Evaluation of Run Length and Available Current on Breaker Ability to Mitigate Parallel Arcing Faults

Part I: Effect of Panelboard Current for 50 Foot Run Lengths

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EXECUTIVE SUMMARY

Electrical wiring in the home can get damaged during installation or afterwards, through over-stapling, crushing, bending, penetration by screws and nails, and through rodent and insect damage. Over time cabling may degrade further due to exposure to elevated temperatures or humidity, eventually leading to arcing faults and ignition of combustibles in proximity. The length of electrical wiring between the circuit breaker panel and the first receptacle is often referred to as the “home-run”. To protect the wiring from damage and subsequent potential for arcing, the National Electrical Code (NEC®) requires protection of the home run wiring using conduit or armored cabling[1] if a receptacle-mounted AFCI (known as Outlet Branch Circuit Arc-Fault Circuit-Interrupter, or OBC AFCI, in the NEC) is used in a residential circuit. This requirement was put in place since such an arc protection device would not be able to provide parallel arcing fault protection for the home run, *i.e.*, de-energize the circuit, if the fault is upstream of the OBC AFCI.

In this situation, the circuit breaker is the only means for mitigating the fault, though it is intended for protecting the wiring from overheating due to an overcurrent condition and is not intended for mitigating arcing faults. Since parallel arcing faults may deliver relatively high currents, there is the possibility that it may trip the circuit breaker and de-energize the electrical circuit. However, the ability of a circuit breaker to mitigate a parallel fault condition has not yet been well characterized in the available literature. Thus, experimental data was required to determine whether a circuit breaker may mitigate a parallel arc fault, and more specifically, the conditions under which effective protection is attained.

Prior work by UL[4] showed that most off-the-shelf residential 15A circuit breakers would be expected to trip magnetically at or above 300A. Arcing tests using these circuit breakers showed that circuit breakers could mitigate an arcing fault, provided the following inequality is satisfied:

$$\rho_L L < \frac{V_{rms}}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{I_{pssc}}\right)$$

where

ρ_L is the resistivity per unit foot of the NM cable gauge being used;
L is the length of the “home run” in feet;
V_{rms} is the supply voltage (typically 120 V_{rms});
I_{pssc} is the short-circuit current at the panelboard; and
I_{mag} is the magnetic trip current of the circuit breaker.

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[1] More specifically, protection must include the use of RMC, IMC, EMT, Type MC, or steel armored Type AC cables meeting the requirement of 2011 NEC § 250.118. (See 2011 National Electrical Code § 210.12(A), Exception 1 for more information.

Since the release of that report, Code proposals have been developed within Code Panel 2 based on this mathematical relationship. These proposals have been hampered by uncertainty in an appropriate value for I_{pssc}, the available current at the panelboard. In some applications of the formula, I_{pssc} is assumed to be arbitrarily large and therefore is neglected. However, the effect of I_{pssc} can be significant until the available current at the panelboard rises very high, to 5kA or higher. Though obtaining solid data on realistic values for I_{pssc} has been difficult, proposals within Code Panel 2 have put forth a minimum available current of 500A at the panelboard. A UL investigation into the available current at receptacles conducted in 1993 tends to substantiate this value.[6] Using 500A for I_{pssc} will tend to significantly shorten the allowable run length if the magnetic trip level (I_{mag}) is held at 300A. However, there is a desire to hold the maximum run length to 50 feet while assuming 500A available at the panelboard. This forces either the wire gauge or the maximum allowable magnetic trip level to be adjusted to balance the equation: since it is preferable to assume that 14 AWG will be used, the magnetic trip level of the circuit breaker must be lowered. This work focuses on experimentally verifying the mathematical relationship when available panelboard current is adjusted while maintaining a 50-foot run length.

Evaluation of the magnetic trip level of circuit breakers in Ref. 4, as well as this follow-up work, show that breaker magnetic trip levels are not sufficiently reliable and consistent to allow for a generalized assumption of an upper bound, as was proposed before. This is substantiated by the finding that for one manufacturer, the distribution of magnetic trip levels for the same model breaker can vary considerably (more than 50A) between two different batches manufactured at different times. Two circuit breakers in this work also showed that while a circuit breaker was able to trip magnetically nine times out of ten, in one test it failed to magnetically trip after many arcing half-cycles exceeded the magnetic trip level of the circuit breaker. This suggests that more controlled verification of the magnetic trip level of a circuit breaker intended for mitigating parallel arcing faults may be needed.

The results of this work show that the mathematical relationship relating magnetic trip level, run length, and available current at the panelboard is accurate for predicting the ability of a circuit breaker to mitigate an arcing fault within eight arcing half-cycles in 0.5 seconds for carbonized path arcing. For point contact (guillotine) arcing tests, the formula was also able to predict behavior at 500A available fault current but was not accurate when the tests were repeated with 1000A available at the panelboard. This was found to be due to the reduced peak arcing current values for point contact arcing, relative to carbonized path arcing. At this time it is not clear whether this effect is characteristic of point contact arcing, or whether it is an artifact of the test apparatus. Further experimental work is underway to resolve this issue.

The results from the experimental work discussed in this report tend to agree with the mathematical prediction for the conditions required to pass the UL1699 eight half-cycle criterion. The mathematical relationship predicts that in a system with 500A available at the panelboard, 50 feet of 14 AWG NM cable used as the home run, and operation is conducted at 25℃, that a circuit breaker will mitigate arcing if the magnetic trip level is at or below 195A. It is also noted that wire and/or circuit breaker temperature can significantly alter the maximum magnetic trip level of the circuit breaker, lowering the value as cable temperature rises; lowering it when cable temperature falls below room temperature. The trip performance of a circuit breaker also may change as a function of internal temperature, which was not investigated in this work.

In conclusion, the mathematical relationship is able to accurately predict the ability of a circuit breaker to mitigate arcing faults. However, it needs to be verified whether point contact arcing will require revision of the formula, or whether resolution of potential issues with the test apparatus will allow the data to fall in line with the carbonized path results.

Key Points

- The most recent circuit breaker testing show that not all models will show consistent magnetic trip values over time, even if the same model number is evaluated from different batches. This suggests that the magnetic trip level of a circuit breaker needs to be verified and/or tested for use in an application where it is expected to mitigate a parallel arcing fault in the home run.
- The mathematical formula relating magnetic trip level, wire length and resistivity, and available panelboard current is accurate for predicting the ability of a circuit breaker to mitigate an arcing fault in the case of a carbonized path arcing fault.
- As the current increases for a point contact arcing fault, the ability of the mathematical relationship to predict behavior begins to diverge. At this time it is not clear whether this is an artifact of the test apparatus or a real effect. This issue is currently being studied: one of two options are possible:
    - The decline in current is a real effect unique to point contact arcing. This result would be unusual since arcing physics would suggest that the normalized current should remain constant, or even slightly increase, with increasing available fault current.
    - The decline in current is an artifact of the test apparatus, such as a poor or degrading contact to the test sample. In this case, it is expected that resolving the issue would re-align the point contact results to that for the carbonized path data, reaffirming the mathematical relationship.

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BACKGROUND

In preparation for the 2014 Edition of the National Electrical Code® (NEC®)[2], several proposals were made to revise Section 210.12 for arc-fault circuit-interrupter protection to permit a listed outlet branch circuit type arc-fault circuit interrupter to be installed at the first outlet on the branch circuit under certain conditions of installation. The Code Panel chose to accept the following revision to this section at the Report on Proposals (ROP) stage:[3]

> **210.12 Arc-Fault Circuit-Interrupter Protection.**
>
> (A) Dwelling Units. All 120-volt, single phase, 15- and 20-Ampere branch circuits supplying outlets installed in dwelling unit family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms, closets, hallways, or similar rooms or areas shall be protected as described by (1), (2), (3) or (4):
>
> (1) A listed combination type arc-fault circuit interrupter, installed to provide protection of the entire branch circuit.
>
> (2) A listed outlet branch circuit type arc-fault circuit interrupter installed at the first outlet on the branch circuit where all of the following conditions are met:
>
> > (a) The branch circuit over current protection device shall be a listed circuit breaker having an instantaneous trip not exceeding 300 Amperes.
> > (b) The branch circuit wiring shall be continuous from the branch circuit overcurrent device to the outlet branch circuit arc-fault circuit interrupter.
> > (c) The maximum length of the branch circuit wiring from the branch circuit overcurrent device to the first outlet shall not exceed 15.2 m (50 ft) for a 14 AWG or 21.3 m (70 ft) for a 12 AWG conductor.
> > (d) The first outlet box in the branch circuit shall be identified.
>
> (3) A listed outlet branch circuit type arc-fault circuit interrupter installed at the first outlet on the branch circuit where the portion of the branch circuit between the branch-circuit overcurrent

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[2] NFPA 70, National Electrical Code®. The National Fire Protection Association, Quincy, MA.

[3] Report on Proposals – June 2013 NFPA 70, Proposal 2-92, Log #3489, NEC-P02. The National Fire Protection Association, Quincy, MA.

> device and the first outlet is installed using RMC, IMC, EMT, Type MC, or steel armored Type AC cables meeting the requirements of 250.118 and using metal outlet and junction boxes.
> (4) A listed outlet branch circuit type arc-fault circuit interrupter installed at the first outlet on the branch circuit where the portion of the branch circuit between the branch-circuit overcurrent device and the first outlet is installed using a listed metal or nonmetallic conduit or tubing encased in not less than 50 mm (2 in.) of concrete.

UL's representative on the Code Panel voted affirmation on this action with the following comment:

> "While we support the panel action, continued support is dependent upon review of additional data that would confirm the availability of sufficient short circuit current capability at the panel of a typical installation.
>
> "The arc fault protection of the branch circuit will be provided by a system that includes an outlet branch circuit AFCI, a circuit breaker having a known instantaneous trip current and a branch circuit of a limited length and resistance to ensure that the fault current is sufficient to trip the breaker during a parallel arcing fault at the installation point of the outlet branch circuit AFCI. The latest UL Research Report[4] takes into consideration the impact of the available current at the panel on the acceptable length of the branch circuit home run to the first outlet. Calculation shows that as the available current at the origin of the branch circuit varies, so does the allowable length of the home run.
>
> "Additional study is needed to provide data regarding the current available at the origin of the branch circuit in a typical installation. From this data, the panel will be able to determine if modification of the panel action should be considered at the ROC."

Objective

The objective of the current research work is to provide additional data on the available fault current at a typical dwelling unit service entrance, and how this available fault current in combination with various lengths of branch circuit home run wiring could affect the tripping ability of the branch circuit breaker. In particular, the ability of the branch circuit breaker to protect against a parallel arcing fault in the home run would be studied. In this Report, special focus is placed on a branch circuit that has 500A available at the

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[4] *Effectiveness of Circuit Breakers in Mitigating Parallel Arcing Faults in the Home Run*, by Paul W. Brazis Jr., PhD and Fan He, PhD. Underwriters Laboratories Inc., Northbrook, IL.

panelboard and has a 50 foot home run length. This combination has received considerable focus from the members of the Code Panel as a potential “worst-case” system. The data in this Report evaluate the effectiveness of circuit breakers to mitigate parallel arcing faults under these conditions.

Prior Work and Findings

In previous work by UL it was found that a conventional circuit breaker can be an effective means of mitigating parallel arcing faults in the home run if the impedance of the home run wiring is less than a critical value, based on the supply voltage, the available current at the panelboard, and the magnetic trip level of the circuit breaker, as follows:[3]

$$\rho_L L < \frac{V_{rms}}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{I_{pssc}}\right)$$

where

ρ_L is the resistance per unit foot of the NM cable gauge being used;
L is the length of the “home run” in feet;
V_{rms} is the supply voltage (typically 120 $\mathrm{V_{rms}}$);
I_{pssc} is the short-circuit current at the panelboard; and
I_{mag} is the magnetic trip current of the circuit breaker.

Using this formula, the Code Panel chose to accept a proposal for a listed outlet branch circuit type arc-fault circuit interrupter installed at the first outlet on the branch circuit where the branch circuit breaker instantaneous trip level did not exceed 300 A, and the maximum length of the home run from the breaker to the first outlet did not exceed 50 ft for a 14 AWG or 70 ft for a 12 AWG conductor. However, this calculation assumes that the available fault current at the service panel (I_{pssc}) is large, and the available current to the first receptacle in the circuit was primarily limited by the resistance of the home run cabling. This Report addresses the effect of limiting I_{pssc} to 500A, the origin of this value is discussed herein.

Available Fault Currents at Dwelling Unit Service Entrances

Installers are often interested in the available fault current at service entrances in order to properly coordinate overcurrent protection devices and protect the conductors and devices connected at that location. Of most interest to these installers would be the maximum available fault current, as required by Sections 110.9 and 110.10 of the NEC. The calculation of available fault current can be quite cumbersome and tedious, and consequently this calculation of available fault currents at dwelling units, especially of the one- and two-family type, is often not performed or not readily available. Local utilities may instead specify a maximum available fault current not to be exceeded at these dwelling unit services in order to help better serve the installer and the AHJ. One utility has noted a maximum value of fault current at 10 kA for individual dwelling units with services up to 200 A. 22 kA is another typical maximum value for multi-family units, or services greater than 200 A.[5] These values of 10 kA or 22 kA are often chosen to coordinate with standard interruption and withstand ratings of circuit breakers and panelboards typical for dwelling unit use.

Minimum values of available fault current are of less interest to installers, except when customer complaints of difficulty starting motors or dimming of lights are involved. Since available fault current is directly related to voltage drop, these issues can be interrelated when customer complaints must be resolved. From the standpoint of the available fault current at a dwelling unit service entrance, the following factors could all influence this maximum current value:

a) Available fault current at the utility transformer primary,
b) The impedance of the utility transformer,
c) The material, size, and length of the utility service drop or lateral,
d) The impedance of the utility revenue meter,
e) The material, size, and length of the service entrance conductors, and
f) All wire connections and splices in this circuit.

Extensive studies of available fault currents at dwelling unit services are minimal at best. In addition to the factors described above, differences in location, such as urban versus rural, single-family versus multi-family, number of customers being served from a transformer, and older versus newer dwelling units can also be of consequence. Utilities may also change equipment with usage and age, thus presenting new values from which newer calculations must be made.

A study from 1993 to evaluate branch-circuit circuit-breaker instantaneous tripping was conducted by UL.[6] This study involved a survey of the available fault current of 1,590 receptacle circuits in 80 single-family dwelling units across the U.S. The available fault current was estimated through measurements of the open circuit voltage, and the closed circuit voltage with a load current at each receptacle. The available fault current was then calculated as follows:

$$I_{SCC} = \frac{V_{OC} \cdot I}{V_{OC} - V_{SCC}}$$

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[5] Information received through the Edison Electric Institute from Baltimore Gas and Electric.

[6] “Fact-Finding Report on An Evaluation of Branch-Circuit Circuit-Breaker Instantaneous Trip Levels,” for Electronic Industries Association by Underwriters Laboratories Inc. File E87837, October 25, 1993.

where

I_{SCC} is the short circuit current
V_{OC} is the open circuit voltage
V_{SCC} is the closed circuit voltage, and
I is the load current

This study found that 15 A receptacle circuits had an average estimated available fault current of 300 A, and 20 A receptacle circuits had an average estimated available fault current of 467 A. No measurements were made at the service entrance of these residences as part of this study.

The raw data from this study was recently re-analyzed to examine the maximum available fault current at any receptacle at each of the residences. This receptacle was assumed to be the closest receptacle to the service entrance panel, but this still would be less than the actual available fault current directly at the service. The results showed the maximum fault current at this receptacle to be 1,947 A, and the minimum to be 358 A, with the median being 777 A. Figure 1 shows a histogram of this restudied data.

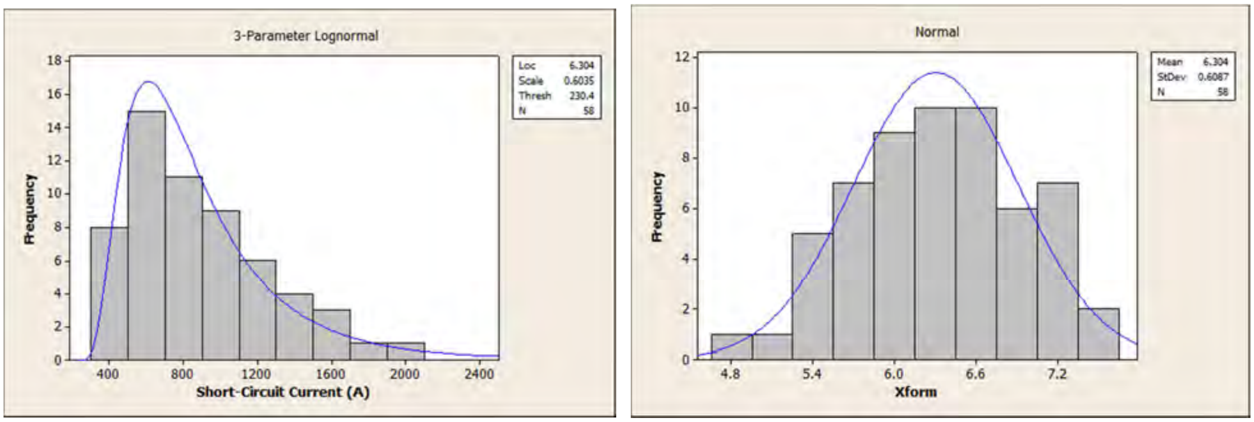

Figure 1. Histogram of maximum available fault currents, using data from Ref. 6. (*Left*) Data with lognormal fit. (*Right*) Data transformed to normal distribution for calculation of percentile values.

The results show that the distribution of the available current fits a lognormal distribution, with the majority of values less than 1,000A, but following a long tail towards larger currents. Using the following transformation of the data, the lognormal distribution can be converted to a normal distribution, which allows for more convenient calculation of mean and standard deviation values:

$$xform(I_{pssc}) = \ln(I_{pssc} - Thresh)$$

where *Thresh* is the “threshold” parameter from the three-parameter lognormal fit as shown in Figure 1 (*left*). The transformed distribution is shown in Figure 1 (*right*). Mean (50th percentile) and standard deviation-derived percentiles are shown in Table 1, calculated through the use of the inverse transform:

$$I_{pssc}(xform) = e^{xform} + Thresh$$

Table 1. Calculated percentiles for the distribution of available current from receptacles located near the panelboard, as shown in Figure 1.

Percentile	1	5	**~25**	50	68	95	99
Xform	4.736	5.111	**5.597**	6.304	6.913	7.497	7.872
I_{pssc} (A)	344	396	**500**	777	1235	2033	2853

The results show that though some available current values are less than 500A, using a lower bound of 500A available is expected to be a reasonable approximation for most residential panelboards for the 25th percentile, or that 75% of all panelboards exceed this value. The actual percentile however is expected to be much lower, as the values in Figure 1 are expected to be lower than the actual panelboard available current, since the vales were measured at a nearby receptacle and not at the panelboard itself.

Work was conducted in the 1990s by the Hydro-Québec Research Institute, IREQ, to evaluate the impedance of Canadian residential and industrial distribution systems.[7] Calculated impedance values were then compared to those determined from 70 sites where experimental measurements were made. This study concluded that for the case of the 120/240 V residential distribution system, the phase to neutral impedance, as seen from the panelboard (service entrance), would be $0.19 + j0.062\ \Omega$. At 120 V, this would equate to an available short-circuit current of about 600 A.

The results from the receptacle study and the IREQ both suggest that assuming a minimum available short-circuit current of 500A at the residential panelboard should be representative of a “worst-case” condition. It is noted however that utility data is not readily available and that utility impedances could change over time without notification. Some installations, particularly in cases of a sub-panel or very

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[7] A. Oury, R. Bergeron, A. LaPerriere, Source Impedances of the Canadian Distribution Systems, Institut de Recherche d’Hydro-Quebec, CIRED 97, 2-5 June 1997, Conference Publication No. 438, IEE.

remote, rural installations, may have much lower available fault current. However, in most typical residential installations, based on what data are available the 500A estimate for minimum short-circuit current appears to have supporting evidence for it. The experimental work described herein therefore uses this value for available short-circuit at the panelboard.

Origin of the 50-Foot Home Run Length Specification

The 50-foot run length that is described in Section 210.12 (2) (c) proposed for the 2014 NEC reflects the example calculation that is discussed in Ref. 10. In this example, the magnetic trip level for circuit breakers are assumed not to exceed 300A, a value that was derived from a study in that report that calculated that value as the 99th percentile upper bound on all 15A residential circuit breakers in the field. This value was based on 32 off-the-shelf circuit breakers from four North American manufacturers. This experiment is revisited in Task 1, where 32 additional circuit breakers (using the same four manufacturers and models as before) are evaluated to determine whether the magnetic trip levels are stable over batches manufactured at different times.

The 50 foot value also was calculated using the assumption that the available fault current at the panelboard is arbitrarily large. At the time this assumption was made due to a lack of information on typical available fault currents at residential panelboards. This was noted in the previous work, and included in the proposed equation relating run length, but was not analyzed or studied further. However, there has been concern that real-world available panelboard currents are not well represented by this simplification, which would significantly reduce the allowable home run length if the other assumptions (namely, the magnetic trip level of the circuit breaker) are held the same. However, the 50-foot run length has already been included in Code proposals; therefore, in this work the focus is in evaluating the performance of circuit breakers with a constant 50-foot run length.

Technical Plan

The technical plan for this project is to conduct arc-fault testing in accordance with UL1699[8] with a listed circuit breaker in combination with a 50-foot NM cable used as a home run. An available fault current of 500A will be used at the line side of the circuit breaker to represent expected dwelling unit fault current. The following arc-fault detection tests from UL1699 will be used:

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[8] Underwriters Laboratories Inc., UL Standard for Safety for Arc-Fault Circuit-Interrupters, UL 1699.

a) Carbonized Path Arc Interruption Test, as described in Sec. 40.3. The fault current levels described in Sec. 40.3.3 will be as described below.
b) Point Contact Arc Test (guillotine) described in Sec. 40.5. The fault current levels described in Sec. 40.5.3 will be as described below.
c) The Carbonized Path Arc Interruption Test (Sec. 40.3) modified to condition the NM cable using the method similar to Sec. 40.4.2 (as opposed to Fig. 40.3).

The experimental work described in this work is part of a larger test plan, as described below. The results in this paper follow the results of Part I, as outlined below:

Part I

1. Part I of the technical plan will use circuit breakers from the four (4) different manufacturers. Eight (8) identical 15 A circuit breakers from each manufacturer will be purchased and characterized with respect to its magnetic trip level.
2. Initial testing will be conducted with a circuit of 500 A available fault current. 50 feet of No. 14 AWG NM cable will be added to the load side of the circuit breaker, and the arc-fault detection tests will be conducted. For each test it will noted if the breaker trips or does not trip, and if it does trip, does it trip within 8 half-cycles within ½ second. For any breaker that trips within 8 half-cycles within ½ second, the testing with that breaker will be considered complete for Part I.
3. Step 2 above will be repeated with the remaining breakers, but with 1000 A available fault current.

Part II

1. Part II of the test plan will use the same circuit breakers from Part I.
2. Initial testing will be conducted with a circuit of 500 A available fault current. 40 feet of No. 14 AWG NM cable will be added to the load side of the circuit breaker, and the arc-fault detection tests will be conducted. For each test it will noted if the breaker trips or does not trip, and if it does trip, does it trip within 8 half-cycles within ½ second. For any breaker that trips within 8 half-cycles within ½ second, the testing with that breaker will be considered complete for Part II.
3. Step 2 above will be repeated with the remaining breakers, but with 30 feet of No. 14 AWG NM cable added to the load side of the circuit breaker. This sequence of testing will then again be repeated with 15 feet of No. 14 AWG NM cable added to the load side of the circuit breaker.
4. After step 3, we will evaluate the need for additional tests at greater than 500A available currents.

Part III

1. Use receptacle AFCIs that are provided to UL.
2. Develop some scenarios with available fault currents, lengths of wire between the breaker and receptacle, and lengths of wire on the load side of the receptacle. Conduct arcing tests at the end of the receptacle load wire. Note tripping of the breaker and/or receptacle.
3. Note – the specifics of these Part III experiments will need to be further developed after the Part I and II testing are completed.

TECHNICAL REPORT

Terminology

The terminology used in the report is presented to facilitate clarity.

- **Half-cycle.** In this work, it is equivalent to 8.33 ms, or 1/120 seconds. It is defined as the time between subsequent zero-crossings of the voltage waveform (which has a fundamental frequency of 60 Hz). Each half-cycle is subdivided into 180 degrees of phase angle, corresponding to the arcsine of the voltage waveform, related to the time-varying voltage:

  $$v(\theta)=V_{rms}\sqrt{2}\cdot\sin(\theta)$$

  For this work, phase angles of $180^\circ < \theta < 360^\circ$ has been reverted to $0^\circ < \theta < 180^\circ$, since the arcing behavior has been found by experience to be identical regardless of sign. Therefore, the absolute value of current and voltage was used for all analysis. In this work, half-cycles are the basic time unit, and are referenced as integer values corresponding to the number of half-cycles past time zero (the time when measurement was initialized).
- **Iteration number.** This is an integer value corresponding to the order in which the measurement was made for a given identical set of test parameters. For example, the first sample measured is identified as test number 1, the second is numbered 2, etc.
- **Manufacturer.** This identifies the manufacturer of the circuit breakers and panels used for each test. Four manufacturers were selected, each are identified by a letter: A, B, C, or D.
- **Breaker Number.** This is the position where the circuit breaker was located in each panel. For each test, a different box was used per manufacturer. Identical breakers were used, with locations within the circuit breaker panel box denoted by the circuit breaker number. To distinguish from the circuit breakers used in the previous work, circuit breakers are numbered 9 through 16. Panel position can be determined by subtracting 8 from this number (*i.e.*, breaker 9 was in panel position 1, breaker 10 in panel position 2, etc.)
- **Short-Circuit Current (A).** Also denoted as I_{max}, this is the maximum available current during a given test (limited by the resistive load added to the test circuit). The value is specified in UL 1699 with a standard method for reducing the available current for a given test (either by use of a calibrated resistive load (“Type 1”) or through the use of long lengths of coiled NM-B cable (“Type 2”)), Figure 2. For this project, only “Type 2” arrangements were used, simulating a parallel arcing fault. If the hot conductor were shorted to neutral at the location of the sample, the amount of current flowing through the circuit would be equal to I_{max}.

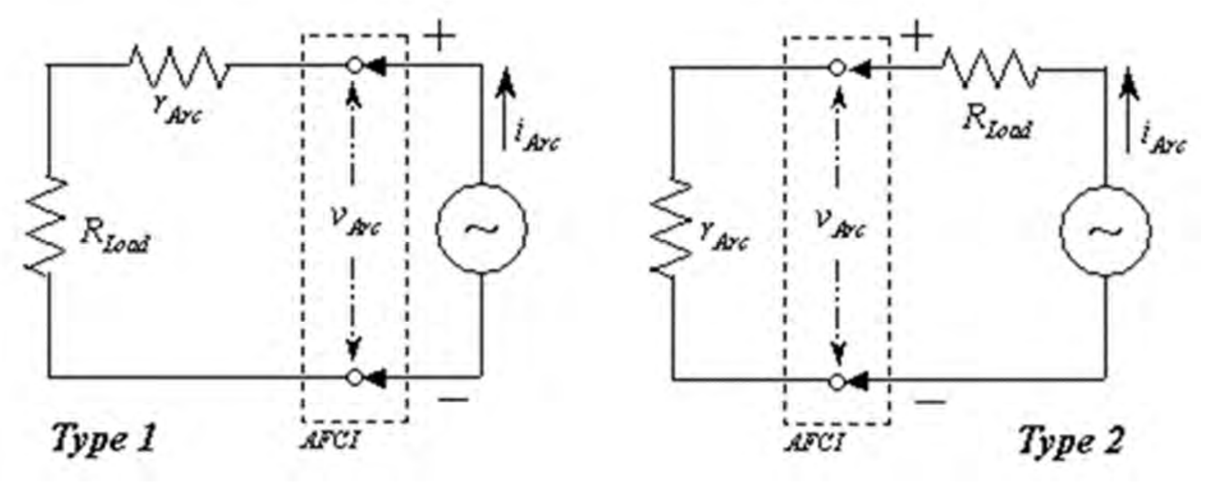

Figure 2. Two configurations of loads used in UL 1699, Section 40 tests. (*Left*) “Type 1”, used in Sections 40.2 and 40.4 for low-current testing. (*Right*) “Type 2”, used in Sections 40.3 and 40.5 for high-current testing.

Due to the large amount of data in each measurement (5 million data points in each of two waveforms for current and voltage), and the large number of iterations (more than 900), a convenient method of extracting a single numerical value per arcing half-cycle was required to allow for a reasonable analysis. This was achieved by the definition of several parameters for each arcing half-cycle which could be expressed as a single numerical value. For each arcing half-cycle, each of the following parameters were collected to characterize the arc (Figure 3):

- **Peak Current.** This is the maximum value (in magnitude) of the current waveform measured through the entire half-cycle.
- **Arc Strike Angle.** This is the phase value (in degrees) when the arc begins, typically characterized by a large change in current with respect to time (large *di*/*dt*). Detection was automated by finding the maximum value in the digitally filtered current waveform (Butterworth three-pole bandpass with $f_{3\mathrm{dB},min}$ = 10 kHz and $f_{3\mathrm{dB},max}$ = 100 kHz). The search was limited from zero phase angle to the phase angle corresponding to the peak current value. This technique leverages the large high-frequency component from the discontinuous change in current at the start of arcing.
- **Arc Stop Angle.** This is the phase value (in degrees) where the arc ends, characterized by a discontinuous drop towards zero current. Detection is similar to that used for identifying the arc strike angle, except search is between the phase angle of the peak current and 180 degrees. As with the strike angle, the detection software leverages the discontinuous change in current which manifests itself as a large spike in the digitally filtered current signal.

- **Arc Strike Voltage.** This is the magnitude of the voltage waveform at the moment of arc strike. This is found by first finding the arc strike angle, then finding the corresponding voltage at the same moment in time.
- **Arc Stop Voltage.** This is the magnitude of the voltage waveform at the moment of arc stop. This is found by first finding the arc stop angle, then finding the corresponding voltage at the same moment in time.

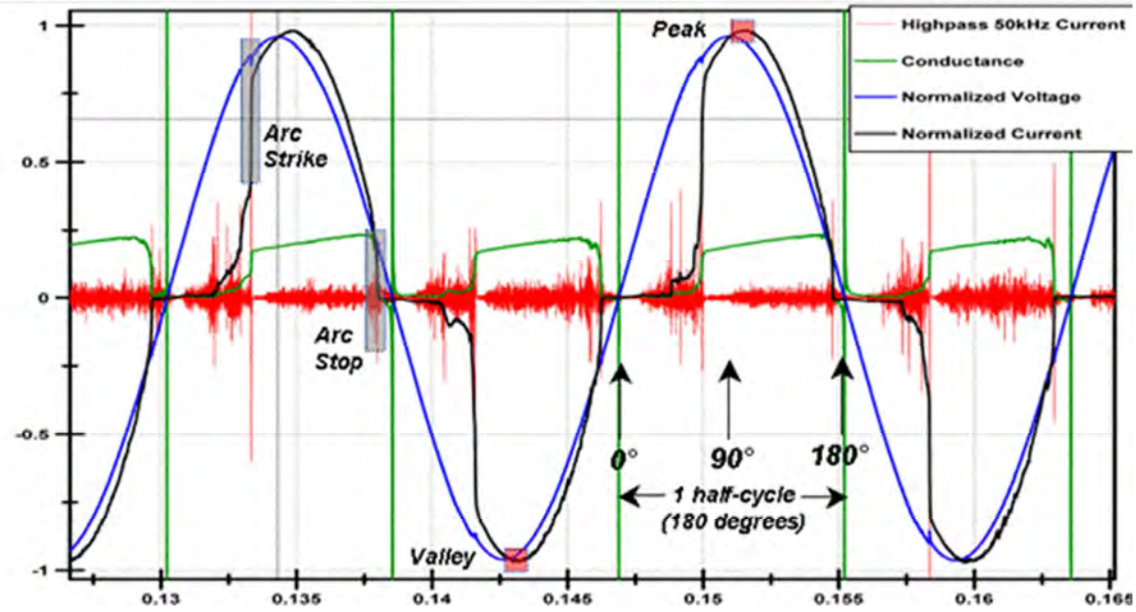

Figure 3. Current and voltage arcing waveforms, showing each arcing half-cycle.

Defining Arcing and Shorting Phenomenon

The peak current is defined in this study as the largest magnitude of current measured within each half-cycle of the waveform. These points were collected automatically using LabVIEW-based software and tabulated with corresponding variables, such as the half-cycle number, breaker manufacturer, age of circuit breaker, etc. To allow for a useful comparison of data from all tests, a normalized peak current was defined and calculated as:

$$\bar{I}_{peak} \equiv \frac{|I_{peak}|}{|I_{\max}|} = \frac{\sqrt{2}}{2} \cdot \frac{|I_{peak}|}{|I_{\max(rms)}|}$$

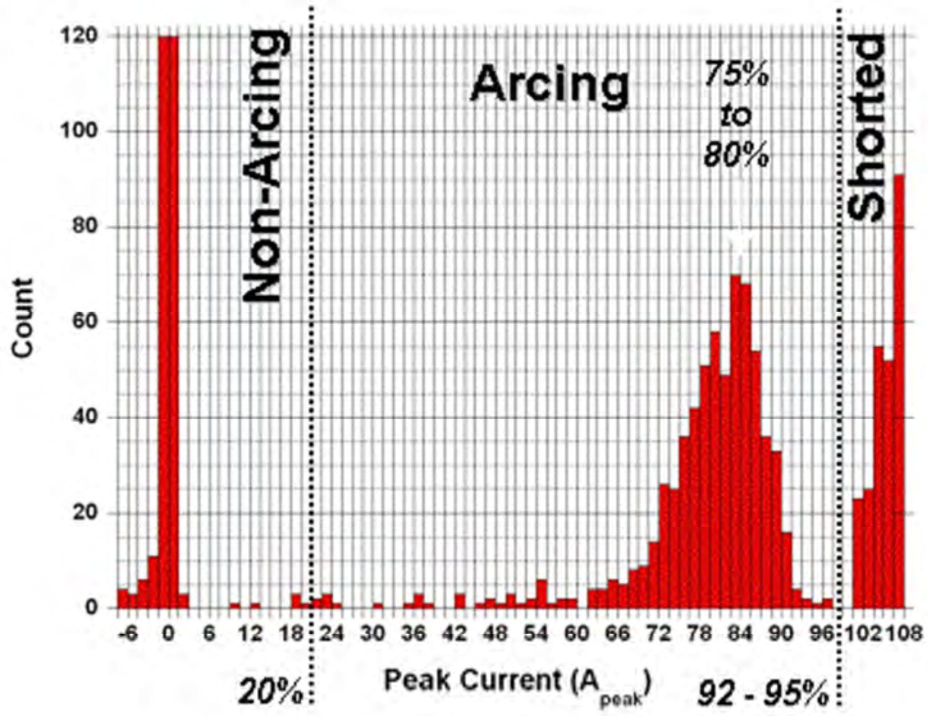

Figure 4. Representative probability distribution function for all peak current values from one series of tests, showing three modes of behavior: non-arcing (<20% I_{peak}), arcing (20% < I_{peak} < 92%-95%), and shorting (>92% to 95% I_{peak}).[4]

Three states of behavior were observed for peak current values: arcing behavior, non-arcing behavior, and shorted. Each of these three modes of behavior was segregated by defining two current thresholds relative to the short-circuit current I_{max} (Figure 4). A threshold of 20% I_{max} was defined as the minimum for arcing behavior. Selection of this value can be considered somewhat arbitrary, and does not follow what is defined in UL 1699 for minimum arcing (which is defined as 5% of I_{max} in the standard). However, a very low value for the threshold, such as 5%, often would be within the large number of insignificant events (very short-duration arcing, noise, etc.) and were not likely to contribute to the understanding of the arcing behavior. At 20% I_{max} a very small percentage of data points were typically found and was a convenient threshold for defining a threshold for arcing. As this was within a “long tail” of the probability distribution function, moving this threshold ±10% in either direction would have a negligible effect on the total number of points included and therefore not affect the analysis.

Test Samples

Circuit Breakers

Four models of conventional circuit breakers available commercially in the United States were selected for this investigation. These are identified in this report as A, B, C, and D. The circuit breakers were rated for 15A or 20A circuit current. For 15A breakers, two batches of circuit breakers were tested, the first batch were purchased and tested in 2011, the second batch was purchased and tested in 2012. Both batches were sourced off-the-shelf from local nationally known home improvement stores.

NM Cable

Commercially available NM cable was purchased for use in the parallel arcing tests. The NM had 14 AWG copper conductors (neutral, hot, and ground), and had a temperature rating of 90°C. The neutral and ground conductors were connected together, allowing parallel faults to occur between either hot and ground or hot and neutral. In nearly all cases, the arcing fault occurred between the hot and ground conductors.

Task 1 - Characterization of Circuit Breaker Trip Performance

The circuit breakers were characterized to determine the current levels at which magnetic tripping occurs, as well as the thermal trip time down to 75A. Each circuit breaker was subjected to symmetric short circuit fault currents until the circuit breaker cleared the fault in one half-cycle (which is defined as the instantaneous magnetic trip) to determine the instantaneous trip current. Eight circuit breakers of one model (referenced as breaker numbers 1 through 8) were assembled in a commercial electric panel for the characterization tests; and the tests were repeated for each of these eight breakers. To evaluate whether breakers of the same manufacturer and model number remain consistent over time, a second batch of eight circuit breakers (referenced here at breaker numbers 9 through 16) were purchased and evaluated one year later, using a new set of 15A circuit breakers with the same model number. New 20A circuit breakers from two manufacturers that use three different mechanism designs were also evaluated.

Test Procedure

A schematic of the test circuit used to develop the trip performance characteristics is shown in Figure 5. The test circuit is controlled using a closing phase angle switch. With this device, a controlled closing on the voltage waveform can be achieved. The use of controlled phase angle closing ensures that the applied voltage waveform always starts at zero degrees (at 0V immediately before the waveform swings towards positive values), so that each breaker sees the same waveform and that the number of half-cycles can be more accurately counted.

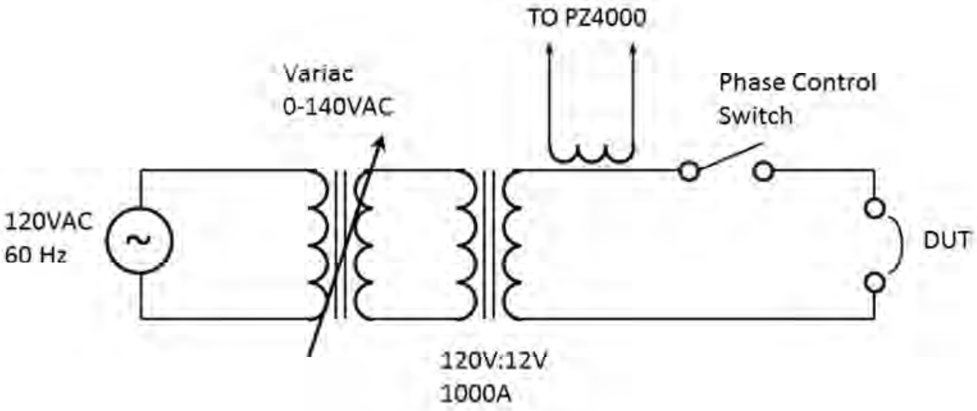

Figure 5. Circuit breaker instantaneous trip calibration test circuit

This switch and the circuit breaker under test were placed in series across a large buck-boost transformer (here, a 10:1 transformer with a secondary rated for 1000A). Control of the current was obtained through adjusting the voltage applied at the primary through a variable auto-transformer. The short-circuit current therefore was governed by changing the voltage across the internal impedance of the circuit breaker. The magnitude of the short-circuit current and the count of half-cycles were monitored through an instrument-grade current transformer connected to a Yokogawa Model PZ4000 digitizer.

Each breaker was tested at 75A, 100A, 150A, 200A, 300A, 400A, and 500A to evaluate the general response of the circuit breaker and to identify a general magnitude of the magnetic trip level. Additional tests were then conducted until the magnetic trip level was identified to the nearest 10A. The trip level was found when the minimum (rms) current required to trip the circuit breaker in one half-cycle was identified. A minimum of 30 minutes was allowed between successive trips to allow for cooling of the circuit breaker bimetal in the event that the previously applied fault current caused the circuit breaker to trip thermally.

Results

The measured magnetic trip level for each circuit breaker is shown in Table 2 and Table 3. Table 2 includes results for the first batch of circuit breakers, and Table 3 includes the measurements conducted one year later on different breakers of the same model number. Results are listed according to panel location (for the second batch of circuit breakers, circuit breaker 9 was located in position 1, breaker 10 in position 2, etc.). Three types of 20A breakers were tested for two of the manufacturers to determine whether other circuit breaker designs show a significant change in magnetic trip level. Type 1 denotes a common breaker model which is readily available in nationwide home improvement stores. Type 2 denotes a GFCI circuit breaker (the ground fault feature was not tested in this work, and the neutral lead was left open for these tests). Type 3 is a less common, specialty breaker differing in design from Type 1 circuit breakers.

Table 2. Magnetic trip level in Amperes at 25℃, breakers purchased in 2011.

			Circuit Breaker Number							
Manufacturer	Handle Rating (A)	Type	1	2	3	4	5	6	7	8
A	15	1	260	220	250	220	190	220	190	220
	20	1	260	300	290	220	260	290	240	200
		2	>500	450	500	500	>500	>500	500	340
		3	240	280	260	280	270	300	270	280
B	15	1	210	210	210	240	200	200	200	210
C	15	1	250	250	290	240	210	210	290	210
D	15	1	180	180	190	190	160	160	160	180
	20	1	190	170	160	160	160	160	190	170
		2	160	180	170	130	170	170	170	180
		3	130	150	160	120	160	130	130	170

Figure 6 shows the relationship of manufacturer, handle rating, and manufacturer to magnetic trip current.

It is observed that there is significant variation in the magnetic trip level for 20A breakers for Manufacturer A, with trip levels for Type 2 breakers being much larger than any other circuit breaker tested in this study (though not labeled as such, the magnetic trip values are more consistent with a “high mag” breaker). By contrast, 15A and 20A circuit breakers from Manufacturer D exhibit similar values. Among manufacturers, magnetic trip currents are similar for Manufacturers A, B, and C, and somewhat lower for Manufacturer D.

Figure 7 shows the distribution of the magnetic trip level for 15A, Type 1 circuit breakers from each of the four manufacturers. Table 4 shows the statistical significance of the influence of batch on magnetic trip level. The results show that Manufacturer C shows a large change in performance for circuit breakers of the same model number but different manufacturing date. The country of origin was the same for both batches. The effect of the batch on the data for Manufacturer B was only moderate, but had some influence. Manufacturers A and D showed no statistically significant change in magnetic trip level.

Table 3. Magnetic trip level in Amperes at 25℃, br eakers purchased in 2012.

			Circuit Breaker Number							
Manufacturer	Handle Rating (A)	Type	9	10	11	12	13	14	15	16
A	15	1	230	280	230	280	230	190	220	270
B	15	1	250	230	230	220	230	280	200	220
C	15	1	290	300	320	340	300	300	300	290
D	15	1	170	150	170	170	180	200	180	180

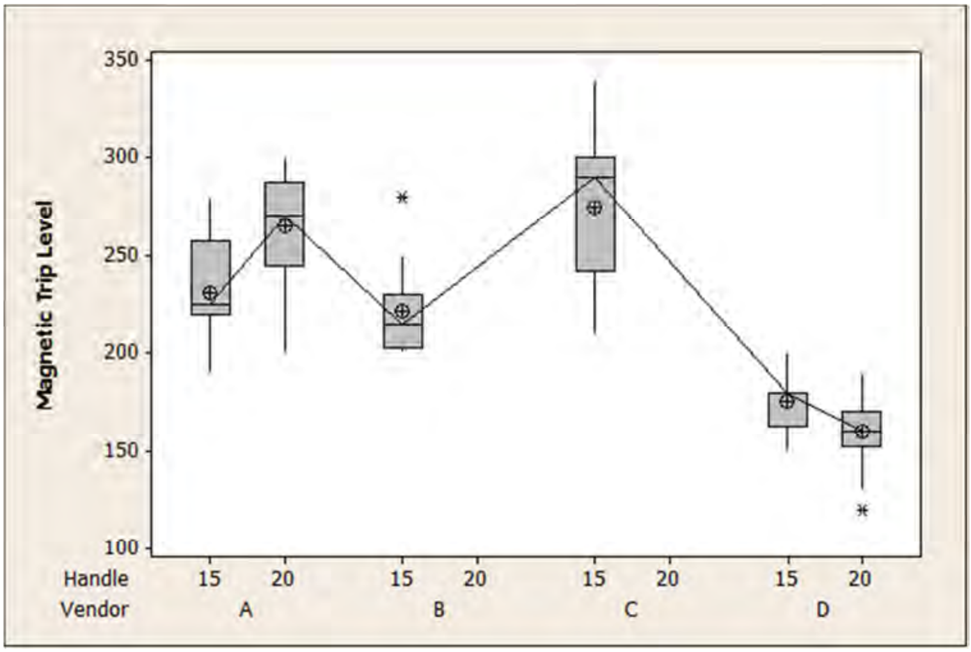

Figure 6. Boxplot showing relationship of manufacturer to magnetic trip current, including data from both batches of circuit breakers of all types (Manufacturer A, Type 2 breakers are eliminated since these were identified to be "high-mag" breakers). The shaded box contains the middle two quartiles of the data set, the horizontal line in the middle of the shaded box is the median value, the crosshair denotes the average value, and the vertical lines show the 95% confidence interval. Asterisks denote statistical outliers.

Analysis of Circuit Breaker Characteristics

The relative influence of each variable on the normalized current was analyzed using ANOVA, and evaluated according to the resulting adjusted R squared ($R_{sq}(adj)$) values.[9] The influence of each test variable on the magnetic trip level (in terms of the $R_{sq}(adj)$ values) is shown in Table 5. The $R_{sq}(adj)$ values give a quantitative view of how much a particular variable influences the data. For example, the $R_{sq}(adj)$ value characterizing the influence of the manufacturer (manufacturer) of each breaker on the measured magnetic trip level is 47%, meaning that approximately 47% of the variation in the magnetic trip data can be explained by using different brands of circuit breakers. Looking at the boxplot in Figure 6, it can be seen that breakers from Manufacturer D exhibit lower magnetic trip levels compared to the other

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[9] R_{sq} is the coefficient of determination, which measures the proportion of variation that is explained by the model. For example, if R_{sq} is equal to 100%, the variable explains 100% of the behavior. Conversely, an R_{sq} value of zero would indicate that the variable has no influence. $R_{sq}(adj)$ is a modified measure of R_{sq}, which takes into account the number of terms in the model and the number of data points. A more complete explanation of R values can be obtained in most works on Six Sigma or other statistical sources. For example, D. Picard (ed.), *The Black Belt Memory Jogger,* Six Sigma Academy, Salem, NH: GOAL/QPC, 2002, p. 173.

three manufacturers. The $R_{sq}(adj)$ value of 47% reflects this change in magnetic trip level. Turning now to the beaker number, which identifies the position the circuit breaker was located in the panel, the $R_{sq}(adj)$ value is 0%, which means that the breaker position had no statistical influence on the magnetic trip level. This suggests that circuit breaker position in the panel can be ignored during any further analysis of the magnetic trip level.

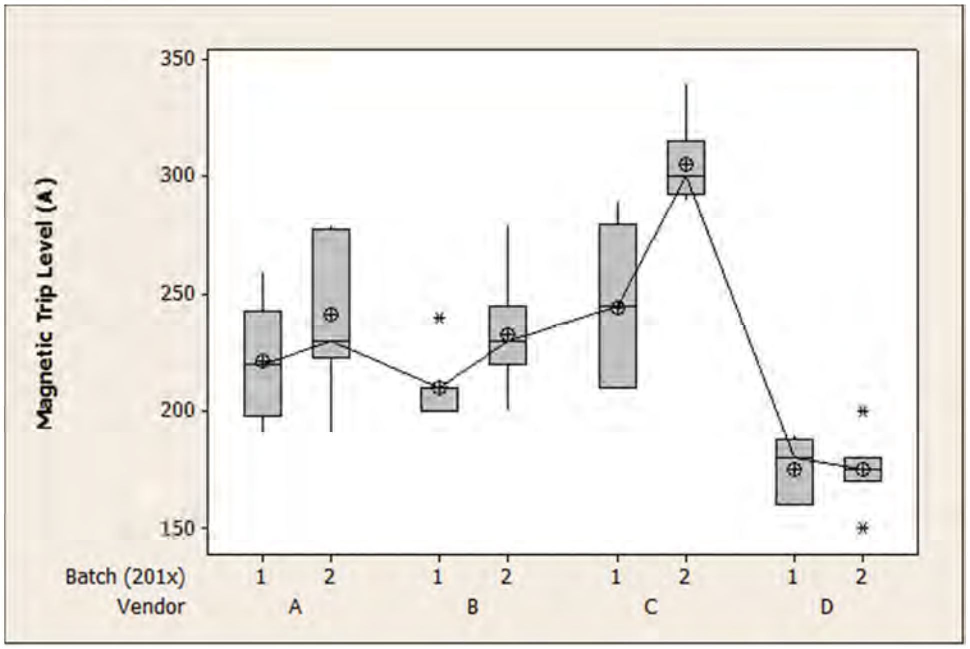

Figure 7. Batch-to-batch comparison for 15A, Type 1 breakers from each of the four manufacturers. Manufacturers A and D did not show a statistically significant variation, which Manufacturer C showed a significant change in magnetic trip level.

Table 4. Results of ANOVA analysis evaluating the influence of the batch number on the magnetic trip level, in order of statistical significance.

Manufacturer	**R_{sq}, %**	**$R_{sq}(adj)$, %**	***P***	***N***
C	60.52	57.70	0.000	16
B	28.22	23.10	0.034	16
A	12.14	5.87	0.186	16
D	0.00	0.00	1.000	16

Table 5. Goodness-of-fit (*R* squared values from ANOVA) for identified independent variables influencing the magnetic trip level for each characterized breaker current level. *N* is number of data points used in each calculation of the *R* values. *P*-values are also given for each variable.

Variable	R-Sq (%)	R-Sq (adj) (%)	P	N
Manufacturer	48.82	46.72	0.000	77
Handle Rating (All)	1.26	0.00	0.331	77
Handle Rating (Manufacturer A, Type 1)	28.42	23.31	0.033	16
Handle Rating (Manufacturer D, Type 1)	4.00	0.00	0.458	16
Breaker Number	4.53	0.00	0.855	77

Evaluating the effect of handle rating (in other words, comparing the difference in circuit breakers rated 15A to those rated 20A) is a bit complex, since the effect of handle rating can be masked by other factors. The analysis for Manufacturer A shows that there is an influence of handle rating on the magnetic trip level, even among the same breaker type. However, Manufacturer D shows zero statistical difference between 15A and 20A circuit breakers of the same type. Interestingly, no statistical difference is found among 15A and 20A circuit breakers if all data are analyzed together.

Figure 8 shows the histograms for 15A and 20A magnetic trip data for all manufacturers for the first batch of circuit breakers. The 15A data was found to be normally distributed but the 20A data showed a more bi-modal distribution. Figure 9 shows the distribution of the magnetic trip level for both batches of 15A circuit breakers. These data were observed to show a slightly better fit to a lognormal distribution (Figure 9, *right*), rather than a normal distribution (Figure 9, *left*). However, there was insufficient data to determine which distribution should be used.

Table 6 shows the mean, standard deviation, and 95% and 99% confidence intervals for 15A and 20A magnetic trip level data. The 15A data are also shown for batch 1 data only, as well as normal and lognormal fits for the combined batch 1 and 2 data. The results show that the 99th percentile can vary considerably depending on the batch of circuit breakers, as well as the type of distribution fit used. A prior analysis using the first batch of 15A circuit breakers only resulted in a 99% upper confidence interval of 299A, while adding data from batch 2 increases this 99% confidence interval to 342A or 394A, depending on the distribution used. It is interesting to note that this increase in the 99% confidence interval due to the second batch data is almost exclusively due to the change in performance from Manufacturer C. If batch 2 data from Manufacturer C is removed from the analysis, the 99% confidence interval falls to 305A, assuming a normal distribution. At this time it is not clear whether a design change was instituted with Manufacturer C, whether a different design type was unknowingly acquired, or whether this range of variability is expected for breakers from Manufacturer C.

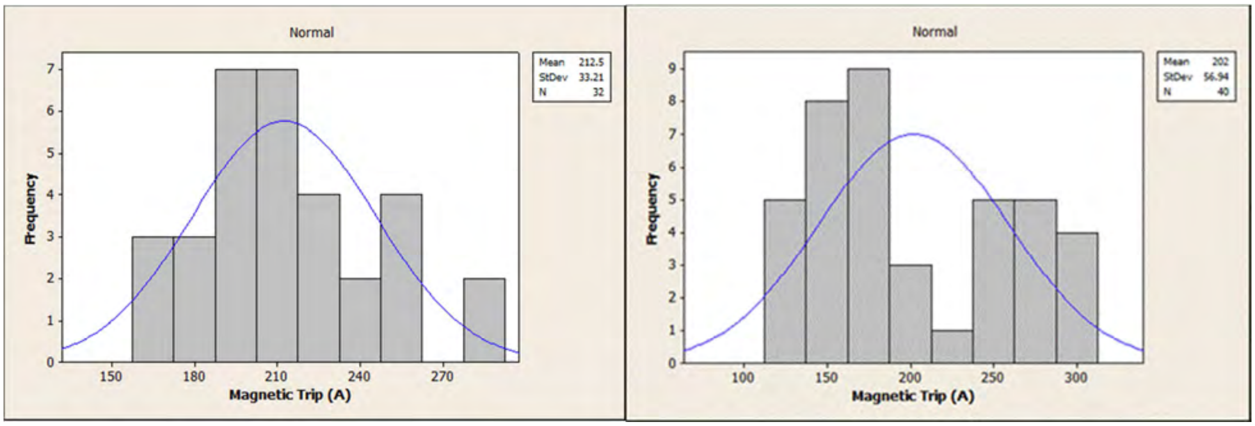

Figure 8. Histogram of the magnetic trip level for all “new” breakers at 25℃. (*Left*) 15A data only, (*Right*) 20A only.

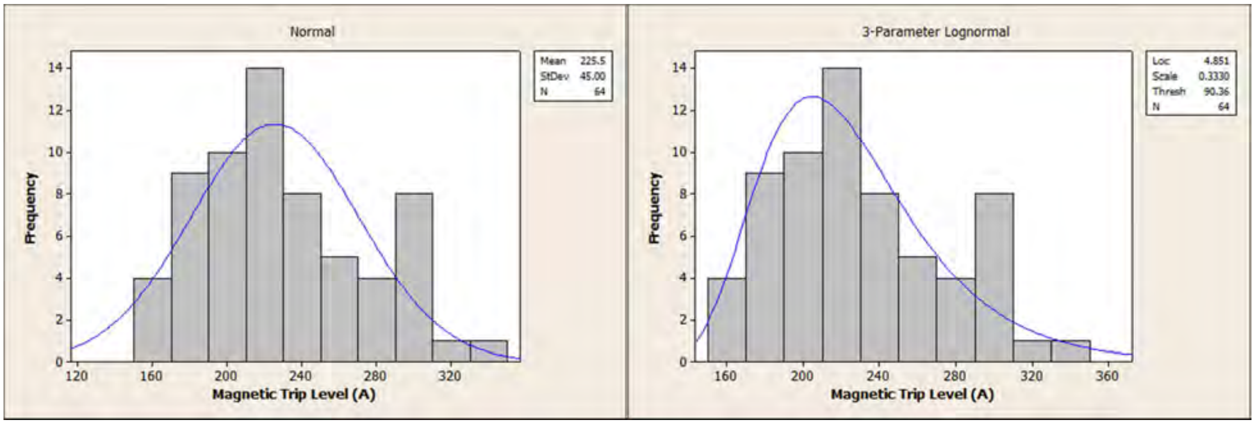

Figure 9. Histogram of the magnetic trip level for all 15A circuit breakers, both batches. (*Left*) Data shown with normal distribution fit. (*Right*) Data shown with lognormal distribution fit.

Table 6. Statistical information from curve fits (Figure 8 and Figure 9) of 15- and 20-Ampere magnetic trip data.

Handle Rating (A)	Mean (A)	Standard Deviation (A)	95% C.I. (A)	99% C.I. (A)
15 (Batch 1 only)	213	33.2	278	299
15 (Normal)	226	45.0	314	342
15 (Lognormal)	218	N/A	337	394
20	202	56.9	314	349

Findings from Task 1

The following findings can be summarized from the breaker magnetic trip data:

- An earlier study of the magnetic trip level for circuit breakers showed that the upper 99% confidence interval for 15A breakers was 299A, with magnetic trip levels being similar for Manufacturers A, B, and C, and Manufacturer D data showing somewhat lower values. A second batch of circuit breakers of the same model type as batch 1 was characterized, and showed a significant difference for circuit breakers from Manufacturer C.
- The inclusion of Manufacturer C, batch 2 data increases the 99% confidence interval to 342A or 394A, depending on the probability distribution used. If the Manufacturer C data are excluded this 99% confidence interval is similar to the earlier finding (305A).
- Batch-to-batch variation was moderate for Manufacturer B, and showed no statistical significance for Manufacturers A and D.
- The results show that though magnetic trip levels may be rather consistent in most cases, batch or design changes could cause significant shifts in the 99% confidence interval.

Task 2 - Parallel Arc Fault Tests: 500A Available, 50 Foot Home Run

In this Task, circuit breakers that have been characterized in the previous Task are placed into a simulated “home run” environment that has an arcing fault present. The primary goal of this Task is to evaluate the performance of 15A residential circuit breakers in mitigating a parallel fault at the end of a home run, simulating a parallel arcing occurring in proximity to the line terminal of a receptacle-located AFCI. For these tests, the available fault current at the panelboard was limited to 500A, the origins of this value being discussed previously in this work. The home run length is set at 50 feet, also discussed previously.

As was discussed in a prior study,[10] the current at the panelboard and the run length govern the expected fault current at the parallel arcing fault, determined by the following equation:

$$\rho_L L < \frac{V_{rms}}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{I_{pssc}}\right)$$

where

ρ_L is the resistance per linear foot of the NM cable gauge being used;
L is the length of the "home run" in feet;
V_{rms} is the supply voltage (typically 120 V_{rms});
I_{pssc} is the short-circuit current at the panelboard; and
I_{mag} is the magnetic trip current of the circuit breaker.

In this Task, L is set to be 50 feet, V_{rms} is 120V, and I_{pssc} = 500A. The resistivity of the copper conductor is dependent on temperature. In this work, the cable temperature is maintained below 30℃, and typically at 25℃. This suggests a value for ρ_L of 2.525 mΩ/ft. Using these assumed values, a minimum value for I_{mag} can be calculated:

$$(0.002525)(50) < \frac{120}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{500}\right)$$

$$I_{mag} < 195 \text{ A}$$

This result therefore suggests that circuit breakers will magnetically trip (defined here as within one half-cycle) if the magnetic trip level of the breaker is 195 A or less. Upon review of Table 3, circuit breakers from Manufacturer D are expected to magnetically trip during testing. Though the other circuit breakers have magnetic trip levels above 195 A, it is not clear whether these will trip within the eight half-cycles specified in UL 1699 for AFCI performance under high-current parallel (>75 A) arcing conditions. The experimental results described herein therefore are conducted to address the question of achieving circuit breaker tripping within eight half-cycles in a system with 500 A available at the panelboard and a home run length of 50 feet of 14 AWG NM cable.

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[10] P. Brazis and F. He, "Effectiveness of Circuit Breakers in Mitigating Parallel Arcing Faults in the Home Run," UL Corporate Research Report, January 2012.

Test Procedures

Arcing Methods

In an earlier study a single arcing method was used for generating arcing tests. This method was based on a sample preparation method described in UL 1699, Section 40.4, but using NM cable instead of SPT-2 appliance cable.[11] Statistical justification of this can be found in a 2009 study by UL,[12] where the four arcing methods found in UL 1699, Section 40 were studied, along with evaluation of the influence of carbonized path and guillotine (*i.e.*, point contact arc testing as described in UL 1699, Section 40.5) on circuit breaker performance as described in Ref. 10. The conclusion of this analysis was that the difference in arcing behavior among these methods was not expected to result in a change in circuit breaker performance; therefore, only one method of arcing was utilized. This study strives to test that assumption experimentally, using arcing methods as described in UL 1699, Sections 40.3, 40.4, and 40.5. The methods used for each are briefly described here.

Developing a Carbonized Path in NM Cable, Section 40.3 Method

The testing described in UL 1699, Section 40.3 utilizes a test box which alternates high (7 kV) and line (120V_{rms}) voltage to a test sample using a relay-based circuit. Application of the high voltage (but high impedance) causes dielectric breakdown across a prepared sample, with the arcing event occurring during the low-impedance, line-voltage cycle. Samples are prepared by taking a length of NM cable and creating a transverse cut through the cable jacket and both insulated conductors of the cable. The metal conductor is not damaged during this process. The cut is then covered in two layers of black electrical tape, which in turn is covered with two layers of fiberglass tape. The sample is then installed into the text fixture, and the high/low voltage cycle is initiated. The cycling continues until an arcing event occurs during the line-voltage cycle. Typically several cycles are required before arcing occurs.

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[11] "UL Standard for Safety for Arc-Fault Circuit-Interrupters," UL 1699, April 2006, Section 40.4, p. 40.

[12] P.W. Brazis et al., "Synthetic Arc Generator for UL1699, Phase 2: Statistical Characterization of Arc Fault Behavior," *UL Internal Report*, 2009.

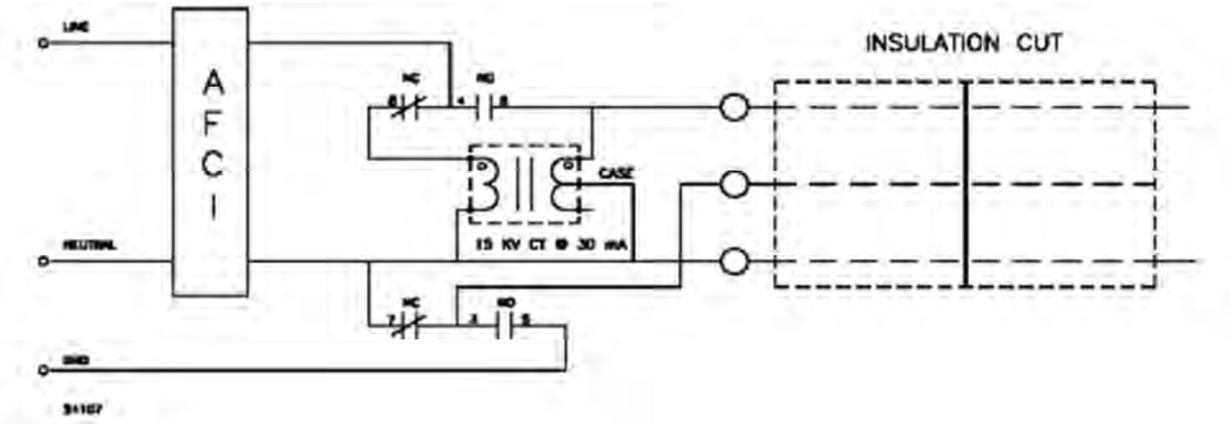

Figure 10. Carbonized path arc interruption test apparatus, as specified in UL 1699, Section 40.3.

For this test, the operation of the test box is modified to enhance the isolation between the high voltage transformer and the waveform characterization equipment. The equipment cannot tolerate voltages exceeding $42V_{peak}$; therefore, the isolation is necessary to prevent equipment damage. Timing of the relay closures are controlled with a programmable logic controller (PLC), with one-second pauses between relay openings/closures to ensure that one relay transition is completed before the next begins. The modified test box test cycle is as follows:

- Wait 100 ms
- Close the relay to energize the high-voltage transformer
- Wait 9900 ms (Expose sample to high-voltage to create carbonized path)
- Open the relay to the high-voltage transformer
- Wait 200 ms
- Close the voltage sense isolation relay
- Wait 200 ms
- Close the line-voltage relay
- Wait 9600 ms (Expose sample to line voltage, monitor for arcing event)
- Open the line-voltage relay
- Wait 200 ms
- Open the voltage sense isolation relay
- Cycle repeats

Developing a Carbonized Path in NM Cable, Section 40.4 Method

To facilitate arcing in a consistent manner, lengths of NM cable were prepared to have a carbonized path across the conductors using the method that follows the procedure in UL 1699 - *Standard for Arc-Fault Circuit-Interrupters*, Section 40.4 and briefly described herein. A transverse cut is made across the midpoint of the NM test specimen to penetrate the outer sheath and the insulations on both conductors, without damaging the copper conductor. This cut is then wrapped with two layers of electrical grade PVC tape and wrapped with two layers of fiberglass tape. A high voltage is then applied from a transformer capable of providing 30 mA short circuit current and an open circuit voltage at least 7 kV. After approximately 10 seconds, the cable specimen is disconnected and then connected to a second transformer capable of providing 300 mA short circuit current at a voltage of at least 2 kV. After one minute of energization, the cable specimen is removed and placed in the test circuit. The carbonized path is considered complete if a 100 W incandescent lamp in series with the path draws 0.3 A, or can start to glow at 120 V. This method is intended for SPT-2 appliance cable but has been found to provide consistent carbonized path for NM cables also.[12] Though the same sample preparation method for Section 40.4 series fault testing is being used, a high-current parallel fault is being established during the breaker testing.

The Point Contact Test, Section 40.5 Method

In addition to the two carbonized path tests, point-contact arcing was also conducted using a guillotine-like apparatus. The guillotine blade makes contact with one conductor by slicing through one conductor at an angle, then forms a point contact with the other conductor as the blade is slowly pushed through the cable. An arcing event occurs at this point contact.

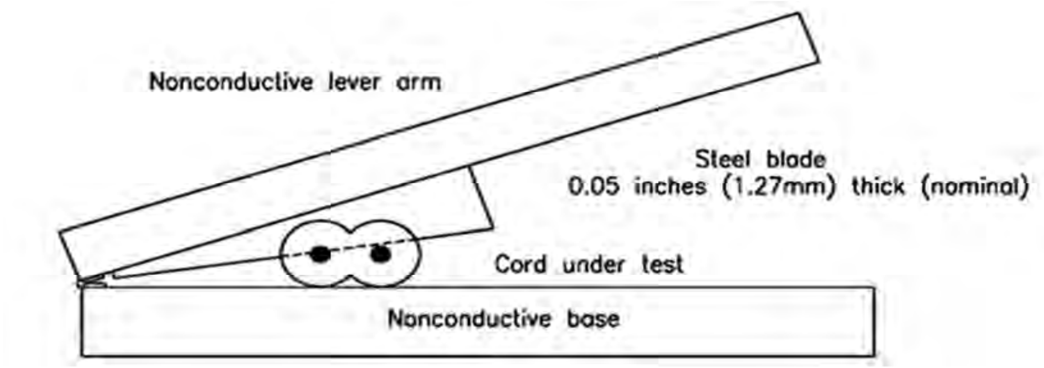

Figure 11. Point contact test apparatus (“guillotine”), as specified in UL 1699, Section 40.5.

Test Arrangement

The test arrangement included a residential circuit breaker (with a known magnetic trip level) mounted in a commercially available panel manufactured by the same manufacturer as the circuit breaker (Figure 12), with the hot connection of each breaker tied to the neutral ground bar inside the circuit breaker panel (the neutral connection for the test circuit was connected directly to the arcing test sample and not through the panel). This enabled each series of circuit breakers to be tested without reconfiguring the panel, by switching the circuit breaker under test to the “on” position and leaving the other breakers in the “off” position. The available current was adjusted through adjusting the wire length between the laboratory test power supply and the panelboard to provide the necessary impedance to control the available current at the penalboard. This available current was characterized through attaching several known resistances at the panelboard with all breakers open, and measuring both current flow and voltage drop. These values then enabled calculation of the short-circuit current at the panelboard. The impedance was adjusted until a short circuit current of 500A ±10% was measured. Available current at the test bench for all tests was in excess of 1000 A.

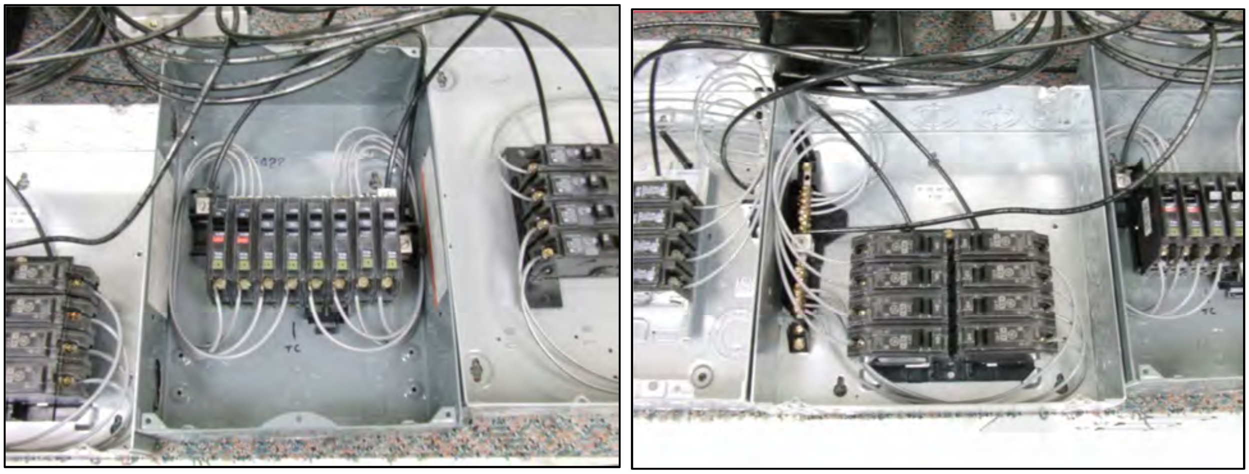

Figure 12. Representative photos of the circuit breakers under test mounted into commercially available electric panels.

The home run was simulated with an unbroken run of 50 feet of NM cable from the panelboard to the sample mount. Small adjustments in the run length were made to accommodate connector resistances and the length of the test sample: the impedance of the home run was measured using a 4-probe (Kelvin) multimeter with the test sample shorted at one end. The NM cable samples were contained within a grounded metallic enclosure to reduce electrical noise from the environment and contain smoke from the test. The temperature of the cables was monitored to minimize changes of cable impedance due to Joule heating during testing. Testing was conducted only if the cable temperature was between 20℃ to 30℃, with testing suspended to wait for the cabling to cool back into this range. The cable temperature was recorded prior to each arcing test, and is shown in Figure 13.

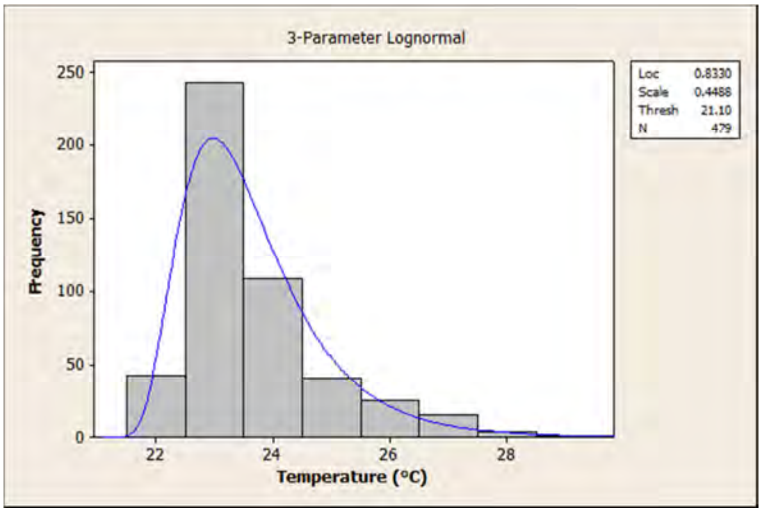

Figure 13. Distribution of cable temperature for all arcing tests, which was specified to be maintained between 20℃ and 30℃.

Parallel Fault Arc Test Procedure

The circuit breaker under test was placed in the “on” position, and power was applied by switching the test bench circuit breaker ‘on’. The bench circuit breaker had a higher handle rating than the breakers under test (20A versus 15A for the test breakers), and was of the “high-mag” type, where the magnetic trip level of the breaker exceeds 500A. In the rare occurrence when the bench breaker tripped, the results from that iteration were not used and the test was repeated. The data acquisition was pre-set to acquire data when 1A current was achieved in the circuit (indicating current flow across the carbonized path). The data were then collected for 0.5 seconds after this trigger event, and 0.025 seconds before the trigger (for purposes of adjusting for zero offset during data analysis). The sample rate was 10 MS/s with a sample resolution of 18 bits. Though some arcing events went longer than the 0.5 second duration, failure was considered to be more than eight arcing half cycles in 0.5 seconds, so arcing event exceeding the recorded timeframe failed UL 1699 criteria. The test data were saved in the National Instruments TDMS format for analysis.

Data Analysis

Analysis of the Parallel Arc Fault Data

The parallel arc fault data were statistically analyzed to determine the influence of the selected variables. The test data were analyzed using automated LabVIEW software which automatically extracted parameters for each arcing and shorting half-cycle and for each test. Each NM cable sample was also visually inspected to determine whether ignition had occurred during the test. Tripping of the circuit breaker was detected though automated inspection of the voltage signal, with breaker trip detection noted when the supply voltage drops below 6 V_{rms} (5% of normal line voltage).

Assessment of Circuit Breaker Performance per UL 1699

As has been mentioned previously, the ability of a circuit breaker to mitigate an arc fault is being evaluated according to the UL 1699 criterion, which requires that an arc fault protection device mitigate the arcing event to eight or less arcing half-cycles over 0.5 seconds. Therefore, a circuit breaker is considered to “pass” if eight or fewer arcing half-cycles are counted for a given arcing test. However, some arcing tests may result in fewer than eight arcing half-cycles without the circuit breaker tripping. Though this technically fulfills the eight half-cycle criterion, it does not evaluate the effectiveness of the circuit breaker. Therefore, the UL 1699 pass/fail criterion needs to be evaluated along with whether the circuit breaker tripped, as is shown in Table 7.

Table 7. Assessment of pass/fail criterion with respect to whether the circuit breaker trips during the test.

		Trip?	
		Yes	**No**
<8 Arcing Half-Cycles?	**Yes**	**PASS.** The circuit breaker mitigated the arcing event by tripping in less than 8 half-cycles.	**INCONCLUSIVE.** Arcing event stopped before circuit breaker could react. Does not evaluate breaker effectiveness.
	No	**FAIL.** The circuit breaker tripped, but not in sufficient time.	**FAIL.** The circuit breaker failed to react to the arcing event, which lasted longer than eight arcing half-cycles.

Though there are four categories of test behavior as described in Table 7, as can be seen in Table 8 and Figure 14 (*left*), there are very few occasions where the circuit breaker tripped, but failed to mitigate the arcing event in less than eight half-cycles. Therefore, further analysis can focus on only three states, circuit breakers tripping in less than eight half-cycles, and the two states where circuit breakers fail to trip and there are either more or less than eight half-cycles of arcing recorded. Eliminating the inconclusive data results in data that can be assessed as either "pass" or "fail", as shown in Figure 14, (*right*).

Table 8. Results from all arcing tests, count of each type of outcome.

Trip?	**Pass/Fail?**	**Number of Occurrences, by arcing method**				**Status**
		40.3	**40.4**	**40.5**	**Total**	
No	Pass	80	23	47	150	Inconclusive
Yes	Pass	59	73	50	182	Pass
No	Fail	21	64	60	145	Fail
Yes	Fail	0	0	3	3	Fail (rare case)

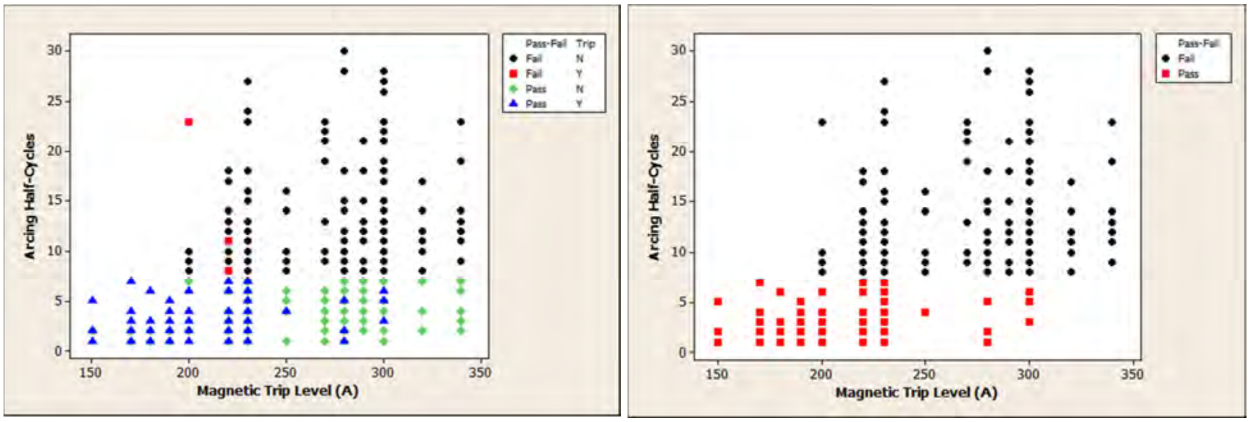

Figure 14. Scatter plots showing circuit breaker performance for all arcing tests, based on number of arcing half-cycles. (*Left*) Data coded by the four criteria as described in Table 7. (*Right*) Data marked pass/fail only, with inconclusive data (less than eight arcing half-cycles but no trip) removed.

Influence of Test Variables on Arcing Data

Since the primary goal of this work is to determine the ability of a circuit breaker to mitigate parallel arcing, and since this ability is measured against the eight half-cycle criterion per the AFCI standard UL 1699, it is of interest here to evaluate the influence of test variables on the number of arcing cycles measured.

ANOVA is used in this work to evaluate the influence of each test variable on the number of arcing half-cycles measured. Table 9 shows the results of the ANOVA analysis. Since it has been shown that arcing events that contain less than eight half-cycles yet do not trip the circuit breaker do not give any information about circuit breaker performance, these data need to be eliminated from the ANOVA analysis. The revised analysis with “inconclusive” data eliminated (as defined in Table 7) is shown in Table 10. It is seen that this second analysis shows a much stronger correlation of some test variables to arcing event length.

The analysis in Table 10 shows that whether the circuit breaker tripped has the largest effect on the number of arcing half-cycles, which reflects the fact that tripping the circuit breaker stops the arcing event before it is able to self-extinguish, having the overall effect of reducing the total arc event length. The magnetic trip level also shows the expected effect on arc event length, as the magnetic trip level of the circuit breaker influences the speed of trip response, with tripping expected to occur within one arcing half-cycle when the magnetic trip level of the breaker is below 195A, the threshold value previously calculated for the test circuit analyzed here. Manufacturer also shows an effect on the number of arcing half-cycles, which can be explained from a review of Table 3, which shows that the magnetic trip level of circuit breakers from Manufacturer D are lower than the other circuit breakers. As magnetic trip level has been shown to affect the number of arcing half-cycles, this fact implies that the circuit breaker manufacturer will also show an influence.

Table 9. Results of ANOVA analysis of the influence of test variables on the number of arcing half-cycles for each test.

Variable	R_{sq}, %	$R_{sq}(adj)$, %	P	N
Breaker Trip	22.87	22.71	0.000	480
Mag Trip Level	23.09	20.94	0.000	480
Manufacturer	20.95	20.45	0.000	480
Cable Temperature	20.36	19.18	0.000	479
Arcing Method*	9.87	9.49	0.000	480
Iteration Number	0.22	0.00	0.906	480
Breaker Position	0.35	0.00	0.977	480

*Arcing method denotes the influence on arcing half-cycles using different test methods per UL 1699: carbonized path tests as described in Sections 40.3 and 40.4, and point contact test as described in Section 40.5.

Table 10. Results of ANOVA analysis of the influence of test variables on the number of arcing half-cycles for each test, with arcing events less than eight half-cycles where the breaker did not trip (“inconclusive” results) eliminated.

Variable	R_{sq}, %	$R_{sq}(adj)$, %	P	N
Breaker Trip	66.61	66.50	0.000	330
Mag Trip Level	51.01	48.99	0.000	330
Manufacturer	42.57	42.04	0.000	330
Cable Temperature	28.31	26.75	0.000	329
Arcing Method*	8.83	8.28	0.000	330
Iteration Number	0.51	0.00	0.797	330
Breaker Position	0.66	0.00	0.951	330

The results suggest that the arcing method (either carbonized path method as well as the point contact method) have a minor statistical influence on the arcing behavior. To further investigate this effect, the data are shown in the boxplots in Figure 15. Though statistically with significance, it is noted that the difference between the methods is small from a practical standpoint. For instance, the median value for all three test methods that tripped the circuit breaker are identical (with a value of two half-cycles). The mean value varies by approximately one half-cycle among the methods (with the average value for the 40.3 method being 1.98 half-cycles and that for the 40.5 method being 3.02 half-cycles). For the tests that failed, the median value varies by only one half-cycle (11 to 12 half-cycles), and the mean varies by less than four half-cycles (10.5 to 14.3 half-cycles). In general, the arcing event length is longest for the point contact test (method 40.5), and shortest for the carbonized path method with test box (method 40.3).

For the instances where the circuit breaker fails to trip, the distribution of the arcing event length reflects the natural event length of the particular method used to generate arcing. In other words, the data show that a guillotine test will tend to create more arcing half-cycles than the other tests (if unimpeded by a circuit breaker, AFCI, or other means of mitigation). Conversely, the test box method tends to create shorter arcing event lengths (and gave the highest percentage of arcing events less than eight half-cycles). The far more interesting case is that where the circuit breaker tripped: here, the same pattern is observed, with guillotine giving the most arcing half-cycles and the test box the fewest.

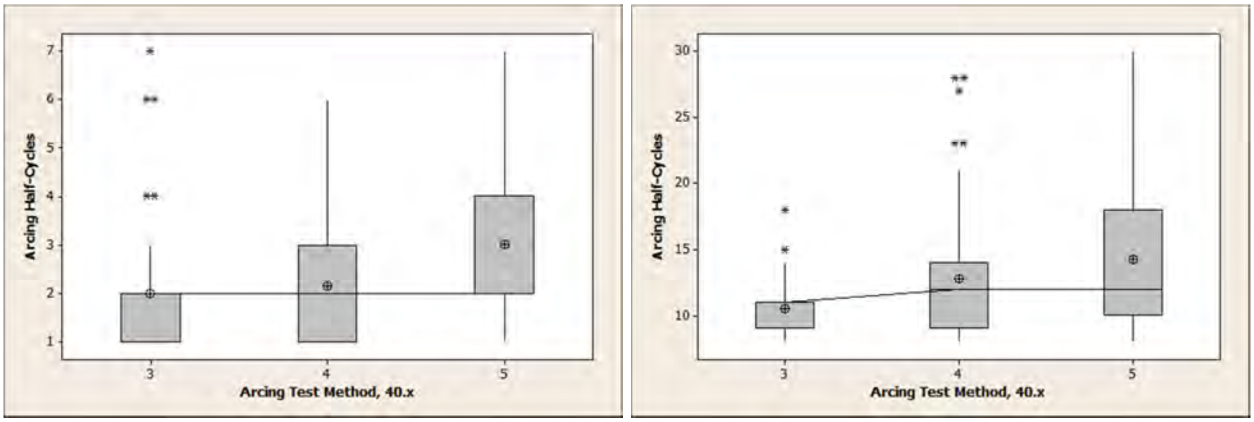

Figure 15. Boxplot of number of arcing half-cycles according to arcing method, with “inconclusive” test data excluded. (*Left*) Data for tests where circuit breakers tripped within eight arcing half cycles. (*Right*) Data where the circuit breaker failed to mitigate the arc per UL 1699 criterion.

The ANOVA analysis also suggests that cable temperature has an effect on the number of arcing half-cycles. This on the surface makes sense, since the cable temperature will affect cable impedance and therefore arcing current. However, it is noted that the cable temperature changes within 10℃, and therefore is not expected to have a significant influence on arcing performance. A boxplot of the relationship of cable temperature and number of arcing half-cycles (Figure 16) also does not show an obvious correlation of arcing performance to cable temperature.

The ANOVA analysis shows that the circuit breaker position and iteration number do not have a statistical effect on the arcing results. This therefore means that the arcing behavior is repeatable when using the same circuit breaker, as well as that performance is consistent among different circuit breakers from the same manufacturer and model number.

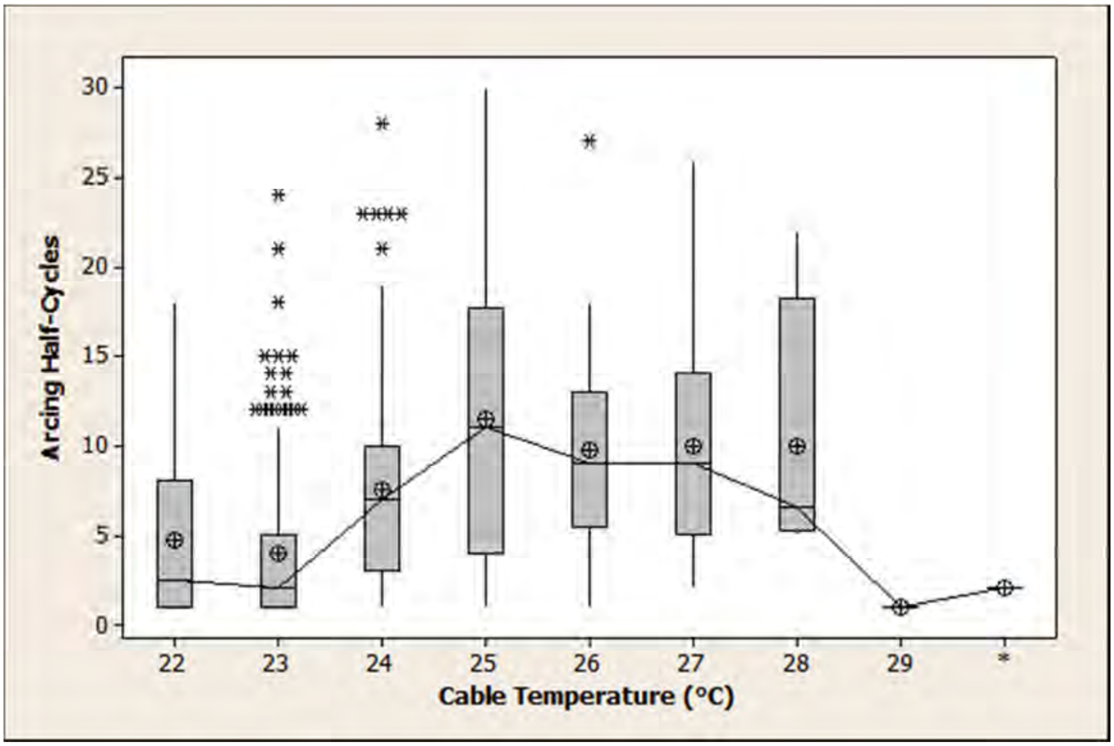

Figure 16. Boxplot showing the influence of cable temperature on the number of arcing half-cycles. The boxplot does not suggest an obvious correlation, as was suggested from the ANOVA results.

Task 3 - Parallel Arc Fault Tests: 1000A Available, 50 Foot Home Run

For Task 3, the same test procedures were used as described in Task 2, with the available fault current increased to 1000A at the panelboard. In this instance, the predicted magnetic trip level of the circuit breaker would change. Starting again with the following relationship:

$$\rho_L L < \frac{V_{rms}}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{I_{pssc}}\right)$$

In this Task, all variables are kept the same as in Task 2, except for I_{pssc} = 1000A. Using these assumed values, a minimum value for I_{mag} can now be calculated for the 1000A case:

$$(0.002525)(50) < \frac{120}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{1000}\right)$$

$$I_{mag} < 257\ \mathrm{A}$$

Therefore, it is expected for the system where there is 1000A available at the panelboard and a 50-foot home run length of 14 AWG NM cable, that circuit breakers will trip magnetically if the magnetic trip level of the circuit breaker is less than 257A.

Data Analysis

Influence of Test Variables on Arcing Data

As in Task 2, a statistical analysis was conducted to evaluate the effect of test variables on the number of arcing half-cycles measured. This analysis was conducted in the same manner as was done in Task 2. Table 11 shows the results of the ANOVA analysis. As before, the revised analysis with "inconclusive" data eliminated (as defined in Table 7) is shown in Table 12. Values are similar for the testing with1000A available at the panelboard as they were for the system with 500A available.

Table 11. Results of ANOVA analysis of the influence of test variables on the number of arcing half-cycles for each test.

Variable	R_{sq}, %	$R_{sq}(adj)$, %	*P*	*N*
Mag Trip Level	31.64	29.74	0.000	480
Breaker Trip	29.09	28.94	0.000	480
Manufacturer	25.52	25.05	0.000	480
Cable Temperature	16.35	15.29	0.000	480
Arcing Method*	8.73	8.35	0.000	480
Breaker Position	1.39	0.00	0.469	480
Iteration Number	0.49	0.00	0.670	480

*Arcing method denotes the influence on arcing half-cycles using different test methods per UL 1699: carbonized path tests as described in Sections 40.3 and 40.4, and point contact test as described in Section 40.5.

Table 12. Results of ANOVA analysis of the influence of test variables on the number of arcing half-cycles for each test, with arcing events less than eight half-cycles where the breaker did not trip ("inconclusive" results) eliminated.

Variable	R_{sq}, %	$R_{sq}(adj)$, %	P	N
Breaker Trip	71.14	71.06	0.000	372
Mag Trip Level	54.62	52.97	0.000	372
Manufacturer	45.67	45.23	0.000	372
Cable Temperature	23.73	22.48	0.000	372
Arcing Method*	10.40	9.92	0.000	372
Breaker Position	2.13	0.25	0.342	372
Iteration Number	0.42	0.00	0.819	372

Assessment of Circuit Breaker Performance per UL 1699

The same analysis methods were used in Task 3 as were used in Task 2. The arcing behavior for 1000A available current is summarized in Table 13 and Figure 17.

Table 13. Results from all arcing tests, count of each type of outcome.

Trip?	Pass/Fail?	Number of Occurrences, by arcing method				Status
		40.3	40.4	40.5	Total	
No	Pass	43	12	53	108	Inconclusive
Yes	Pass	110	109	73	292	Pass
No	Fail	6	38	32	76	Fail
Yes	Fail	1	1	2	4	Fail (rare case)

In the tests where 500A available fault current was used, it was predicted that circuit breakers with magnetic trip levels less than 195A would mitigate arcing to less than eight half-cycles. This was indeed observed, with all circuit breakers with magnetic trip levels at or below 190A successfully mitigating arcing to less than eight half-cycles. The 1000A results however show markedly different results, with a number of circuit breakers with magnetic trip levels below 257A failing to trip within eight half-cycles. To investigate this further, the arcing tests where circuit breakers failed to mitigate arcing within eight half-cycles is shown according to arcing type in Figure 18. Aside from two (potential) outliers, all failed tests from circuit breakers with magnetic trip levels below 257A were from guillotine (UL1699, Section 40.5) tests.

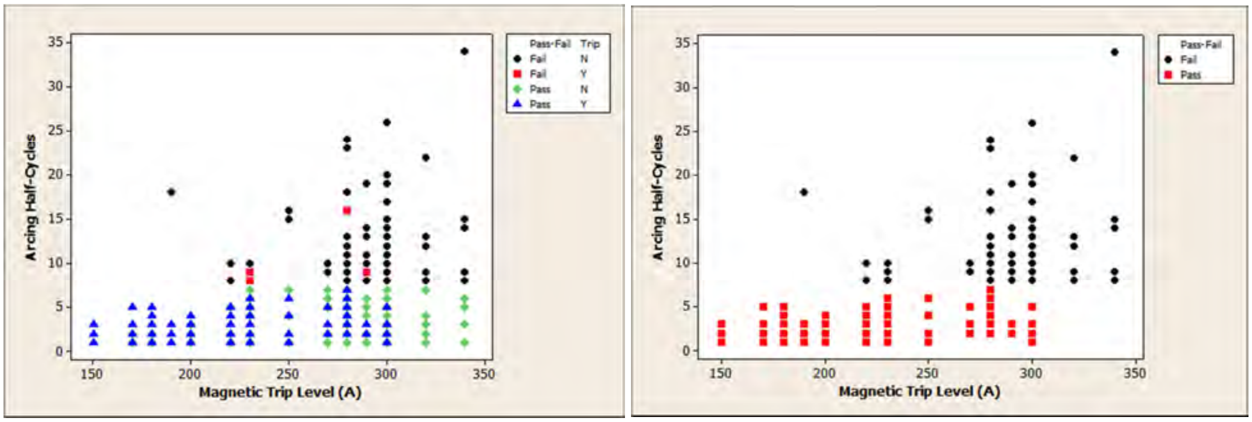

Figure 17. Scatter plots showing circuit breaker performance for all arcing tests, based on number of arcing half-cycles. (*Left*) Data coded by the four criteria as described in Table 13. (*Right*) Data marked pass/fail only, with inconclusive data (less than eight arcing half-cycles but no trip) removed.

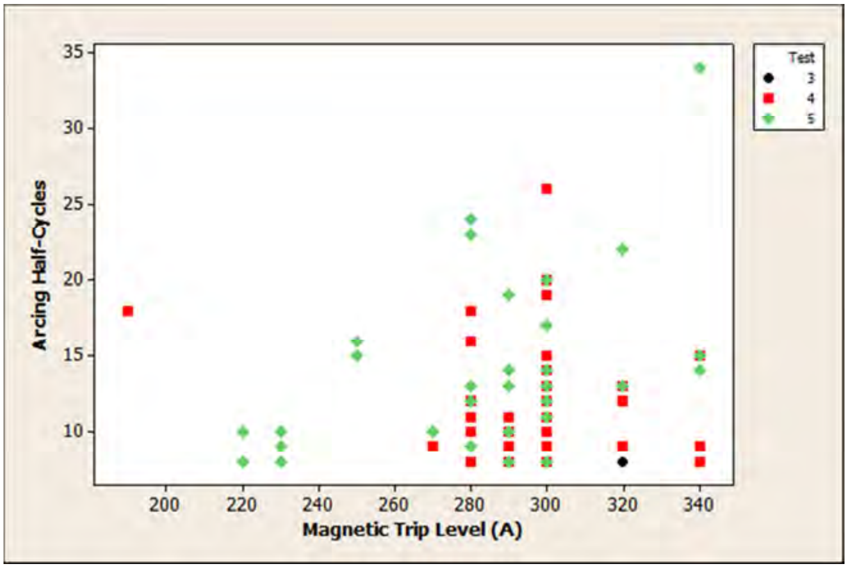

Figure 18. Failed arcing tests, categorized by arcing type. Note that failures below 257A are nearly all attributed to guillotine (40.5) tests.

Table 14. List of failed arcing tests where circuit breakers with magnetic trip levels below 257A .

Manufacturer	Breaker Number	Magnetic Trip Level (A)	Iteration Number	Test (40.x)	Number Arcing Half-Cycles	Breaker Trip?
B	12	220	2	3	8	N
A	14	190	4	4	18	N
B	9	250	1	5	15	N
B	9	250	2	5	16	N
B	10	230	5	5	9	N
B	11	230	3	5	9	N
B	12	220	1	5	8	N
B	12	220	3	5	11	N
B	13	230	1	5	8	Y
A	11	230	4	5	8	Y

Table 14 lists each arcing test where circuit breakers with magnetic trip levels below 257A failed to mitigate arcing in less than eight half-cycles. Since these circuit breakers failed to operate as predicted, each will be evaluated to explain the root cause for each failure.

Table 15. Carbonized arc testing data for Breaker 12 from Manufacturer B, which showed one test failure.

Test (40.x)	Iteration Number	Number Arcing Half-Cycles	Breaker Trip?	Test (40.x)	Iteration Number	Number Arcing Half-Cycles	Breaker Trip?
3	1	3	Y	4	1	1	Y
3	2	8	N	4	2	1	Y
3	3	1	Y	4	3	1	Y
3	4	4	Y	4	4	1	Y
3	5	1	Y	4	5	2	Y

There were two failures of the carbonized tests, one each for Section 40.3 and 40.4 methods. For the Section 40.3 failure (Table 15), the circuit breaker failed to trip on an arcing event that was exactly eight half-cycles, which is at the limit of the UL1699 criterion. Considering that in the other nine carbonized arcing test cases this circuit breaker tripped within four half-cycles or less, the one failure may be an outlier in the test data. However, it is noted that the arcing event stopped on its own, without the circuit breaker tripping on the event, and the arcing event consisted of eight arcing half-cycles occurring in succession. The data for the circuit breaker that failed the 40.4 testing once (Table 16) shows a similar pattern, but far more dramatic: while nine of the carbonized tests exhibited the circuit breaker tripping within two half-cycles, in one case the circuit breaker failed to trip over eighteen half-cycles. In this test, twelve arcing half-cycles occur in succession before there is any pause in the arcing current. The results from these two tests may suggest that the magnetic trip feature of a circuit breaker may not always react immediately to an arcing event.

Table 16. Carbonized arc testing data for Breaker 14 from Manufacturer A, which showed one test failure.

Test (40.x)	Iteration Number	Number Arcing Half-Cycles	Breaker Trip?	Test (40.x)	Iteration Number	Number Arcing Half-Cycles	Breaker Trip?
3	1	1	Y	4	1	2	Y
3	2	1	Y	4	2	1	Y
3	3	1	Y	4	3	2	Y
3	4	1	Y	4	4	18	N
3	5	2	Y	4	5	2	Y

The rest of the failures were encountered during the point contact (guillotine) testing. Two of the failures show that the circuit breaker tripped but only after eight or nine half-cycles, very close to the UL1699 criterion. Most of the other circuit breakers failed to trip on relatively short arcing events (less than 10 half-cycles). Circuit breaker 9 from Manufacturer B was the only circuit breaker to fail on more than ten arcing half-cycles: this can likely be attributed to its magnetic trip level, 250A, being very close to the predicted threshold.

Table 17 lists the peak current magnitude for each arcing half-cycle for the circuit breakers that failed to trip but were predicted to pass the UL1699 criterion. These same circuit breakers were successful in mitigating arcing during carbonized path arcing tests. The data for these same five tests for the same four circuit breakers are listed in Table 18.[13] Comparing the peak current values for each test show that for all of the point contact arcing half-cycles, the magnetic trip level was never exceeded, and was missed by approximately 25A to 40A. In contrast, the carbonized arcing tests did exceed the magnetic trip level for all circuit breakers. However, at a magnetic trip level at 250A (close to the predicted maximum level of 257A), the magnetic trip level was exceeded more than once before tripping. In the case of Breaker 9, Iteration 1, the magnetic trip level was exceeded three times, followed by an additional four arcing half-cycles below the magnetic trip level, before the breaker tripped.

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[13] Note that though the same iteration numbers for each test failure are shown, no correlation was observed among iteration number (as is shown in Table 11 and Table 12).

Table 17. Arcing half-cycle number and peak current for each arcing half-cycle occurring for point contact tests that failed to trip in eight half-cycles. Count of arcing half-cycles begins at the occurrence of the first arcing half-cycle recorded during each test.

Breaker 9, Iteration 1 (I_{mag} = 250A_{rms}; 354A_{peak})		**Breaker 9, Iteration 2** (I_{mag} = 250A_{rms}; 354A_{peak})		**Breaker 10, Iteration 5** (I_{mag} = 230A_{rms}; 325A_{peak})		**Breaker 11, Iteration 3** (I_{mag} = 230A_{rms}; 325A_{peak})		**Breaker 12, Iteration 3** (I_{mag} = 220A_{rms}; 311A_{peak})	
Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)
1	306.98	1	275.86	1	157.93	1	190.25	1	266.92
8	120.33	6	294.79	38	254.68	3	185.87	24	96.003
9	303.66	26	309.15	39	287.96	4	69.055	28	282.58
15	304.38	29	315.27	40	297.09	6	166.76	31	72.51
16	304.78	30	327.74	41	282.23	8	180.46	32	166.80
22	132.25	31	307.89	42	270.51	11	268.67	33	284.28
24	321.35	32	312.83	43	267.21	12	278.94	35	274.79
25	314.71	33	312.26	44	259.90	15	283.91	36	258.61
26	314.96	34	302.16	57	292.53	31	283.73	38	246.50
27	312.44	35	281.49					43	252.56
28	316.61	36	310.28					55	208.48
30	285.62	37	297.43						
31	316.29	38	299.16						
33	317.49	39	298.19						
39	295.11	40	307.83						
		42	239.66						
Number of Half-Cycles Where I_{mag} Was Exceeded									
	0		0		0		0		0
Maximum Peak for Each Test (A)									
24	321.35	30	327.74	57	292.53	15	283.91	33	284.28
Number of Amperes Magnetic Trip Level Was Exceeded/(Not Exceeded) (A)									
	(32.65)		(26.26)		(32.47)		(41.09)		(26.72)

Table 18. Arcing half-cycle number and peak current for each of the circuit breakers listed in Table 17 using a carbonized path arc (using method in UL1699, Section 40.4). Count of arcing half-cycles begins at the occurrence of the first arcing half-cycle recorded during each test. Shaded values did not exceed the magnetic trip level of the breaker.

Breaker 9, Iteration 1 (I_{mag} = 250A_{rms}; 354A_{peak})		**Breaker 9, Iteration 2** (I_{mag} = 250A_{rms}; 354A_{peak})		**Breaker 10, Iteration 5** (I_{mag} = 230A_{rms}; 325A_{peak})		**Breaker 11, Iteration 3** (I_{mag} = 230A_{rms}; 325A_{peak})		**Breaker 12, Iteration 3** (I_{mag} = 220A_{rms}; 311A_{peak})	
Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)	Half-Cycle No.	Peak Current (A)
1	379.30	1	315.24	1	315.01	1	303.00	1	350.99
2	373.62	2	340.75	2	356.34	2	346.34		
3	359.07	3	337.83						
4	350.32	4	326.87						
5	336.27	5	362.31						
6	322.76	6	369.84						
7	301.48								
Number of Half-Cycles Where I_{mag} Was Exceeded									
	3		2		1		1		1
Maximum Peak for Each Test (A)									
1	379.30	6	369.84	2	356.34	2	346.34	1	350.99
Number of Amperes Magnetic Trip Level Was Exceeded/(Not Exceeded) (A)									
	25.30		15.84		31.34		21.34		39.99

Table 19. Summary of peak current distributions for peak arcing current data.

Available Current (A)	**Arcing Type (40.*x*)**	**Lower Quartile**	**Mean**	**Median**	**Upper Quartile**	***N***
500	**3**	0.728	0.792	0.833	0.879	288
	4	0.748	0.798	0.811	0.867	728
	5	0.664	0.701	0.741	0.772	1087
1000	**3**	0.723	0.797	0.834	0.888	265
	4	0.726	0.784	0.797	0.860	444
	5	0.597	0.650	0.692	0.740	781

Comparing the peak current distributions for carbonized path and point contact arcing (Figure 19) shows peak current values normalized to the short-circuit current for both 500A and 1000A tests) shows that the peak current values for point contact arcing tended to be lower than that observed for carbonized path. The point contact arcing showed a median peak arcing current of 278A, while the carbonized path had a median peak arcing current of 320A. Since the peak short circuit current of the system is 402A, the median value for carbonized path is 80% of short-circuit current, and 69% for the point contact arcing.

The statistical information in Table 19 demonstrates the reason why some circuit breakers failed to trip for some 1000A point contact tests, but all tripped successfully for the 500A point contact tests. Though the peak current values for the point contact arcing test for both 500A and 1000A tests was lower than for carbonized path, the values fell further relative to the carbonized path arcing tests when 1000A was available. This lowered the distribution of the peak currents sufficiently below the expected normalized current of 80%. Therefore, during point contact arcing tests there was a high probability that the peak arcing current would be less than 80% of short-circuit current, causing an inability to exceed the magnetic trip level of the circuit breaker within eight arcing half-cycles.

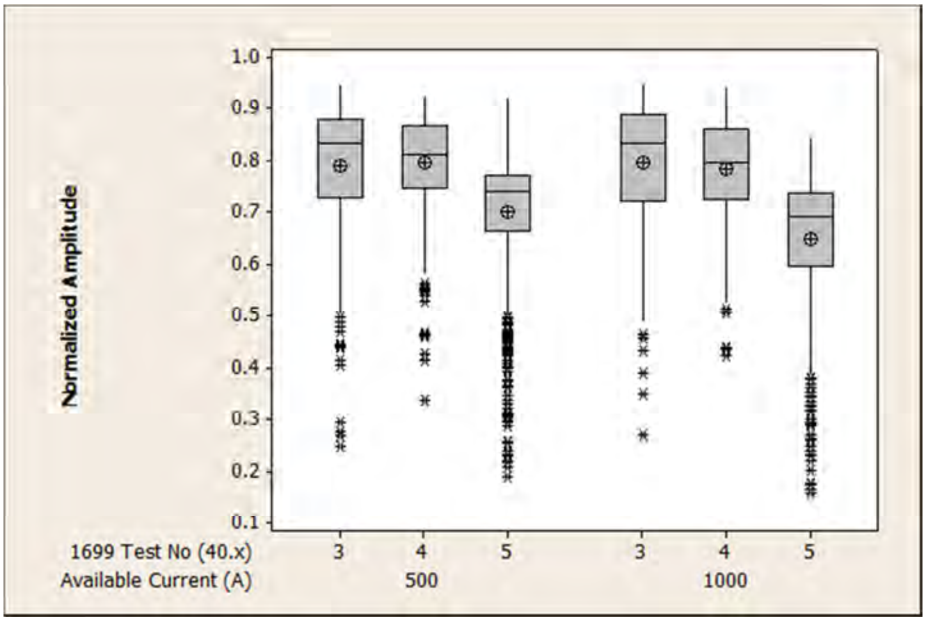

Figure 19. Boxplots comparing peak current values for carbonized path (per the method described in UL1699, Sections 40.3 and 40.4) and point contact arcing (per UL1699, Section 40.5).

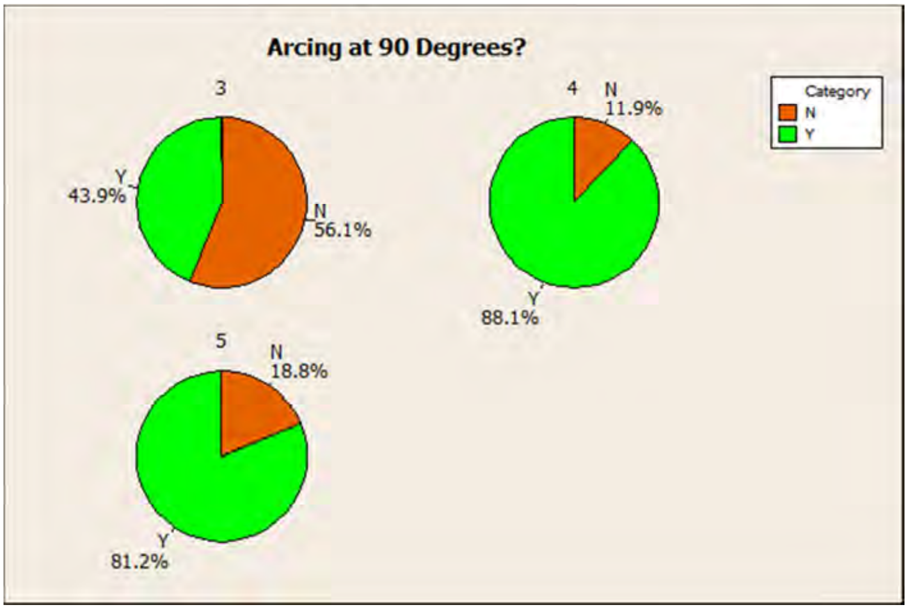

Figure 20. Pie charts showing fraction of arcing half-cycles that occur during the voltage maxima at ±90°.

This reduction in overall peak arcing current for the point contact test is not expected and needs to be investigated further before conclusions are reached. A review of the strike/stop data shows that the issue is not due to a large number of arcing half-cycles occurring at low voltage: in fact, the majority (81%) of arcing half-cycles occurs during the ±90° voltage c ycle when arcing current is expected to be at a maximum (Figure 20). This is significantly less than what is observed with the Section 40.4 carbonized path arcing, but is not expected to be an issue when eight half-cycles are allowed to occur (since the probability of all eight arcing half-cycles not occurring during the voltage maxima is vanishingly small). Furthermore, more than half of all arcing half-cycles for the Section 40.3 carbonized path arcing did not occur at ±90°, and this group of tests showed peak currents at or exceeding 80% of short-circuit current.

The drop in the normalized current as available current increases also does not appear to be an artifact of this particular study. Previous work completed in 2010[14] also shows a drop in the normalized current for point contact arcing tests as the available current increases (Figure 21), which agree closely with the data for point contact tests shown in Table 19. This shows that the trend of falling normalized peak current as available current rises is not unique to this work, but was also observed previously. In that earlier work, circuit breakers were not used; therefore, the presence of circuit breakers is not a significant cause of the change in peak current values.

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[14] P.W. Brazis et al., "Synthetic Arc Generator for UL1699, Phase 2: Statistical Characterization of Arc Fault Behavior," *UL Internal Report*, 2010, Table 13 and Figure 9 (pp. 28-29).

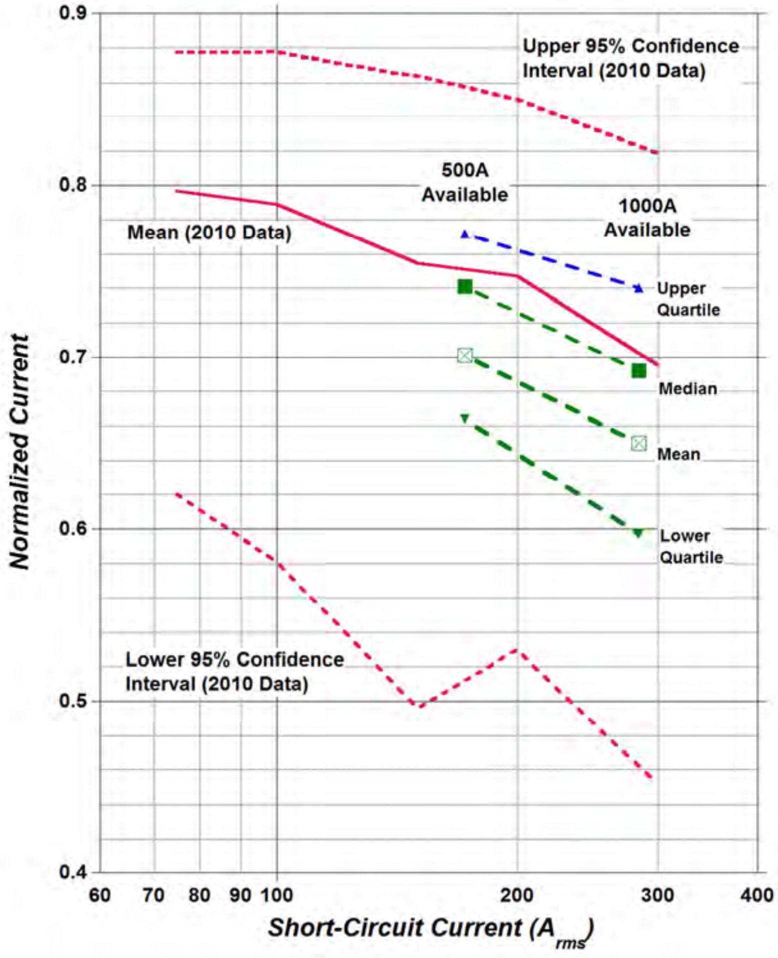

Figure 21. Comparison of peak current data to earlier point contact results completed in 2010 (Ref. 14).

These results only leave two options for the cause of this drop in current:

- The effect is related to the physical behavior of point contact arcing, which means that point contact results need to be used to define a lower bound for magnetic trip level for circuit breakers.
- The effect is an artifact of the test apparatus, which needs to be modified for more accurate testing, which will unify results between carbonized path and point contact arcing.

This latter option would suggest that the drop in normalized current is due to some artificial cause, due to the point contact test apparatus, rather than a cause attributable to point contact arcing in itself. A possible cause in this regard is the contacts to the test sample: if these contacts are corroded and/or oxidized, a resistive path in series with the sample would be present. This would have the effect of lowering the normalized current as the panelboard impedance falls below that of the contact. The drop in mean normalized current over time in Figure 21 supports this possibility, as increased corrosion with time would increase the contact resistance, and therefore amplify the effect. Present work is investigating the origin of the drop in normalized current, with the results being discussed in a later report.

The short-circuit current is measured for the carbonized path and point contact tests by placing a shorted sample across the test leads. The same sample contact points are used to evaluate any contribution of contact resistance, additional wire length, or any other effect may have on available short-circuit current. This is conducted with one circuit breaker closed. The test is repeated eight times to evaluate variation in the measured short-circuit current. These tests show that the short-circuit current for the point contact apparatus is 405A, and is 437A for the carbonized path test, a difference of approximately 8%. Recalculating Table 19 gives the results shown in Table 20.

Table 20. Recalculated values for the 1000A values from Table 19, based on short-circuit measurements evaluating contact or other secondary effects.

Available Current (A)	**Arcing Type (40.*x*)**	**Lower Quartile**	**Mean**	**Median**	**Upper Quartile**	***N***
1000	**3**	0.676	0.743	0.773	0.826	286
	4	0.666	0.720	0.731	0.789	444
	5	0.602	0.655	0.694	0.742	776

As can be seen, the point contact data continues to show lower values, but only by a few percent, more reminiscent of what was observed during the 500A tests. These results show that though point contact arcing may show slightly lower peak arcing current distributions, it would not be expected to be sufficiently low to change the ability of the mathematical relationship to predict a circuit breaker's ability to mitigate arcing faults. To verify this, the change in short-circuit current needs to be converted to an effective equivalent home run length, and the maximum magnetic trip level can then be re-calculated for this new length.

Assuming that the cables are at the same temperature and both 14 AWG copper, and assuming the same voltage on each:

$$\rho_L L_1 = R_1 = \frac{V}{I_1}$$

$$\rho_L L_2 = R_2 = \frac{V}{I_2}$$

Since the carbonized path tests used 50 feet of 14 AWG NM cable, it is assumed that L_1 = 50 feet, and I_1 is 437A. I_2 is the short-circuit current observed for the point contact test, 405A. Combining and solving for L_2:

$$\rho_L L_2 I_2 = \rho_L L_1 I_1$$

$$L_2 = L_1 \frac{I_1}{I_2}$$

$$L_2 = (50)\frac{(437)}{(405)} = 54 \text{ feet}$$

Therefore, the additional impedances in the point contact test apparatus used for the experimental work gave results equivalent to adding four feet to the home run length. Now using L = 54 feet then gives a revised value for I_{mag} for 1000A available current at the panelboard:

$$(0.002525)(54) < \frac{120}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{1000}\right)$$

$$I_{mag} < 244 \text{ A}$$

Comparing this new value to the circuit breaker results in Figure 17 shows that the failure of Breaker 9, Manufacturer B (which has a magnetic trip level of 250A) falls away, leaving only circuit breakers between 220A and 230A that continue to fail despite being predicted to pass the eight half-cycle criterion. Review of Table 17 also shows that each arcing half-cycle fails to reach $345\text{A}_{\text{peak}}$ (which is 244A_{rms}); therefore, the prediction is still overestimating the maximum magnetic trip level by approximately 20-30A. Further work is needed to verify whether this discrepancy continues to be an artifact of the test apparatus, or whether a slightly lower threshold is required for the mathematical relationship (for example, if the assumption that arcing currents tend to be 80% of short-circuit current is changed to 70%, I_{mag} above becomes 215A, which would correctly predict circuit breaker performance in all cases tested at 1000A). Further work during Part II of this project will first ensure that the available short-circuit current is identical for all arcing tests, then will investigate whether the mathematical relationship needs to be modified to be accurate for all arcing types, or whether the point contact arcing tests continue to suffer from instrumentation issues.

Summary of Findings

Using the formula that was derived in Ref. 10, it was calculated that for a system that has 500A available at the panelboard and has a 50-foot home run of 14 AWG NM cable, and assuming cable temperature between 20℃ and 30℃, that the magnetic trip level of the breaker needs to be less than 195A for the circuit breaker to protect the home run. Review of the circuit breaker data (in particular, Figure 14, *right*) shows that this calculation is accurate, showing that all circuit breakers that have a magnetic trip level of 190A or less pass the UL 1699 eight half-cycle criterion. Circuit breakers with magnetic trip levels of 200A or greater show a high probability of allowing more than eight half-cycles of arcing to occur. Therefore, in the case of 500A, the experimental results show that the mathematical relationship relating magnetic trip level, run length, and available fault current accurately predicts real-world behavior.

Turning now to the circuit breaker data (as shown in Table 2 and Table 3), the data show that many of the residential circuit breakers have magnetic trip levels exceeding 195A. In addition, tripping tests with the most recent batch of circuit breakers even revealed a number of circuit breakers with magnetic trip levels exceeding 300A, which was previously proposed as a probable (99%) upper bound on all residential circuit breakers. These results together therefore show that not all circuit breakers would be appropriate for use in mitigating parallel arcing faults in a branch circuit with a 50-foot home run length and 500A available at the panelboard. Therefore, accepting 500A and 50 feet as specifications for home fun parallel arc fault protection with a receptacle-located AFCI can only be applied if the circuit breaker at the panelboard can be guaranteed to have a magnetic trip level at 195A or less.

The 1000A results showed that though the predicted maximum allowable magnetic trip level was correct for carbonized path arcing, but the results were inconclusive for point contact arcing. The issue was shown to be due to a lower peak arc current compared to the carbonized arcing tests (the median dropping from 85% to 70% of peak short-circuit current). Since it is not clear whether the drop in current is due to some effect unique to point contact arcing, or whether it is an artificial artifact of the test apparatus, it is not yet clear whether any modification to the mathematical formula is needed at this time. Further experimental work is being conducted to resolve this issue.

Temperature Considerations

Even if the 195A magnetic trip level (assuming 500A available at the panelboard) can be assured, temperature may also have an effect that may alter the short-circuit current in the home run, alter the magnetic trip level of the circuit breaker, or both. Regarding the temperature dependence of the circuit breaker, both thermal and magnetic behavior may be altered due to temperature changes, typically due to thermo-mechanical changes in the mechanism. Circuit breakers may or may not be designed to perform uniformly over temperature, depending on manufacturer and design type. For use in mitigating arcing faults, it would be preferable at minimum for the magnetic trip performance of the circuit breaker to be constant over the range of operating temperatures (*i.e.*, performance can be over a relatively narrow range for circuit breakers used indoors only; circuit breakers used outdoors would require a wider temperature range.

Another factor affecting the available short-circuit current is the cable temperature, which is likely to vary independently from the temperature of the circuit breaker. As the resistance of a cable will change with temperature, the short-circuit fault current, and therefore the necessary magnetic trip level of the circuit breaker, may need to be adjusted for different cable temperatures. It is noted that cable resistance per unit length is usually listed in the literature at 25℃ (room temperature), as was the temperature that the experimental work was conducted herein. Conversion between resistances can be accomplished using the following expression:

$$T_2 = \frac{R_2}{R_1}(k + T_1) - k$$

where R_2 is the resistance at temperature T_2, R_1 is the resistance at temperature T_1, and k is the coefficient of resistance (for copper, k is equal to 234.5℃). Using this formula to solve for R_2, the equivalent resistance at 25℃ can be adjusted to any desired temperature, for example for converting to 90℃:

$$90 = \frac{R_2}{2.525}(234.5 + 25) - 234.5$$

Solving for R_2 gives a resistance of 3.157 mΩ/ft at 90℃ for 14 AWG copper. Similar calculations can be made for other cable temperatures. These values for ρ_L can then be inserted into the equation relating cable length to magnetic trip levels to determine maximum magnetic trip levels. Again using 90℃ as an example:

$$(0.003157)(50) < \frac{120}{2}\left(\frac{\propto}{I_{mag}} - \frac{1}{500}\right)$$

$$I_{mag} < 173\ \mathrm{A}$$

Continuing these calculations, resistance per foot for 14 AWG copper cable and maximum magnetic trip levels can be calculated for a range of cable temperatures, these are given in Table 21 for 500A available at the panelboard. The calculations assume a home run length of 50 feet.

Table 21. Calculated resistance per foot for 14 AWG cable and maximum allowable magnetic trip level for different cable temperatures, 500A available and 50 foot home run length.

Temperature, ℃	−35	−10	0	10	25	40	60	90
$\rho_L(T)$, mΩ/foot	1.941	2.184	2.282	2.379	2.525	2.671	2.866	3.157
Maximum $I_{mag}(T)$, A	221	209	205	201	195	189	182	173

Conclusions

Circuit breaker testing was conducted for common residential circuit breakers from four North American manufacturers. This work involved testing of a second batch of circuit breakers, and was compared to data from circuit breakers of the same model and manufacturer conducted one year earlier. The results show that the magnetic trip level was consistent for three of the manufacturers, but showed a significant change in trip level for one of the manufacturers. These revised values show that the magnetic trip level of circuit breakers is not as well controlled as was previously found in a previous study. The new data suggest that the 99th percentile upper bound may need to increase to at least 350A, perhaps as high as 400A, though this may suggest that for the application discussed in this work, circuit breakers with a known magnetic trip level may be required.

The experimental results in this work show that the mathematical relationship relating the magnetic trip level, cable run length, and available fault current can be accurate within at least 5A to 10A. The predicted maximum allowable magnetic trip level for a circuit breaker was195A for a system with 50 feet of 14 AWG NM cable, 500A available at the panelboard, and the cable temperature at 25±5℃. The experimental data show that off-the-shelf circuit breakers tested to have a magnetic trip level at 190A or less mitigated the arcing event to less than eight half-cycles in every case. Circuit breakers with magnetic trip levels 200A or greater failed to mitigate a large fraction of the the arcing events in eight half-cycles. Calculations for different cable temperatures are also given, showing that the maximum allowable magnetic trip level for cable uniformly at 60℃ is expected to be 182A, and at 90℃ to be 173A. It is noted that these experiments were not conducted, due to project scope; however, these calculations are based on well-known and well-characterized relationships for the resistivity of copper.

For the 1000A testing, the mathematical relationship was able to correctly predict pass/fail behavior for carbonized path arcing tests, but was inconclusive for point contact arcing tests. At this time it is not clear whether the drop in normalized peak current is a real effect or attributable to the test apparatus. Further tests are being conducted to resolve this issue.

Some of the circuit breaker tests showed occasional failure to trip magnetically, even though several arcing half-cycles exceed the magnetic trip level of the circuit breaker. In this work, two instances of this behavior were observed, where each breaker successfully tripped nine out of ten times, but failed on the tenth. This suggests that the reliability of the magnetic trip mechanism of a circuit breaker may not be sufficiently near 100% (here, the data suggested that the reliability was closer to 90%). However, this phenomenon was not investigated further. In the case that a circuit breaker is required to trip magnetically for home run protection, studies on the reliability of a circuit breaker to trip magnetically may need to be quantified.