The atmospheric corrosion test utilizes a mixed flow gas corrosion test chamber that can generate Class II and Class III environments [9]. These corrosion tests cover most environments applicable to PV systems by simulating light or moderate industrial environments.

The accelerated test results will be evaluated against field test data from connectors in outdoor environments. A test bench has been established in a high-desert environment to subject BOS connectors to an outdoor setting. In addition, connectors are being fabricated to endure current stress in the same outdoor location. Due to the expected slow degradation of these connectors, the field data will be supplemented by connectors collected from existing installations that are of a known age. In addition, year-round temperature data collected from the field as well as measurements from the arc generation setup will also be used to help translate the lab results to long-term expected lifetimes.

In addition to quantifying the rate of degradation, the model results must be converted into an arc fault risk metric. An arc fault generator developed and implemented at Sandia National Laboratories, powered by a PV simulator was used to generate arcing events in both new and aged connectors. A layout of the arc fault generator is shown in Fig. 2. The likelihood of arcing is based on objective parameters from the experiment, such as separation distance and temperature measurements.

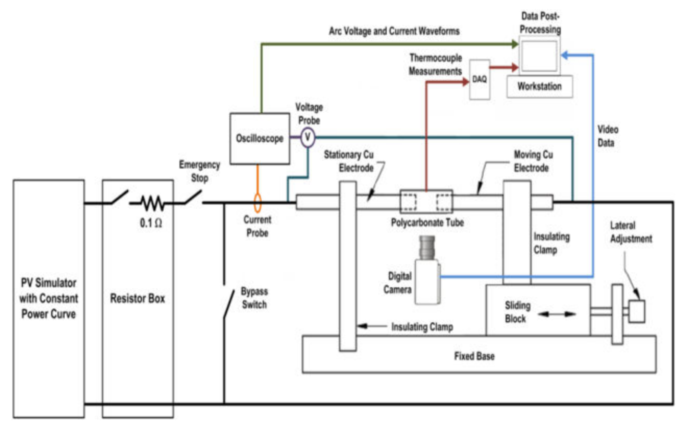

Fig. 2. Diagram of the arc fault generation experiment that was applied to new connectors as well as connectors that have been exposed to accelerated tests or field conditions. The effect of degradation on the necessary separation to induce arc fault were used to quantify arc fault risk and define the failure criteria for the degradation model.

Two techniques were used to further characterize the arc faults. Thermocouples were used to measure the connector pin temperature prior to arcing. The purpose of the temperature measurements is to provide further insight into the nature of the plasma associated with the arc fault. In addition, any changes in temperature as a precursor to sustained arc fault can also be utilized to create prognostic tools. Optical emission spectroscopy was also performed on the arc faults. Preliminary results are shown in this paper, where the ability to detect material composition is demonstrated.

III. BOS Connector Accelerated Test Results

This study summarizes the existing results of BOS connectors that have been subjected to thousands of hours of testing. Current results include data from damp heat, atmospheric corrosion, and the high desert outdoor environment.

A sample of nine BOS connectors after over 6000 hours of damp heat testing at 85°C/85% relative humidity is shown in Fig 3. While there have been minor increases in resistance, all of the measurements remain below 5 mΩ. Observable variation in resistance begin to develop, especially after 4000 hours, with changes on the time scale of hours. The cause and arc fault implications of these connectors are topics of future work. In addition to damp heat, this study also seeks to examine the degradation effect of grime contamination on the contacts. Laboratory-created, reproducible grime simulating coastal and desert environments have been applied to a subset of the samples [10-12]. Currently, the grime-contaminated connectors are indistinguishable from the control samples.

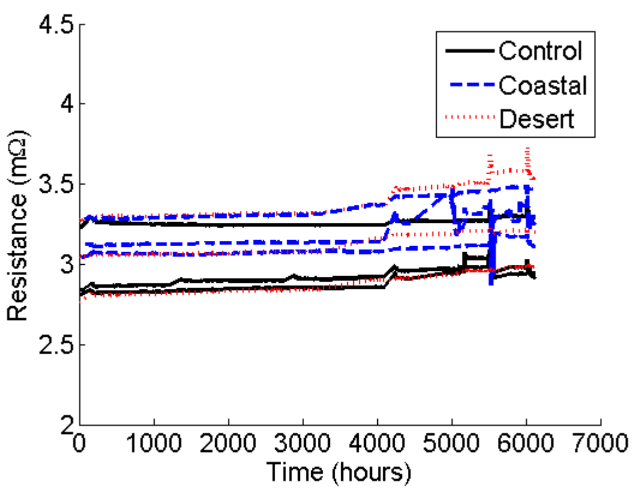

Fig. 3. Resistance over time for over 6000 hours of damp heat test. Three sets of connectors are shown here: 1) control set, 2) samples with grime simulating a coastal environment applied to the contacts, and 3) samples with grime simulating a desert environment applied to the contacts. The resistance has remained below 5 mΩ throughout the duration of the damp heat test. Variation begins to develop after 4000 hours. The cause of this instability and its implication to arc fault risk are under study.

Fig 4 shows the contact resistance measured as a function of time for 99 connectors in a Class II atmospheric corrosion chamber. Gradual degradation in one connector from the sample began after the 4000 hour mark. However, after 5000 hours of testing, the resistance remained below 5 mΩ.

An outdoor test bed was implemented to expose 51 connectors to high desert elements and explore the impacts of environmental degradation on their packaging and contacts. After 2500 hours of testing, no catastrophic failure events were observed. Due to temperature fluctuations, the resistance measurements were found to be noisier than the laboratory results in the previous figures.

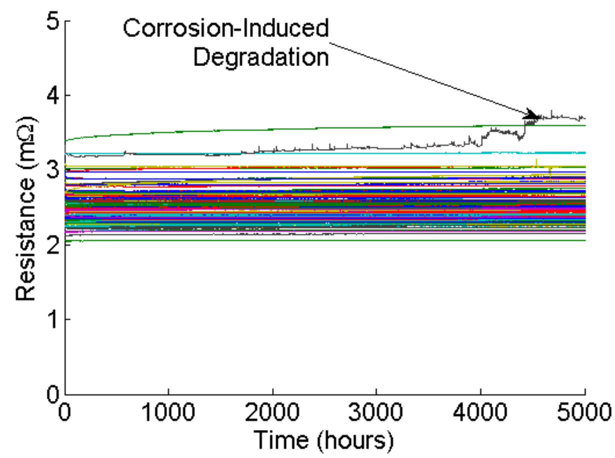

Fig. 4. Contact resistance as a function of time for 99 connectors in a class II corrosion chamber over the course of 5000 hours. Corrosion-induced degradation of one connector out of the sample is visible. Additional data through continued monitoring will provide estimates on the amount of time needed to reach the failure criteria defined by the arc fault experiment.

It is likely that longer-term exposure is necessary before measurable degradation will occur in these samples. Compared to the accelerated tests, these samples are subjected to mild stresses. In addition, the noise introduced by the temperature variation will require a greater level of degradation and data observation before the changes can be detected.

This outdoor test, however, can provide value to the PV community by quantifying the seasonal variation in BOS connector contact resistance throughout the year. The measurements can provide margins to the subsequent arc fault risk assessment.

IV. BOS Connector Arc Fault Test Results

The degradation of BOS connectors are further contextualized by translating the results into arc fault risk. To accomplish this task, an experiment was built by running power from the arc fault generator (shown in Fig. 2) across the connectors under test. In order to induce arc fault, the connector pins were gradually separated until arcing occurred. In-situ voltage and current measurements were acquired during translation and used to calculate the resistance.

The separation distance prior to the first detected spark as well as the translation necessary for a sustainable arc was used to infer the relative risk of arc fault between connectors. While the connector pins are separated, the resistance across the connector rises due to a gradual decrease in surface area. If a decreased amount of translation is necessary to produce a sustainable arc, then the resistance increases and the connector disturbance needed to cause an arc fault event also increases.

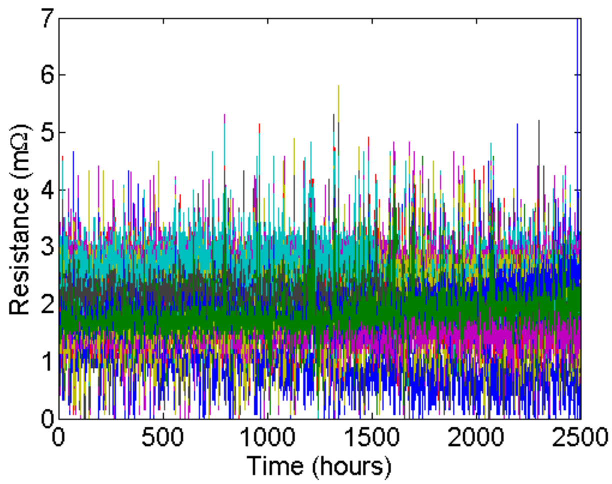

Fig. 5. Contact resistance data for connectors exposed to the elements in a high-desert outdoor environment. The measurements are noisier than the laboratory measurements due to temperature cycles. The results will be used to help infer connector lifetime from accelerated test results.

Using this approach, we characterize a set of five new connector pins from three different manufacturers. The results are compared to an identical connector pin that has been exposed to a Class III corrosion chamber environment for a month without the protection of its casing. The position of the first spark and sustained arc fault between these connectors are compared. The use of resistance as a precursor to an impending arc fault is also explored.

Fig. 6. shows a plot of the resistance as a function of position from Manufacturer A. The five dark lines refer to individual samples that have not been through corrosion chamber exposure. The dashed red line represents the measurement of the contact pin that had experienced prolonged exposure in the corrosion chamber. The position is translated relative to each other such that 0 mm refers to the last point of Ohmic contact detectable by a digital multimeter. The blue circle represents the location of the first detected arc and the blue “x” indicates where a sustained arc began to occur.

The measurements in Fig. 6 indicate that the initial contact resistance of Manufacturer A connectors were not significantly affected by the time spent in the corrosion chamber. Compared to the control part, however, the degraded connector experienced its first arc and also sustained arc with less separation than the control samples. Furthermore, there is an earlier increase in resistance prior to the first point of arc fault and a shorter distance separating the first arc from the point where a sustained arc fault was detected.

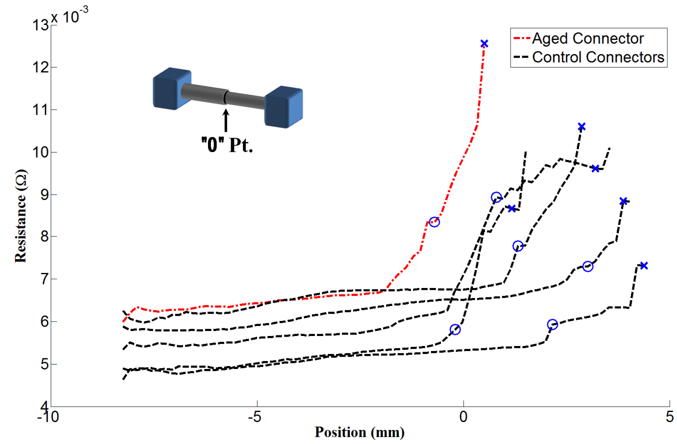

Fig. 6. Measured resistance plotted as a function of translational stage position during arc fault experiment for manufacturer A. The measurements are shifted such that 0 mm on the x-axis represents the location of where Ohmic contact was last detectable by a multimeter prior to the experiment. The five dark solid lines represent five new connector pins that were tested. These results are compared with the dashed red line, which shows the measurements from a connector pin that has been through exposure in a Class III corrosion chamber. The blue circles indicate the location of the first detected arc. The blue “x” shows the location where a sustained arc began to occur.

Fig. 7 shows a similar set of measurements using connector pins from Manufacturer B. Despite having the same material composition as Manufacturer A, The initial resistance of the connector from Manufacturer B was adversely affected by the corrosion chamber. Aside from this initial shift of increased resistance, however, the degraded connector pin began arcing at a similar location to the control samples. Therefore, it could be argued that despite increased Ohmic losses, the arc fault risk due to corrosion is not significantly altered for connectors from this manufacturer. The difference between the results in Fig. 6 and Fig. 7 is possibly due to geometric design or relative layer thicknesses and remains a subject of further study.

Fig. 8 shows results of the same experiment performed on connectors from Manufacturer C. Manufacturer C differs from the other two brands in this study due to its physical design as well as a silver-plated coating. The silver-plated coating in particular makes the connectors particularly susceptible to corrosion chamber effects. The initial resistance was nearly an order of magnitude higher than the control samples, and the resistance measurements throughout the experiment were less stable. The change in resistance as a function of position also decreased prior to the point of arc fault. Despite the dramatic increase in resistance compared to the control sample, the arc fault risk of connector C did not increase significantly.

Overall, the effect of corrosion-chamber-induced degradation on Ohmic resistance and arc fault risk was evaluated for connector pins from three different manufacturers. Manufacturer A and B had the same bulk material composition but different designs. While Manufacturer A did not experience an initial resistance increase from the corrosion chamber, it had a higher arc fault risk. While the resistance of Manufacturer B was adversely affected by the corrosion chamber, its arc fault risk was comparable to Manufacturer A. Manufacturer C experienced a significant increase in resistance due to the corrosion chamber, potentially for reasons associated with its silver-plated coating. Its arc fault risk, however, was comparable to the control samples. Furthermore, increases in resistance was observed prior to arc fault in connectors from manufacturers A and C, which can potentially be used for arc fault prevention prognostics. In summary, the results suggest that arc fault risk is dependent on a combination of material composition as well as design geometry.

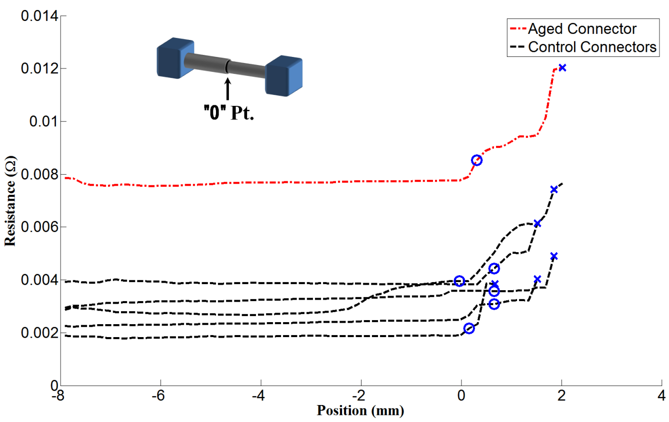

Fig.7. Measured resistance plotted as a function of translational stage position during arc fault experiment for manufacturer B. The five dark solid lines represent five new connector pins and the dashed red line represents a corroded connector. The blue circles indicate the location of the first detected arc. The blue "x" shows the location where a sustained arc began to occur.

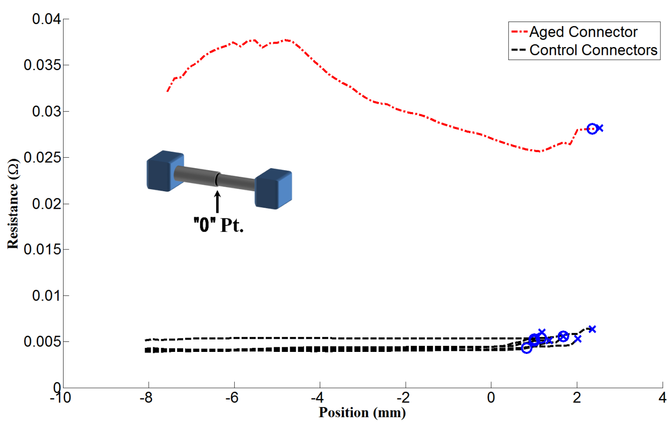

Fig. 8. Measured resistance plotted as a function of translational stage position during arc fault experiment for manufacturer C. The five dark solid lines represent five new connector pins and the dashed red line represents a corroded connector. The blue circles indicate the location of the first detected arc. The blue "x" shows the location where a sustained arc began to occur.

V. Thermal Analysis Of BOS Connectors

Thermal effects have previously been shown to impact connector degradation. Research by Shea [5] found correspondence between temperature rise of electric cabling and degradation which led to failure and combustion. In this work, a k-type thermal couple was placed on each connector and tested to evaluate the effects of Joule heating on resistance variation leading to an arc fault. During testing just prior to a sustained arcing event, discrete sparks were observed for all connectors. An average temperature rise of 2.1°C/mm was observed prior to the first spark for most connectors tested. However, this temperature increase was found to increase substantially prior to sustained arc formation, which typically occurred within 4-10 seconds. As shown in Fig. 9 the temperature of the connectors were found to follow the resistance increase as the position of each respective connector was separated from its sleeve. A position of -8 approximated a complete connection, while a position of 0 indicated the onset of separation. It was at this position where the first arcs were typically observed. The results of this study also found clear temperature signatures for the onset of initial sparks as well as for the onset of sustained arc faults.

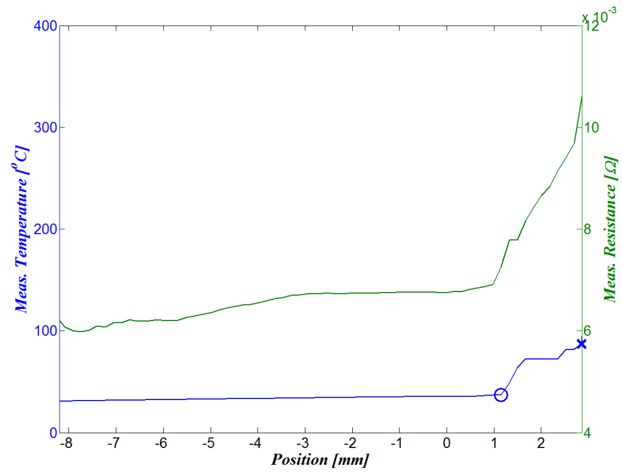

Fig.9. Measured connector temperature and resistance plotted as a function of translational stage position during arc fault experiment. The blue "o" indicates the onset of the first observable spark event, while the "x" indicates the onset of sustained arcing.

VI. Optical Emission Spectrum Analysis

The spectrum of the optical emission resulting from the arc fault was analyzed to explore the possibility of optical emission spectroscopy as a tool to better understand the arc fault process. Optical spectra of the arc plasma optical emission were acquired using an Ocean Optics S2000 fiber spectrometer, which consists of an integrated linear silicon CCD array and miniaturized optical bench. The spectrometer has a resolution of 0.33 nm, and a spectral measurement range of 340 – 1019 nm. The arc plasma spectra were optically coupled to the spectrometer using a diffusive cosine corrector free-space to fiber adapter. The position of the detector was adjusted relative to the arc to avoid saturation. A spectrum integration time of 100 ms was typically used, and series of 100+ spectra were captured per arc discharge experiment to examine the change in emission and plasma conditions as a function of time.

Fig. 10 provides a summary of the arc spectra of fresh connectors from three different brands, (labeled "A," "B," and "C") compared with that of copper electrodes. The copper content in the connectors can be confirmed through the presence of similar peaks. Connector A and B have similar spectral peaks, while Connector C has additional peaks that are not present in Connector A and B. This matches prior knowledge on the material composition of the connectors, establishing this technique as a potential tool for materials analysis. Opportunities to obtain temperature measurements and material composition as a function of location are being actively explored.

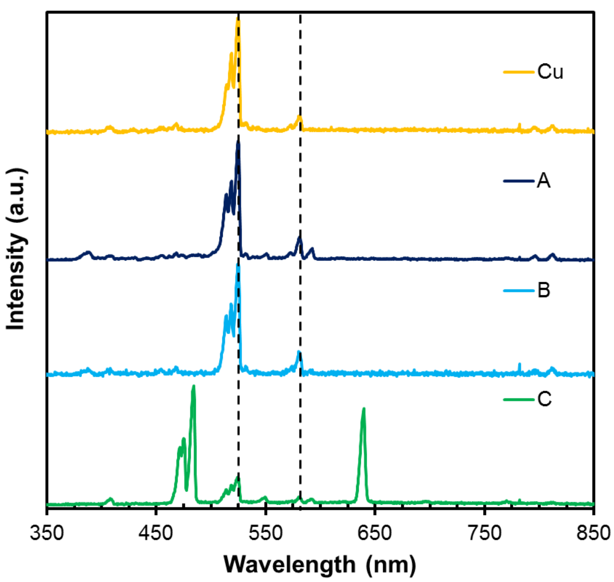

Fig.10. Optical emission spectrum measurements of the arc plasma discharge from three connector brands (A, B, and C) compared with that of copper electrodes. The presence of copper is readily apparent by the presence of common peaks labeled with the dashed lines. Connector A and Connector B, which are both tin-plated copper, have similar spectra. This similarity provides confidence in the technique as a method for materials analysis. The presence of alternate materials in Connector C is also detected by this technique in the form of additional peaks.

VII. Conclusion

This project studies BOS connector degradation from the perspective of arc fault risk. Accelerated tests for future reliability model development found connectors to be resilient to corrosion degradation. A technique to evaluate arc fault risk of connectors has been developed, along with techniques to characterize the process. Through further study, the combined results will allow PV operators to formulate a data-driven approach to BOS connector maintenance.

VIII. Acknowledgements

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