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Preliminary Photovoltaic Arc-Fault Prognostic Tests using Sacrificial Fiber Optic Cabling

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Abstract

Through the New Mexico Small Business Assistance Program, Sandia National Laboratories worked with Sentient Business Systems, Inc. to develop and test a novel photovoltaic (PV) arc-fault detection system. The system operates by pairing translucent polymeric fiber optic sensors with electrical circuitry so that any external abrasion to the system or internal heating causes the fiber optic connection to fail or detectably degrade. A periodic pulse of light is sent through the optical path using a transmitter-receiver pair. If the receiver does not detect the pulse, an alarm is sounded and the PV system can be de-energized. This technology has the unique ability to prognostically determine impending failures to the electrical system in two ways: (a) the optical connection is severed prior to physical abrasion or cutting of PV DC electrical conductors, and (b) the polymeric fiber optic cable melts via Joule heating before an arc-fault is established through corrosion. Three arc-faults were created in different configurations found in PV systems with the integrated fiber optic system to determine the feasibility of the technology. In each case, the fiber optic cable was broken and the system annunciated the fault.

ACKNOWLEDGMENTS

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NOMENCLATURE

AFCI	arc-fault circuit interrupter
AFD	arc-fault detector
DC	direct current
DETL	Distributed Energy Technologies Laboratory
MSI	Management Sciences, Inc.
NEC	National Electrical Code
NMSBA	New Mexico Small Business Assistance
PV	photovoltaic
SNL	Sandia National Laboratories
UL	Underwriters Laboratories

1. INTRODUCTION

Management Sciences, Inc. (MSI) developed and patented technology for detecting damage to wiring and conduit systems. While this technology was originally developed for military aircraft, Sentient Business Systems (working in close partnership with MSI) is pursuing expanding the technology to help protect and detect photovoltaic (PV) systems from arc-faults. There is currently an extensive effort by a number of companies to develop PV arc-fault detectors and arc-fault circuit interrupters (AFCIs) [1-4] due to requirement 690.11 in the *National Electrical Code®* (*NEC*) [5]. These devices typically use the noise on the DC system to identify the arc-fault and then mitigate it by de-energizing the PV system. This approach requires an arc-fault to be present before remediation is possible. One clear advantage of Sentient Business Systems' technology is that it doubles as a prognostic tool, which is capable of either automatically de-energizing or simply warning the home or plant owner of a dangerous situation *before* an arc-fault occurs.

In order to provide the advanced warning, translucent polymeric fibers are embedded in the PV modules and incorporated in the DC cabling. A periodic light signal is passed through the polymeric fiber optic cable to a photodetector to verify the integrity of the system. If there is a hot spot, abrasion, or other damage to the electrical conductors, the fiber optic line is melted or cut and the photonic signal does not reach the receiver before the electrical system is disconnected and the arc-fault is established. The quantity of damage required for an alarm can be tuned by adjusting the fiber optic material, geometry, and layout. The light signal can also be provided at an appropriate rate, so there is only a short delay in the fault response.

Since the translucent polymeric fiber is intended to be incorporated in the modules and electrical cabling during the manufacturing process, a number of integrated samples were created to demonstrate the system results when there was an arc-fault in the PV system. These samples simulated two types of series arc-faults inside a PV module and an arc-fault from a PV cell to the module frame. The arc-faults created enough heat and localized pressure to sever the fiber optic connection and sound the alarm. This was demonstrated to be an effective alternative to using the electrical signal-based AFCIs when the fiber optic is located close to the arc-fault.

2. DESCRIPTION OF THE TECHNOLOGY

2.1 Prior Art

Management Sciences' use of polymeric fiber optics to determine damage to conduits originated with internal research and development and is described in four patents [6-9]. Initial development was to detect incipient or real damage to electrical conductors in electrical cables caused by chemicals, chafing, abrasion, and/or hot spots. It was believed that this technology could also be applied to photovoltaic systems in order to detect problems to the electrical circuitry. In the event of hot spots, which are believed to precede arc-faults, the polymeric fiber optic would melt and cause the system to shut down. In the event of physical wear or trauma, the fiber optic cable would be broken and the light signal would not reach the photodetector. The principle behind the photonic emitter/detector pair and the wear mechanisms is shown in Figure 1.

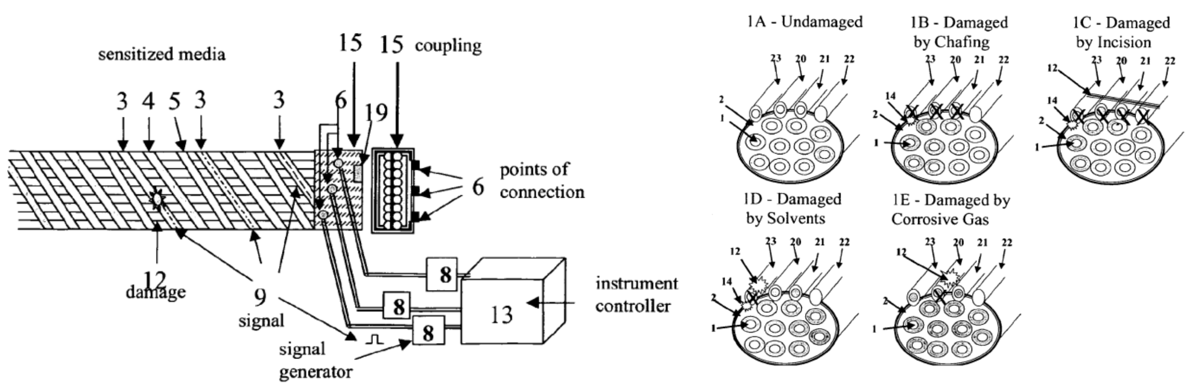

Figure 1. Method for detecting damage to conduit or electrical systems [5].

2.2 Proposed Configuration for PV Systems

Sentient Business Systems has proposed to incorporate fiber optic cables in the modules and around DC cabling. These optical paths will be connected with optical fiber connectors built into the electrical contact connectors. The polymeric fiber system can be subdivided into any number of modules and DC runs to isolate the fault when there is an alarm. One proposed layout for the module is shown in Figure 2. One potential wrapping scheme for the DC cabling is shown in Figure 3. A prototype system with a fiber optic cable is shown in Figure 4. Polycarbonate sheet may be cold bent with the minimum radius based upon a bend ratio of 100. The inexpensive, polymeric fiber optical strands can be as small as 0.1 mm in diameter which equates to a bending radius of 10 mm, so the electrical path can easily be followed using the overlayed optical fiber.

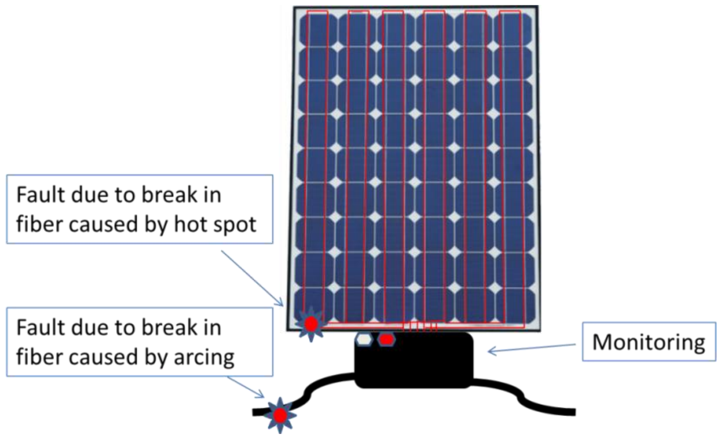

Figure 2. Arc-fault detector design for multi-cell modules. Red lines indicate the optical fiber.

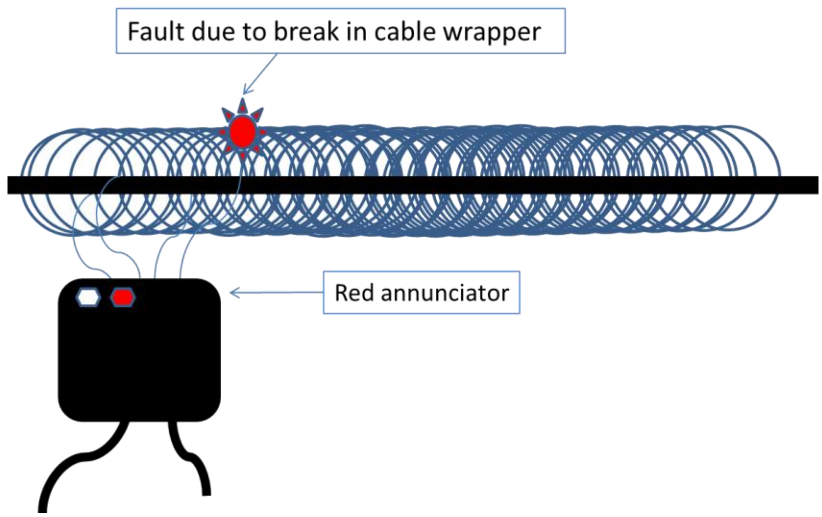

Figure 3. Fiber optic arc-fault detector deployed on a section of DC cabling.

Figure 4. Prototype fiber optic arc-fault detector. The black tab can be lifted to break the fiber optic connection and a red LED will illuminate.

3. PROOF-OF-CONCEPT TESTING

Three arc-faults were created on samples of crystalline Si modules to demonstrate the feasibility of arc-fault detection using fiber optic cabling. The tests were conducted at the Distributed Energy Technologies Laboratory (DETL) at Sandia National Laboratories. For each of the tests two parallel strings of 200 W (3.83 A I_{SC}) modules were used to create the arc-fault power. The arc-fault was generated with a fiber optic cable located on the conductor, such that it would melt under the high temperatures and pressures when the ionization of the atmosphere occurs. For these initial tests, the connectivity of the optical path was continuously measured to identify faults. In all three cases, the arc-faults were detected in less than 1 second. This is sufficient to meet UL 1699B [10] requirements for arc-fault detectors and is on the same time scales that other arc-fault detectors are operating [2].

3.1 Series arc-fault in module busbar

A module busbar sample was extracted from a PV module and the tempered front-side glass and EVA encapsulant were removed to allow connectors to be soldered to the ends. The middle of the busbar was cut with a razor blade and a single steel wool fiber was taped across the gap, as shown in Figure 5. The fiber optic cable was run along the top and over the gap in the busbar. The power through the busbar sample was created by two strings shorted through the sample. The arc current was ~7.3 A. This simulated string current was used to guarantee an arc was formed, but would not be typical for most PV strings. When the arc-fault flash was generated, the high temperatures easily melted the fiber optic cable, shown in Figure 6.

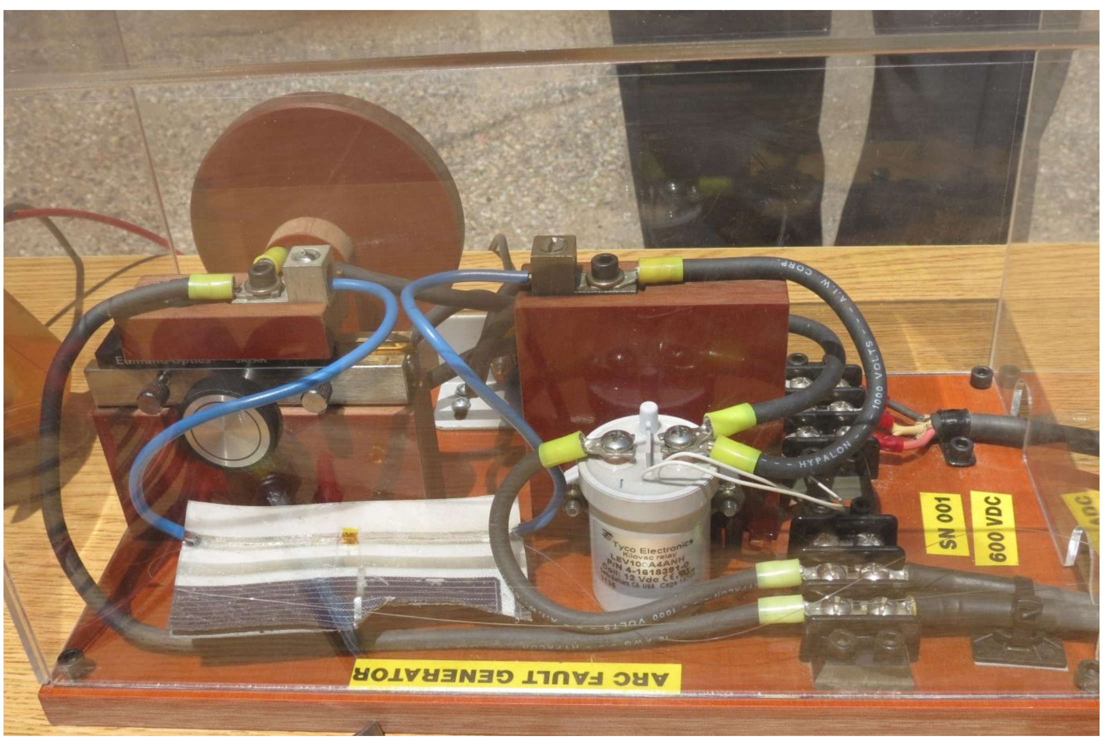

Figure 5. Series arc-fault experiment using a cut busbar sample.

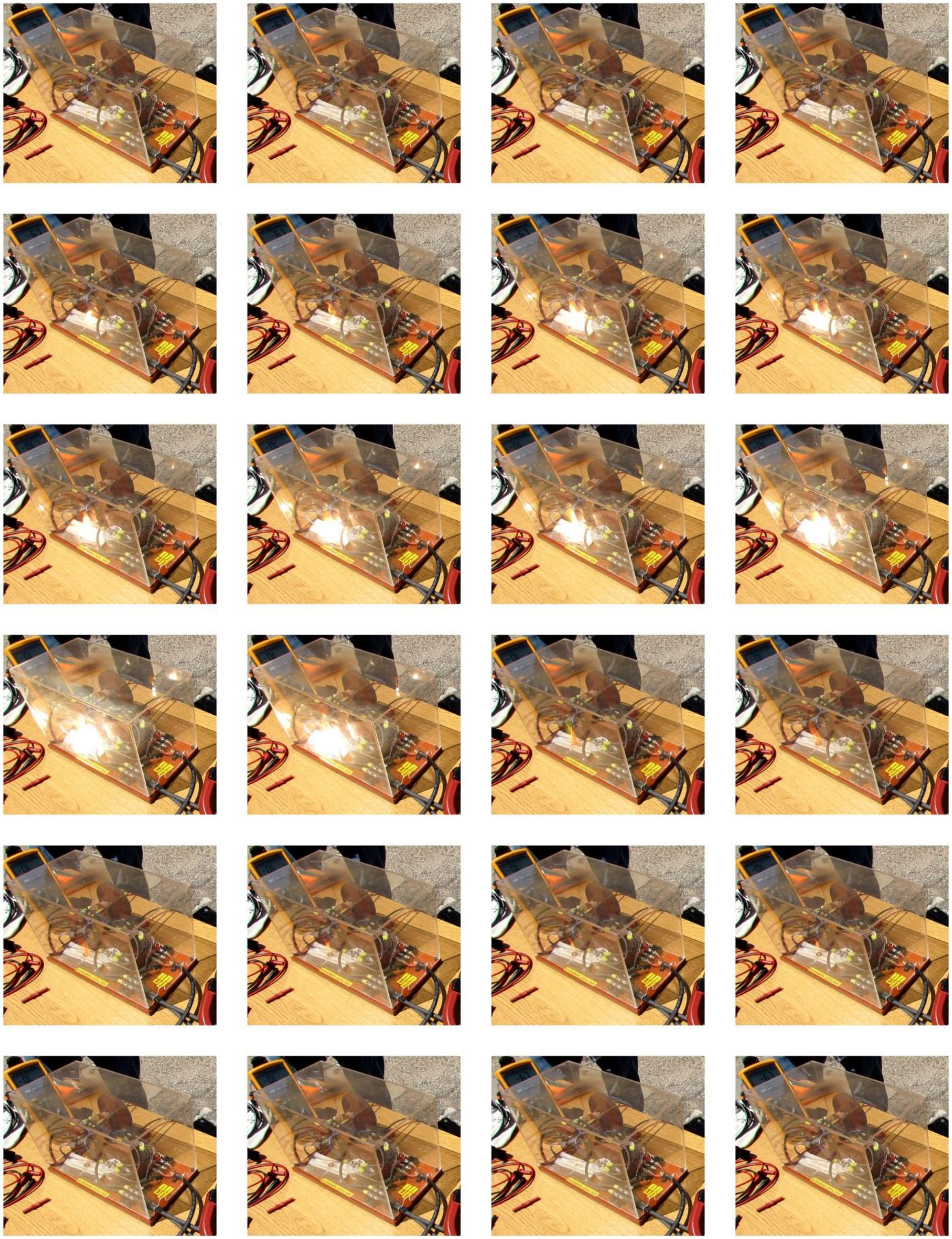

Figure 6. Simulated series arc-fault on the busbar conductor. Consecutive frames were taken from video shot at 23.98 frames/sec. Total time represented is 1.00 second.

3.2 Series arc-fault between busbar and collector ribbon

Another possible arc-fault scenario in a module is due to a poor solder connection between the busbar and the collector ribbon, which runs on the top and bottom of the cells. To simulate an arc-fault in this location, the busbar and ribbon were extracted from a PV module and mounted on a polycarbonate plate. The collector ribbon was then disconnected from the busbar to establish the arc-fault, as shown in Figure 8. Again in this case two strings in parallel powered the arc fault, so the current is greater than would be typically seen in a series fault. In this simulation, the polymeric fiber cable was vaporized and the detector no longer saw the light signal.

3.3 Arcing fault from PV cell to module frame

The final arc-fault test was a type of ground-fault where an arc is generated from the PV cell to the equipment ground. A fiber optic cable was placed along the side of the cell, shown in Figure 7. If these fiber optic cables were monitored separately, the type of arc-fault could be determined. The collector ribbon was charged to V_{OC} and the frame was grounded. A piece of steel wool was placed across the cell to the frame to initiate the arc-fault. The resulting damage, illustrated in Figure 7 and Figure 9, broke the polymeric fiber connection and the fault was detected.

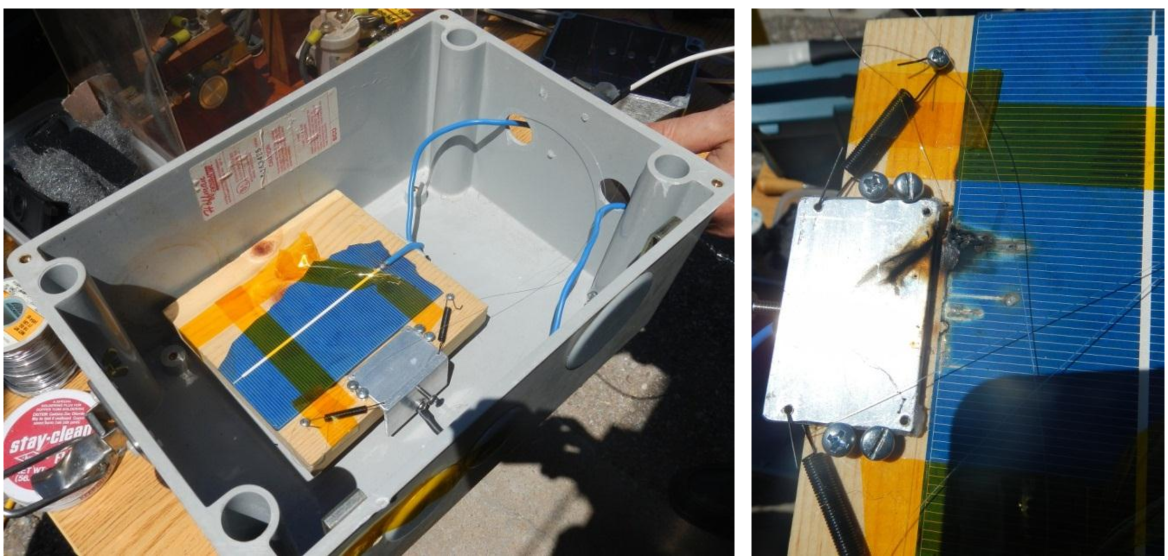

Figure 7. Arc-fault to ground setup (left) and damage caused by the arc (right).

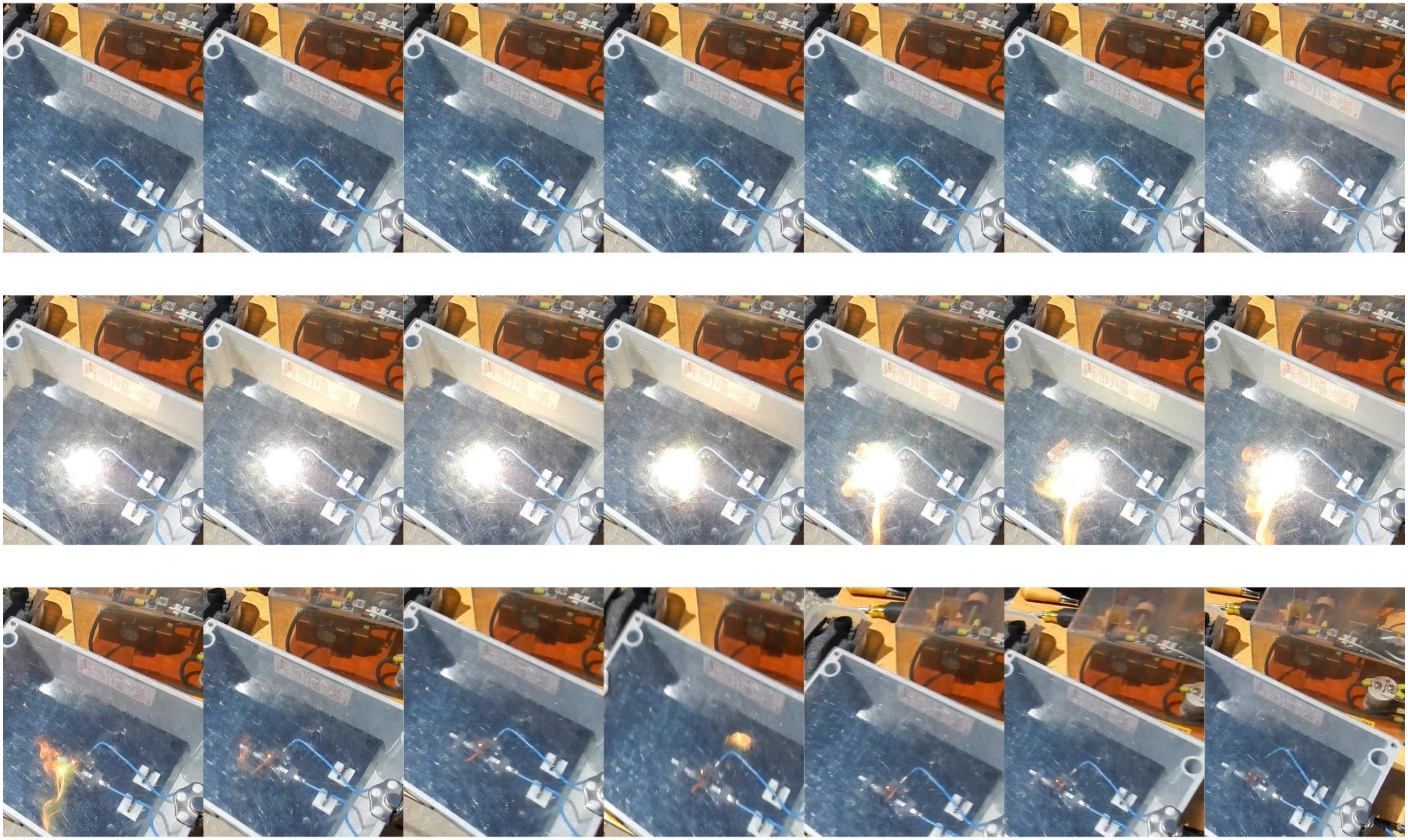

Figure 8. Simulated series arc-fault between the module busbar and collector ribbon. Consecutive frames were taken from video shot at 23.98 frames/sec. Total time represented is 0.88 seconds.

Figure 9. Simulated arc-fault from a PV cell to the frame. Consecutive frames were taken from video shot at 29.97 frames/sec. Total time represented is 2.00 seconds.

3.4 Prognostic Arc-Fault Detection

The previous sections evaluated the detection of spontaneous arc-faults, however, in many cases, ohmic heating from corrosion or other electrical degradation from the manufacturing process or material defects may act as an arc-fault failure precursor. By tuning the melting temperature of the fiber optic, the failure precursor is detected and the PV system can be de-energized before the arc occurs. The percentage of PV arc-faults that undergo this heating is unknown, but many systems exhibit localized heating or “hot spots,” e.g., at a deteriorating cell lap joint. The heating may eventually cause further damage and lead to an arc-fault event. This hot spot will create enough localized energy that the aforementioned polymeric fiber may be melted or otherwise deteriorated in a manner so as to cause attenuation or loss of the optical signal.

Sentient Systems prepared a simple test case using a copper strip (see Figure 10) to create a resistive section of the copper with the polymeric fiber laid over this resistive section. Wires were soldered to each end of the copper foil and the test coupon was mounted to a wood block for testing. 6 A current was passed through the test section and the light transmission through the polymeric fiber was measured using the photodetector. After approximately 3 minutes, the amount of light transmitted by the fiber dropped off substantially and the test was terminated. The resulting damage to the polymeric fiber is shown in Figure 11. This latent fault was detected substantially before the fault could deteriorate into a full “arc fault” condition. Determining the fiber optic melt temperature and the optical transmission alarm threshold are areas of future study.

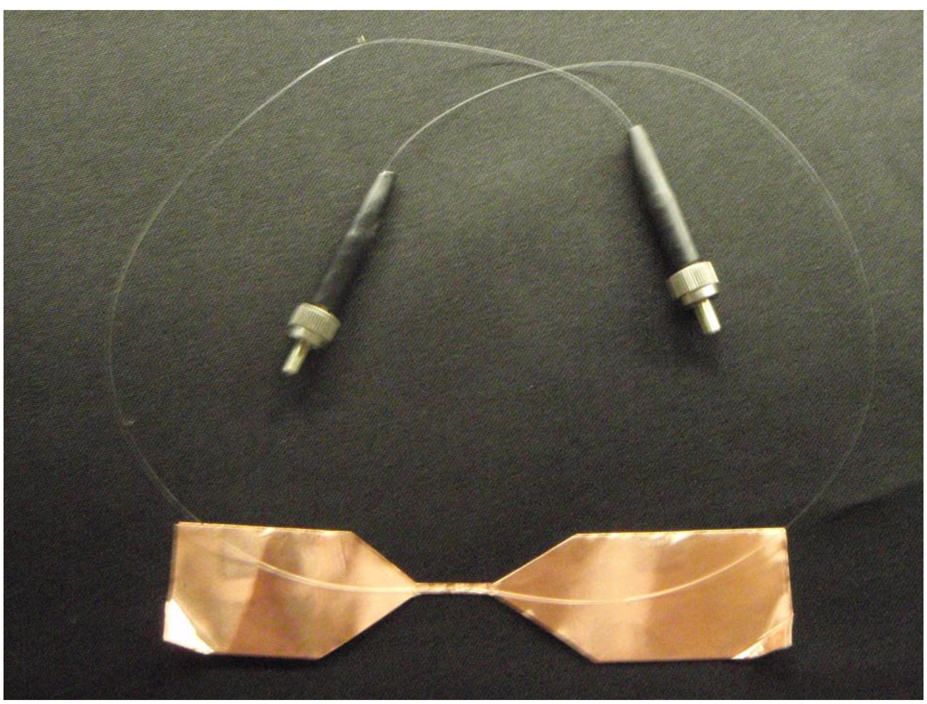

Figure 10. Resistive test fiber setup.

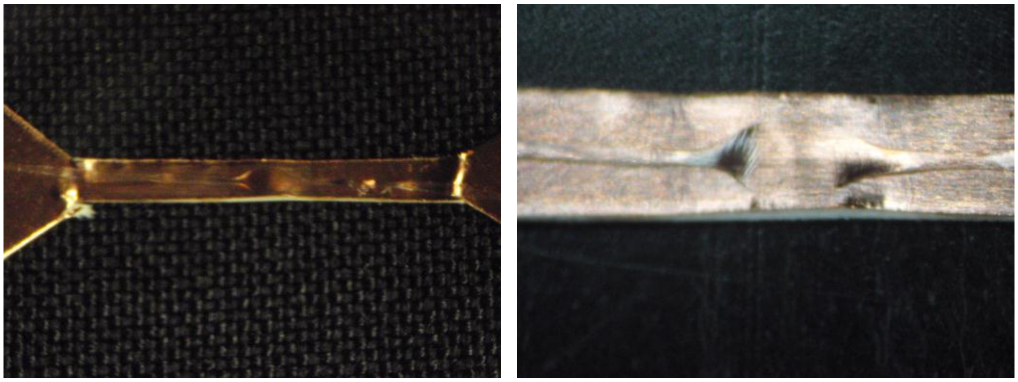

Figure 11. Fiber damage from "hot spot" test.

4. CONCLUSIONS

Sentient Business Systems, Inc. has created a novel arc-fault detector that uses a sacrificial translucent polymeric fiber to warn when there is damage to a PV system. This technology is different from classical electromagnetic technologies in that it can prognostically indicate when an arc-fault may exist by warning home and plant owners of abrasion and/or overheating to the system. Three arc-faults were created with PV module samples. In each of the tests, the translucent polymeric fiber optical cable quickly melted and the photodetector no longer received the optical signal. The detection time can be adjusted by changing the pulse cycle rate and detection algorithms to pass the UL 1699B trip time requirements for listing arc-fault detectors.

While these preliminary tests show that under direct exposure to an arc-fault the fiber optic cable melts and the system detects the fault, there is significant work remaining to vet this technology. The repeatability, robustness, and reliability of the technology must be verified and module, wiring, and connector manufacturing partners need to be identified. Further, comparing the costs for this system to more traditional arc-fault detector systems must be considered. It should be noted that the additional, prognostic capabilities could incentivize some customers to favor this methodology. Knowledge of when a failure is going to occur prior to a fault allows operations and maintenance (O&M) scheduling and costs can be optimized to replace failing components before they force the entire system to shut down.

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