ARC MAPPING IN THE ADVENT OF AFCI, GFCI, AND GFEP CIRCUIT PROTECTION DEVICES

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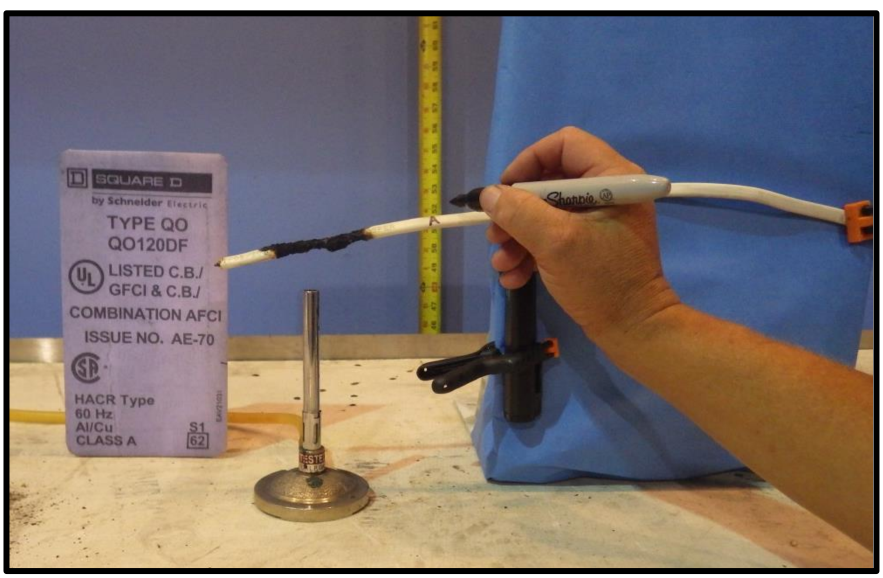
ABSTRACT

Arc mapping is a tool that can be used to locate the portion of an energized circuity where insulation was first compromised so as to allow an arc discharge. In theory, the arcing will bring about fast response of the Over Current Protection (OCP) such that the arcing is short lived. Finding this singular arc allows one to state that the arc bead is generally where the thermal flux brought about the gaseous discharge as the insulation failed. The implications of the arc bead are as follows:

- It establishes that the circuit was energized
- It establishes that OCP was present and functional
- It helps to establish the geometry of fire progression

The goal of this paper is to establish what the investigator should expect to find while arc mapping areas where the AFCI devices were installed in the subject electrical systems. The results presented are collected from actual test burns involving non-metallic sheathed cables (NM-B).



BACKGROUND

The 2014 revision of NFPA 70, article 100, defines an AFCI (Arc-Fault Circuit Interrupter) "as a device intended to provide protection from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to de-energize the circuit when an arc fault is detected."

"Arc" is defined in the 2014 revision of NFPA 921 in section 3.3.7 as "a high-temperature luminous electric discharge across a gap or through a medium such as charred insulation." Arcing through char is further defined in section 3.3.10 as "arcing associated with a matrix of charred material (e.g., charred conductor insulation) that acts as a semiconductive medium."

It is arcing though char that this test is designed to simulate as defined by NFPA 921. The goal of this experiment is to determine whether or not an AFCI combination circuit breaker will allow for the formation of copper beads on the surface of the energized electrical copper conductors. The beads are used in arc mapping; a systematic evaluation of the electrical circuit configuration, spatial relationship of the circuit components, and identification of electrical arc sites to assist in the identification of the area of origin and analysis of the fire's spread.

UL Standard 1699

Although many are familiar with the existence of UL Standard 1699, the standard that specifically addresses the design characteristics and testing parameters of which an Arc Fault Circuit-Interrupter must conform to, the actual contents of the 84 page document are not as well known. UL Standard 1699 defines Arcing as "a luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes;" and an Arcing Fault as "an unintentional arcing condition in a circuit." UL Standard 1699 goes on to define a Carbonized Path as "a conductive carbon path formed through or over the surface of a normally insulating material."

UL Standard 1699, section 40.1.1 states "in order to demonstrate that the AFCI can detect and protect against arcing, a representative AFCI of each rating shall be tested for each test within the appropriate test series as defined in Table 34.2 and described in this Section. Unless otherwise indicated, the tests are to be conducted with nonmetallic sheathed cable (Type NM-B) shall utilize cable specimens which include a bare equipment grounding conductor." Table 34.2, Arc fault detection tests table, defines the tests specific for a combination AFCI circuit breaker (specific to NM-B cable) to include (but not limited to):

- 40.2 – Carbonized path arc ignition test
- 40.3 – Carbonized path arc interruption test

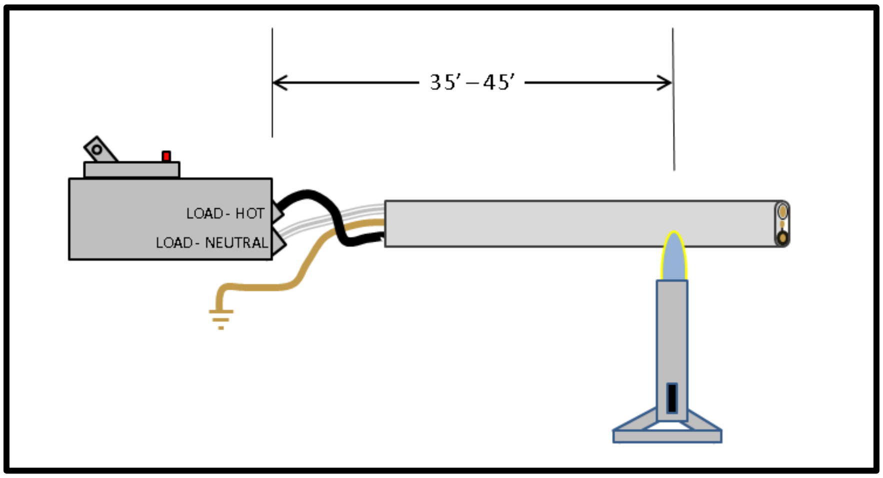
The carbonized path test sequences, as described in Section 40.2 and 40.3 of the Standard, creates a conductive (carbonized) path between the conductors using the discharge of a high voltage neon sign transformer. The transformer is specified to have an output of 15 Kilovolts with center tap capable of providing 30 milli-Amperes of current on the secondary side of the transformer. The high voltage arcing establishes a path across the cut surfaces of the insulation of the conductors. A small channel of insulation material is charred by the prescribed process.

TEST SET-UP

The test set-up consisted of placing a controlled flame under a commonly available electrical cable. The flame was adjusted to facilitate burning of the insulation on the cable. The cable was energized by an AFCI circuit breaker. The burning of the insulation was continued until the circuit breaker tripped. The length of time the flame was applied to the energized circuit was recorded and the burned section of wire was examined for the presence of electrical activity in the form of electrical arcing.

The controlled heat source was a natural gas powered Bunsen burner. The test cable was a 50-ft length of Romex 14/2 solid SIMpull NM-B solid copper cable which includes a bare equipment grounding conductor. We tested a Square-D QO120DF 20-amp combination AFCI and an Eaton CHFCAF115 15-Amp combination AFCI. The circuit breakers were connected to electrical power using an electrical panel that the manufacturer designed for the device.

The flame of the burner was placed approximately four inches from the end of the cable. Each test sequence was recorded in its entirety on video. A non-contact voltage detector was used to visually indicate the status of the circuit breaker (and the presence of electrical power in the test cable).



TEST RESULTS

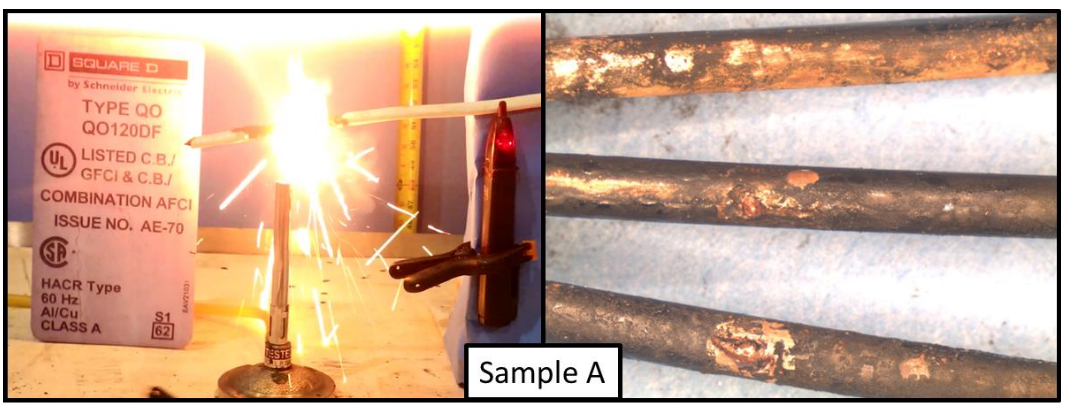
A full length video of each test specimen was made to capture the event in real time. The photos below were generated using a screen capture tool (Snip-It) while viewing the video frame by frame. The micrographs of the physical damage on the copper conductors were taken with a Leica MZ7.5 Stereoscope utilizing multi-layer imaging to increase the depth of field focus.

The circuit breaker time to trip was documented for each test sequence. The recorded observations were limited to whether or not an arcing event was witnessed at the time the circuit breaker tripped.

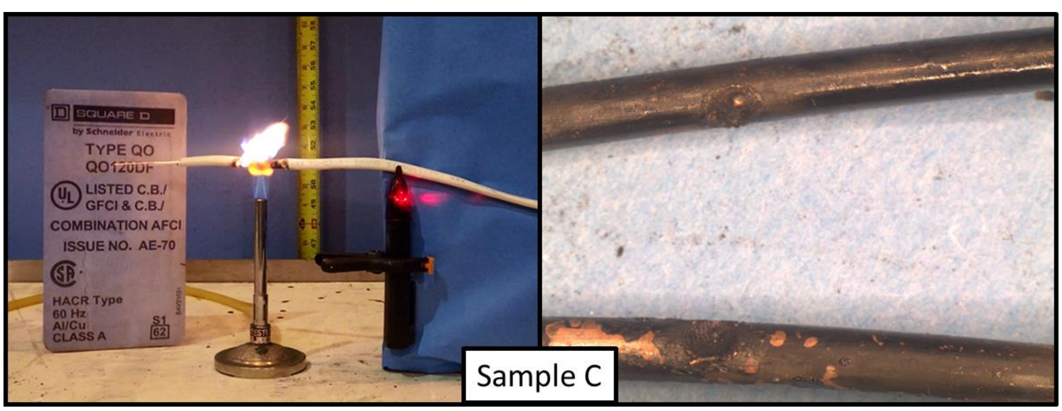
A single Square-D AFCI combination circuit breaker was used in all 13 test sequences (labeled A through M). A single Eaton AFCI combination circuit breaker was used in all 6 test sequences (labeled E1 through E6). The circuit breaker was allowed to cool off between each test sequence a minimum time of 20 minutes.

- The Square-D circuit breaker tripped in all 13 test sequences.
- In 6 out of 13 tests, the Square-D AFCI combination circuit breaker produced a visible arc with physical evidence of the arc on the copper conductors of the test cable.
- The Eaton circuit breaker tripped in all 6 tests sequences.
- In 5 out of 6 tests, the Eaton AFCI combination circuit breaker produced a visible arc with physical evidence of the arc on the copper conductors of the test cable.

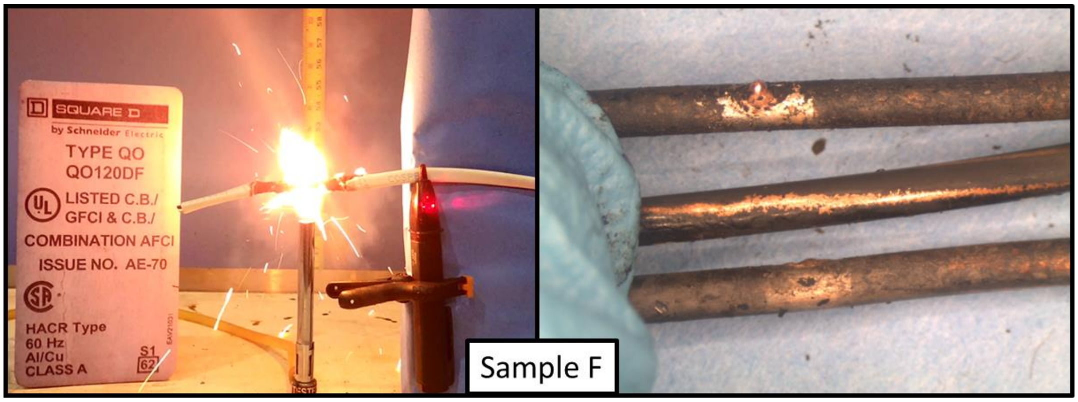
Sample	Time to Open (minutes)	Observations
A	10:02	Visible Arcing
B	12:19	No Arcing
C	3:05	Visible Arcing
D	1:49	No Arcing
E	11:25	No Arcing
F	9:18	Visible Arcing
G	3:25	No Arcing
H	2:07	No Arcing
I	21:06	No Arcing
J	8:06	Visible Arcing
K	14:50	Visible Arcing
L	16:22	No Arcing
M	5:07	Visible Arcing
E1	25:02	Visible Arcing
E2	25:07	Visible Arcing
E3	29:36	Visible Arcing
E4	18:12	No Arcing
E5	11:00	Visible Arcing
E6	29:41	Visible Arcing

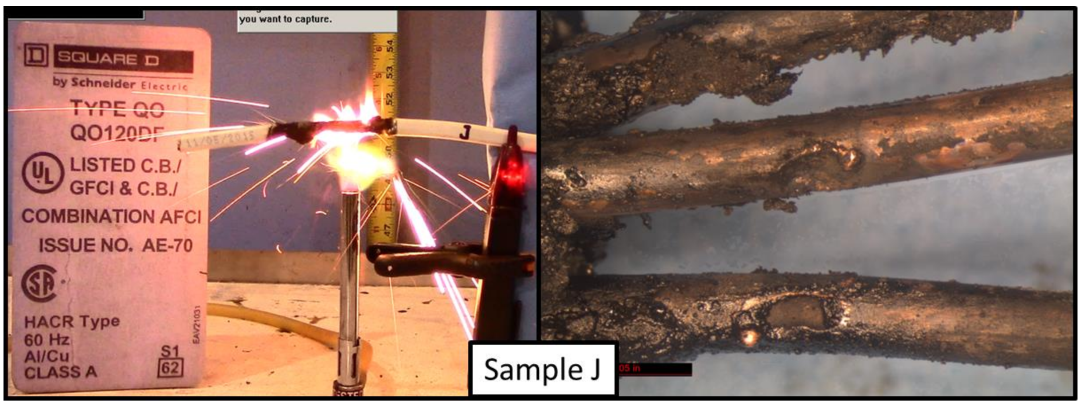


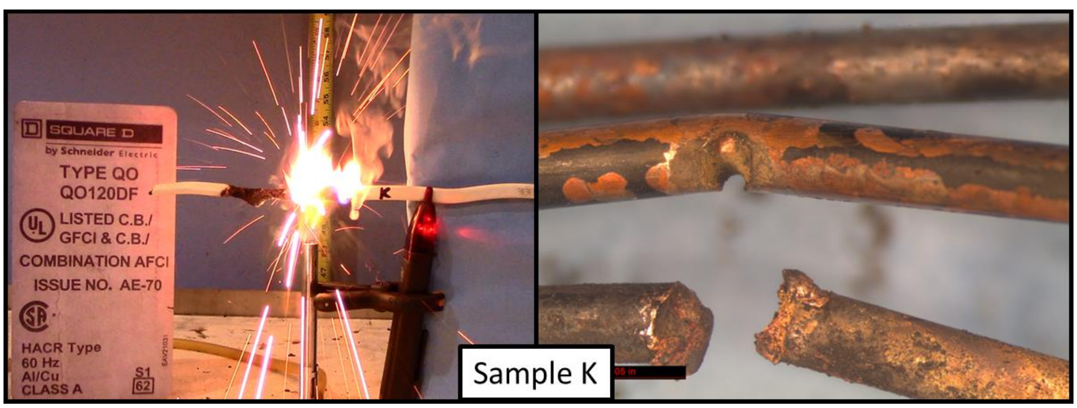
Sample A



Sample C


SQUARE D
by Schneider Electric
TYPE QO
QO120DF
LISTED C.B./
GFCI & C.B./
COMBINATION AFCI
ISSUE NO. AE-70
HACR Type
60 Hz
Al/Cu
CLASS A
Sample F


you want to capture.
SQUARE D
by Schneider Electric
TYPE QO
QO120DF
LISTED C.B./
GFCI & C.B./
COMBINATION AFCI
ISSUE NO. AE-70
HACR Type
60 Hz
Al/Cu
CLASS A
J
Sample J


SQUARE D
by Schneider Electric
TYPE QO
QO120DF
LISTED C.B./
GFCI & C.B./
COMBINATION AFCI
ISSUE NO. AE-70
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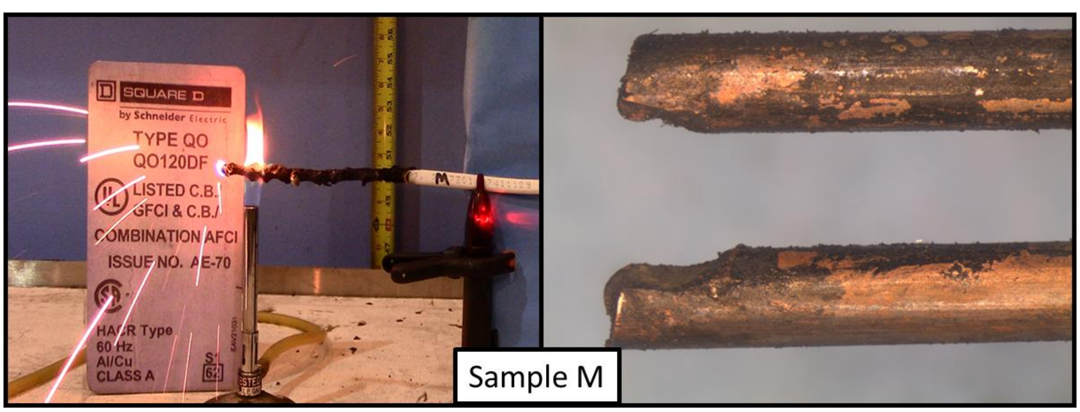
60 Hz
Al/Cu
CLASS A
K
Sample K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by Schneider Electric
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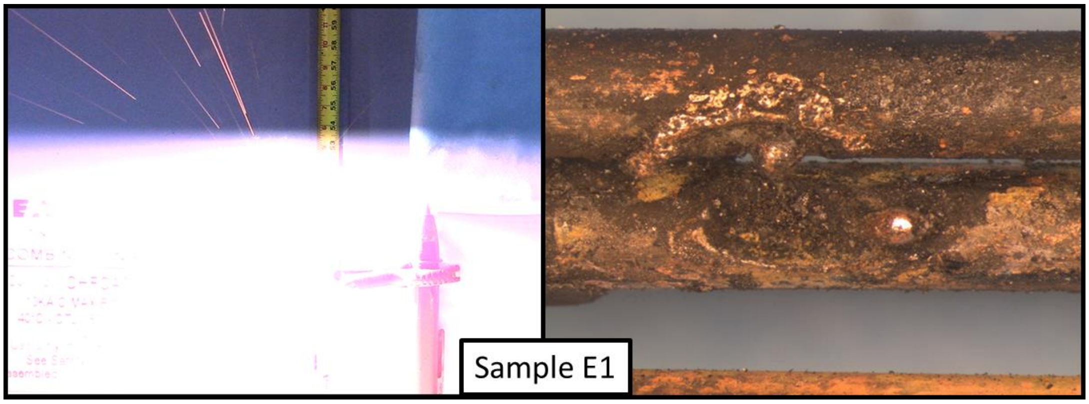
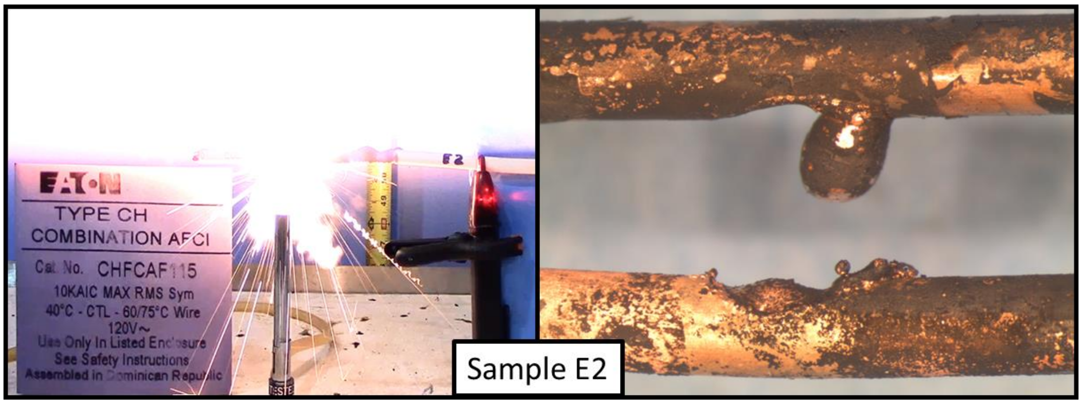
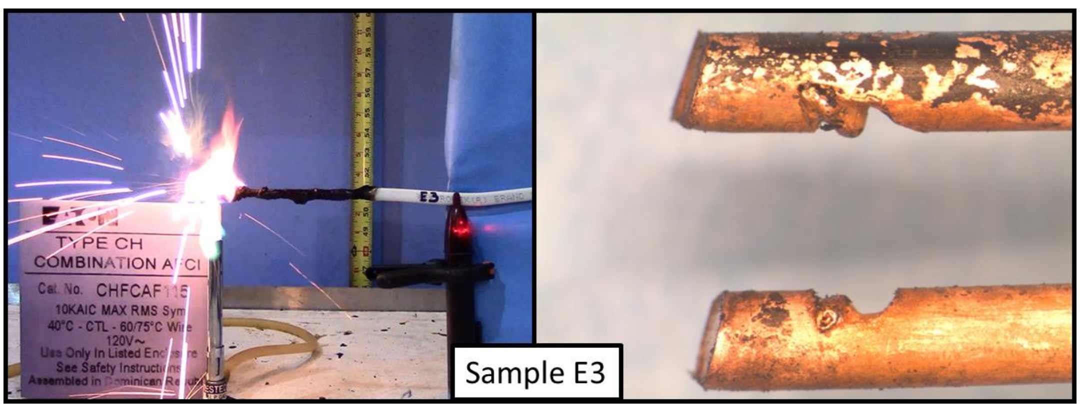
QO120DF
COMBINATION AFCI
HACR Type
60 Hz
Al/Cu
CLASS A
M
Sample M



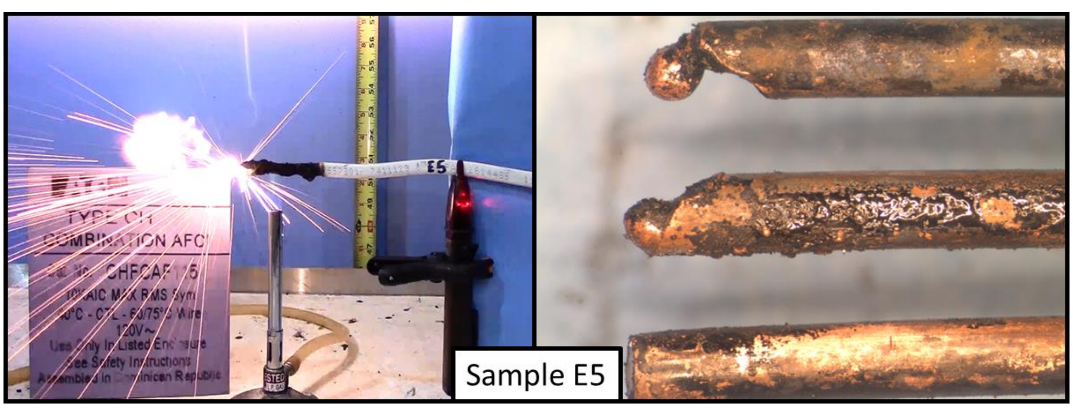
Sample E1



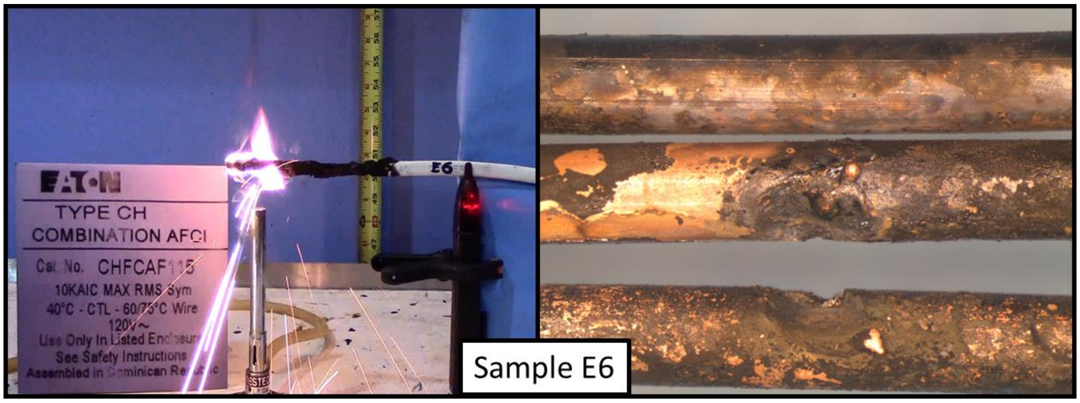
Sample E2



Sample E3



Sample E5



NOT ALL AFCI'S ARE CREATED EQUAL

The reader is cautioned that not every AFCI works the same. Basically, every AFCI is designed to test for the signature of an arcing connection. However, this is where the similarity ends. It is necessary for the investigator to know more about the brand and model of ACFIs in use. Why? Because the manufacturers have added other safety features in the AFCIs, of which, there is no uniformity among manufacturers. More specifically, manufacturers have included the following types of features in their various circuit protection devices:

Ground Fault Circuit Interrupter (GFCI)
Ground Fault Equipment Protection (GFEP)
Grounded Neutral Sensor (GNS)

Most are familiar with the GFCI circuit protection device, which responds to a current imbalance of 5 mA or more between hot and neutral. The GFEP is similar, but is NOT listed for shock protection – a typical imbalance or trip value is 30 to 50 mA. The GNS senses a condition whereby the ground and neutral are shorted together downstream; when this happens, the Equipment Grounding Conductor (EGC) is electrically in parallel with the neutral, allowing the EGC to carry current in normal operation – a condition that is absolutely forbidden by the NEC.

Any one of these features (GFCI, GFEP, GNS) may be present in the specific circuit protection device which is associated with the circuits being examined at a scene. The circuit protection device can be tripped in association with any one of these features in reaction to the fire, along with the AFCI circuitry, as well as from direct heat impingement on the device. As an example, a neutral touching a ground conductor (EGC) on an unloaded circuit will cause the AFCI to trip. Without being aware of this phenomenon, the investigator may incorrectly conclude the status of the power to the downstream circuitry prior to the fire.

One AFCI manufacturer, Cutler Hammer, has realized the value in knowing exactly what condition caused an AFCI to trip. Their AFCI units have back-up batteries and logic that remember why the AFCI tripped. Their 'error' codes are as follows:

1	Mechanical Disconnect	Short Circuit, Overload, or manually cut off
2	Low current arc	A low current series arc detected
3	High current arc	A parallel arc detected, usually from damaged wiring
4	Short delay	Short circuit detected

5	Overvoltage	Line voltage > 160 volts
6	Ground fault	GNS activated
7	Self-test failure	Self-diagnosis failure

The astute investigator will learn to understand these codes, and how they may impact arc mapping. Without understanding how the AFCI works, to specifically include ancillary functions, the investigator may well be drawn to incorrect conclusions.

CONCLUSION

The data from the above test sequences clearly indicates the following:

- Electrical arcing can occur on the copper conductors energized by an AFCI combination circuit breaker,
- Copper beads (on the electrical conductors) were documented in all cases where an arcing event was witnessed, and
- A tripped AFCI combination circuit breaker does not ALWAYS indicate that an arcing event occurred on the copper conductors.

The presence of an AFCI combination circuit breaker may reduce the number of arcing events that occur during a fire. However, as demonstrated in this paper, an AFCI combination circuit breaker will not always prevent the formation of electrical arcing or the physical manifestation of arc marks (copper beads) on an energized electrical conductor during the course of a fire. The physical evidence of arcing, on the energized electrical conductors located throughout a fire scene, can still be recovered and used in the process of arc mapping a fire scene, as per NFPA 921, even when the wiring was protected with AFCI combination circuit breakers.

ABOUT THE AUTHORS

Kevin R. (KR.) Davis, PE, CFEI, CVFI: An Electrical Engineer that received as BSEE from the University of Missouri-Rolla, and is licensed to practice engineering in numerous states. Mr. Davis has nearly 20 years of product design and development experience while working for Delco Products, Ford Motor Company, Harley-Davidson, Peterbilt and Hatteras Yachts. He has been certified in marine electrical systems by the ABYC and currently works for Goodson Engineering performing failure analysis on electrical systems.

Mark Goodson, PE: An Electrical Engineer that received a BSEE from Texas A&M in 1979, and is licensed to practice engineering in numerous states. After engineering school, he attended UT Southwestern (Dallas) in a forensic medicine track. He was the first PE to serve on the State of Texas Electrical Board. From 1989 to 1991, he served as a Court Special Master. He is the PE selected to sit on the Texas State Fire Marshal Science Advisory Workgroup, SAW. He was a member of the Editorial Review Board for the Fire & Arson Investigator. Mr. Goodson is the principal in the firm Goodson Engineering of Denton, Texas. He holds three Patents on fire safety, and has four more pending. He has published 36 peer reviewed technical articles, with 30 of them dealing with fire science. He has published in the Fire & Arson Investigator, Journal of Forensic Sciences, American Journal of Forensic Pathology, and the Forensic Sciences Gazette. Mr. Goodson serves as a consultant to many Medical Examiners' Offices in Texas.