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

Part II: Effect of Run Length with 500A Available at the Panelboard

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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.

This report is Part II of an investigation into the ability of a circuit breaker to mitigate parallel arcing faults in the home run where both run length and available current at the panelboard are varied (which changes the available fault current). The current study also includes experimental testing using three types of arcing tests, all based on UL 1699 methods, which include carbonized path and point contact arcing. This work expands on an earlier study where the performance of a circuit breaker was evaluated with short-circuit currents ranging from 75A to 300A: the available short-circuit current values for the present study broaden this range to 390A.

The initial study on this topic attempted to evaluate the magnetic trip level of residential 15- and 20-amp circuit breakers to determine whether a generalized magnetic trip distribution could be found. The initial set of circuit breakers, which were sampled from four North American manufacturers and included circuit breakers of different designs for each manufacturer, suggested that 99% of all circuit breakers would magnetically trip at or below 300A for 15A breakers and 350A for 20A breakers. However, follow-up

[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.

testing one year later negated this findings, with circuit breakers of the same model number but of a different batch had significantly different magnetic trip levels, varying by 50A or more for some manufacturers, yet unvarying for others. These results showed that magnetic trip levels could conceivably be controlled, but were not in all cases. The revised data showed that panelboard current and run length would need to be set assuming magnetic trip thresholds as high as 400-450A would be needed, which makes arc mitigating using magnetic trip levels not specifically calibrated for this application impractical as well as potentially unreliable. Therefore, the results of Part I of this work showed that circuit breakers with magnetic trip levels calibrated for the purpose of mitigating parallel arcing faults would be necessary.

Through the research work, a mathematical relationship was derived to relate run length, wire gauge, and available current at the panelboard to the maximum magnetic trip level required to predict the ability of a circuit breaker to mitigate arcing faults (per the UL1699 eight half-cycle criterion). This formula had been updated first to include the effects of panelboard available current, and in Part II was amended to also include the series contact resistance that is observed in point contact arcing. Short-circuit measurements conducted in Part II of this work show that this contact resistance is approximately 30 mΩ. Though this series contact resistance is present only for point contact arcing, it is included in the formula for all calculations since it is unlikely that the type of arcing would be known. However, it can be removed in special applications where it is known that the arcing will be carbonized path only. As a result of the work in Parts I and II, the final relationship is the following:

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

or in terms of run length:

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

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});
R_C is the series contact resistance for point contact arcing;
I_{pssc} is the short-circuit current at the panelboard; and
I_{mag} is the magnetic trip current of the circuit breaker.

It is noted that the factor 0.8 is still used in this formula, though the derivations in Part II of this value show that 0.75 is a more accurate threshold. However, the assessment of this value is done without consideration of the effect of R_C. Evaluation of the formula to the arcing results show that the R_C value

compensates for the added margin needed. Using 0.75 and R_C results in calculated magnetic trip values that are conservative by approximately 20A. Therefore, maintaining 0.8 and adding the term R_C results in a mathematical relationship that predicts circuit breaker performance within a margin of 10A.

The mathematical relationship was then used to predict whether a given circuit breaker would trip within the eight half-cycle criterion when the home run length was varied from 15 feet to 50 feet, and available panelboard current was 500A or 1000A. Results from Part I of this work showed that the relationship failed to predict point contact results accurately for higher available short-circuit currents: the addition of the R_C term in Part II corrected this issue. The formula was used to predict the outcome of more than 2,200 arcing tests, and was successful in predicting behavior for all but one test. For the single outlier it was found that the circuit breaker did perform as predicted in 9 out of 10 tests. It was not clear why this breaker failed on the tenth. To allow for further analysis, detailed data on this circuit breaker's performance is given in Appendix A.

Key Points, Parts I and II

- Follow-up circuit breaker testing shows that not all models have consistent batch-to-batch magnetic trip values. 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. The addition of an additional term representing the contact resistance present in a point contact arc corrects for errors encountered in Part I of this work. This contact resistance is approximately 30 mΩ.
- This revised mathematical relationship was found to accurately predict the ability of a circuit breaker to mitigate a parallel arcing fault in the home run. This was proven for available panelboard currents of 500A and 1000A, with home run lengths from 15 feet to 50 feet. It is anticipated that this relationship will apply for other panelboard currents, home run lengths, and cable gauges. Calculations based on this formula can be found in Appendix D.
- Temperature considerations are not included in these calculations; the effects of temperature were covered in Part I and Appendix C of this work and still apply.

TABLE OF CONTENTS

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

[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 the effect of run length on a branch circuit that

[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.

has 500A available at the panelboard. The 500A (along with a home run length of 50 feet) specification 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. The performance of circuit breakers at 500A and 1000A available at the panelboard, as well as 500A available with varying home run lengths between 15 feet and 50 feet were included in this work to determine the mathematical relationship of run length, panelboard available current, home run length, and cable gauge to the magnetic trip level of a circuit breaker. This relationship is then intended to give a scientific basis to future Code Panel discussions and subsequent Code decisions.

Prior Work and Findings

In Part I, magnetic trip levels of circuit breakers was re-visited to evaluate whether the magnetic trip level is consistent among different batches of the same model of circuit breaker (Table 1). The results showed that the magnetic trip level for circuit breakers can vary significantly. As can be seen in Figure 1 and Table 2, while the magnetic trip level did not significantly change among different batches for Manufacturers A and D, the change for Manufacturer C was very large; in fact, the change in the distribution of magnetic trip level negated the previous conclusion that 99% of all residential, non-"high mag", 15A circuit breakers have magnetic trip levels at or below 300A. The new results suggested that the 99% confidence interval may actually be 350A, or even 400A, depending on whether a normal or lognormal distribution model was used (it was not clear which was more appropriate). Nevertheless, the results showed that the current state of magnetic trip calibration for residential circuit breakers is not tightly controlled, at least when magnetic trip levels are considered over all manufacturers.

Table 1. Magnetic trip level in Amperes at 25°C, breakers 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

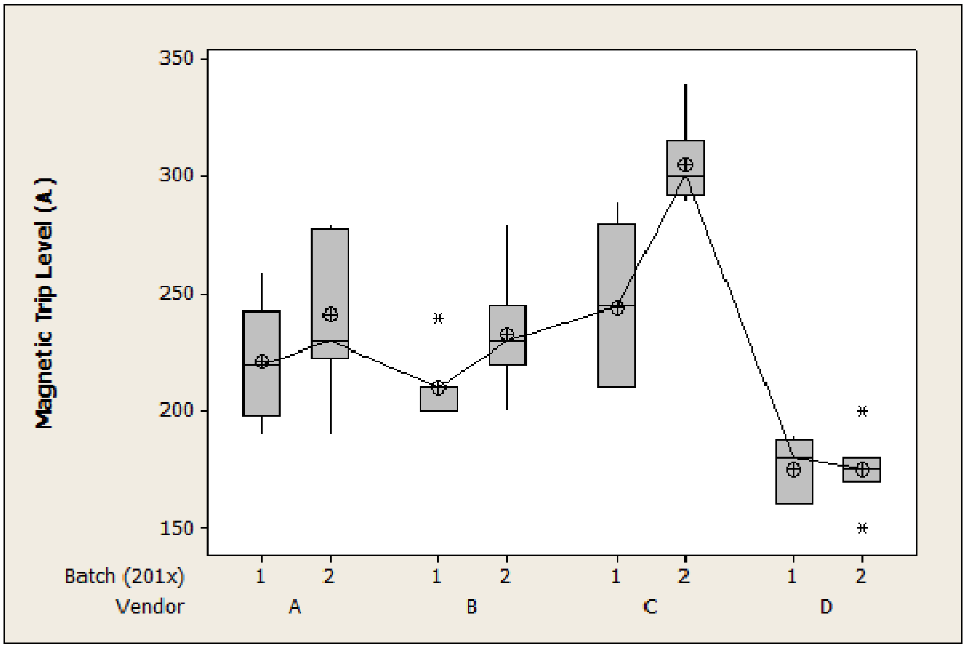

Figure 1. Batch-to-batch comparison for 15A, Type 1 breakers from each of the four manufacturers. Manufacturers A and D did not show a statistically significant variation, which Manufacturer C showed a significant change in magnetic trip level.

Table 2. 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

In previous work by UL it was proposed 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:[4]

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

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 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 arbitrarily 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 and varying the home run length.

In Part I of this work, it was found that at 500A available at the panelboard resulted in circuit breakers matching the predicted performance to an accuracy of 5A. However, the tests at 1000A available current showed deviation from predicted performance for point contact (guillotine) arcing events. The root cause of this deviation was traced to a lower arcing current relative to the short-circuit current values observed during carbonized path arcing tests (Figure 2). Effects of run length, percentage of arcing events occurring at 90 degrees phase angle (when the supply voltage is at a maximum), and unique environmental issues were ruled out at potential causes. Remaining potential sources of deviation included two potential causes 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.

To address the latter cause, the point contact test apparatus was modified to utilize identical run length cabling and sample connectors as was used for the carbonized path tests. For Part II, both arcing methods use an unbroken run of NM cable fastened to new, clean screw terminal blocks. Where possible, the same components are swapped between test apparatuses and re-used for both test methods. Therefore, any remaining deviation in peak current values is expected to result from the physical behavior of the arcing event. This is evaluated later in this report.

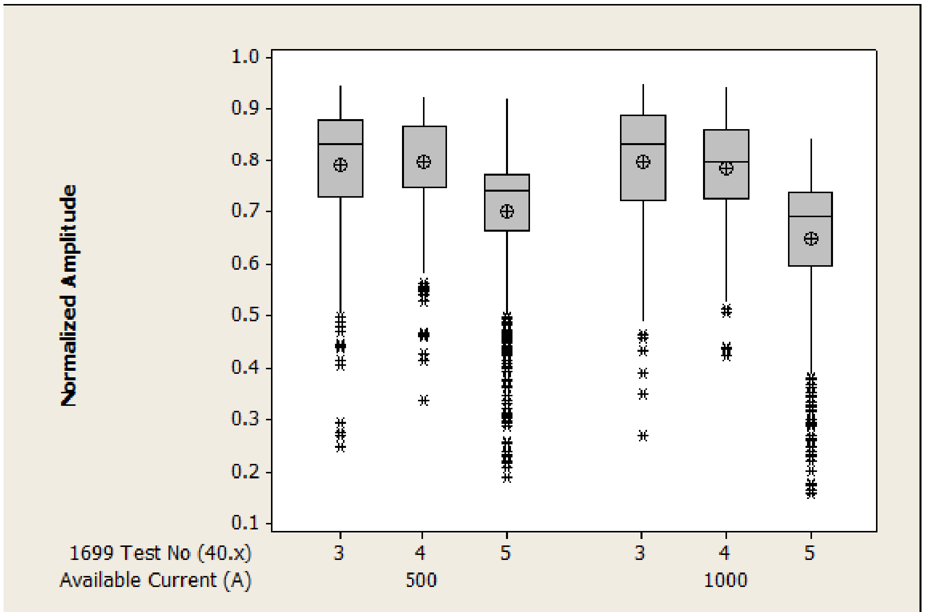

Figure 2. Boxplots comparing peak current values for carbonized path (per the method described in UL1699, Sections 40.3 and 40.4) and point contact arcing (per UL1699, Section 40.5).

Technical Plan

The technical plan for this project is to conduct arc-fault testing in accordance with UL1699[5] with a listed circuit breaker in combination with NM cable lengths ranging from 15 feet to 50 feet 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:

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 II, as outlined below:

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

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 180º < θ < 360º has been reverted to 0º < θ < 180º, 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_{ssc}, 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 3. 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_{ssc}.

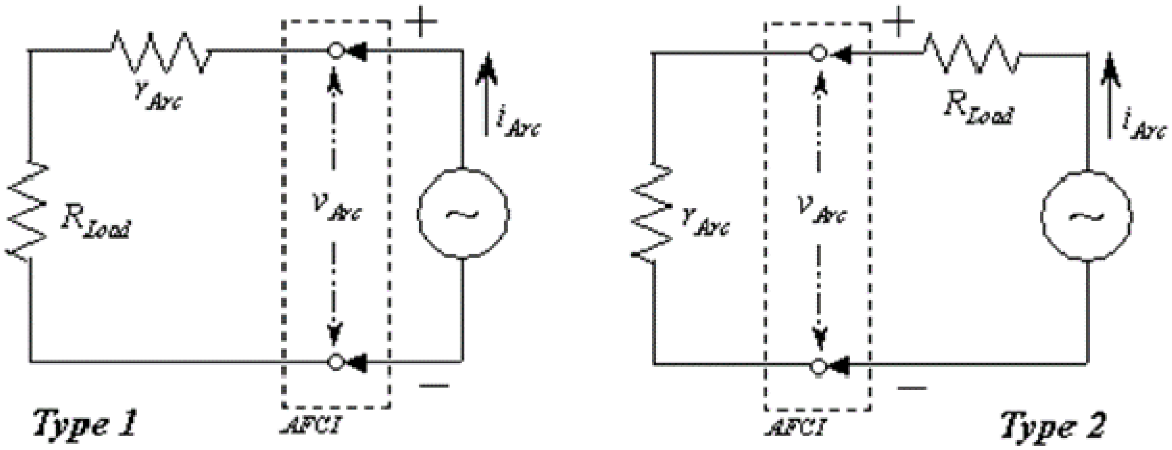

Figure 3. Two configurations of loads used in UL 1699, Section 40 tests. (*Left*) “Type 1”, used in Sections 40.2 and 40.4 for low-current testing. (*Right*) “Type 2”, used in Sections 40.3 and 40.5 for high-current testing.

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 2,200), 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 4):

- **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 $f_{3dB,min}$ = 10 kHz and $f_{3dB,max}$ = 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. Strike angle data for each arcing type are given in Appendix B.
- **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. Stop angle data for each arcing type are given in Appendix B.

- **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.

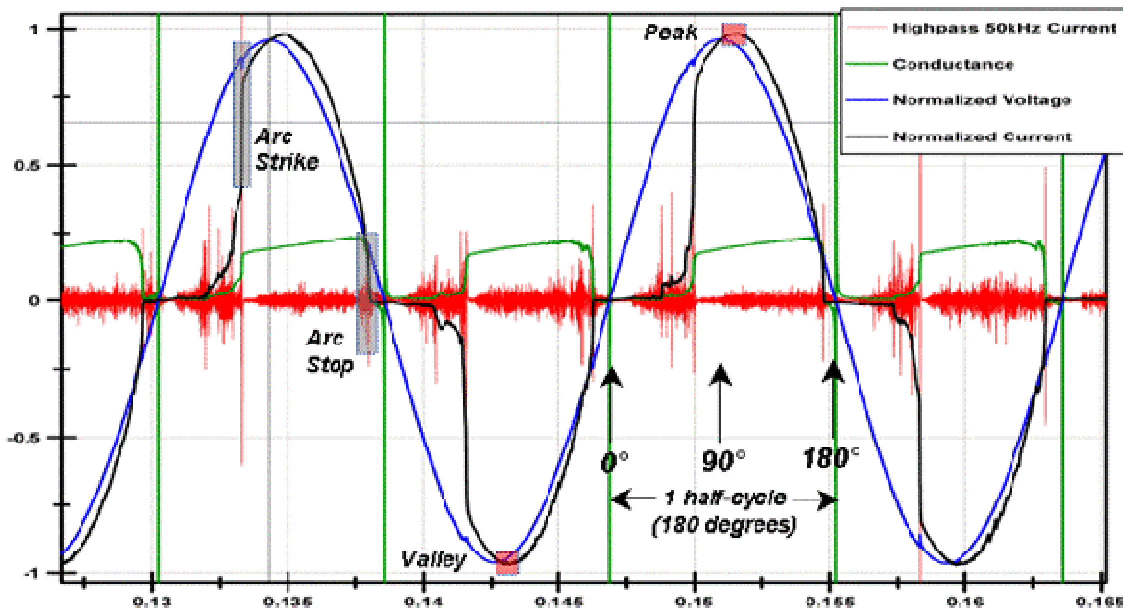

Figure 4. Current and voltage arcing waveforms, showing each arcing half-cycle.

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:

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

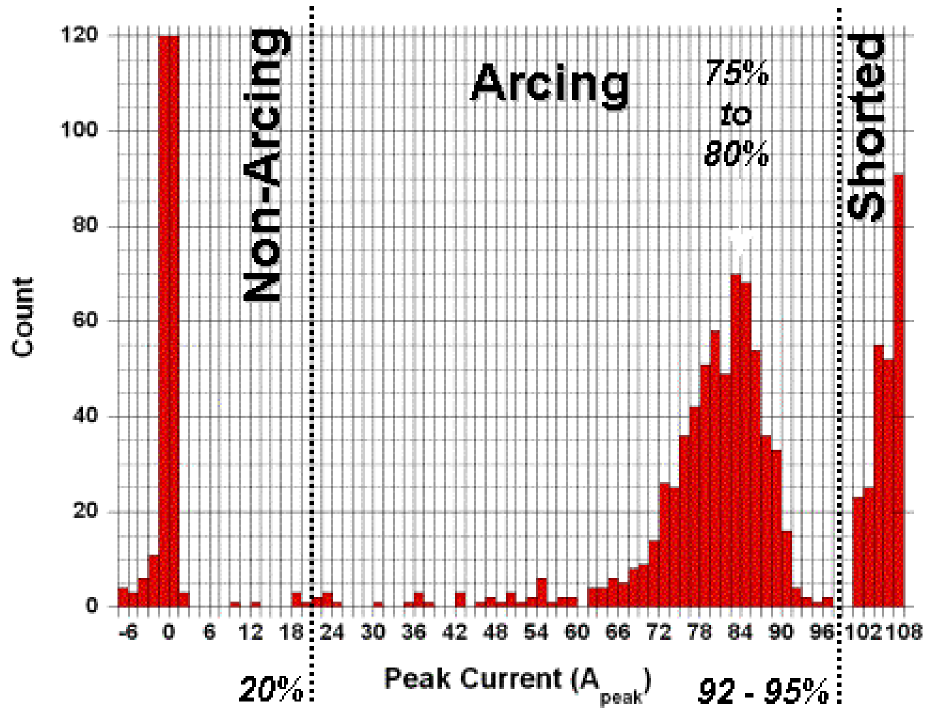

Figure 5. Representative probability distribution function for all peak current values from one series of tests, showing three modes of behavior: non-arcing (<20% I_{peak}), arcing (20% < I_{peak} < 92%-95%), and shorting (>92% to 95% I_{peak}).[4]

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_{ssc} (Figure 5). A threshold of 20% I_{ssc} 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_{ssc} 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_{ssc} 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. Histograms of the distribution of normalized peak current for each arcing type are given in Appendix B.

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. Unless otherwise noted, the data in this Report focus on data from the 2012 batch of circuit breakers. The magnetic trip levels of each of these circuit breakers are listed in Table 1 of this Report, and the characterization of these circuit breakers are described in Part I.

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 – Evaluation of Consistency between Point Contact and Carbonized Path Arcing Tests

One unresolved issue from the Part I work was whether the deviations in the point contact arcing behavior were a result of issues with the test apparatus, or were due to some unique characteristic of the point contact arcing event. This Task evaluates this issue, with the end goal in a decision of whether the predictive formula used throughout this work can continue to assume that the arcing peak current is 80%

of short-circuit current, or whether this assumption needs to be reassessed. The result will be a single predictive equation that is applicable for both carbonized path and point contact arcing.

In Part I, and particularly with 1000A available fault current, the mathematical relationship between run length, magnetic trip level, and available fault current was accurate in predicting the ability of a circuit breaker to mitigate arcing within eight half-cycles for carbonized path arcing, but was not accurate for point contact arcing. In Part I, it was demonstrated that this deviation was due to a lowered peak normalized arcing current (normalized with respect to the short-circuit current) for point contact arcing compared to carbonized path arcing. Even after corrections were made for variations in the short-circuit current for each test it was observed that the peak arcing current was significantly lower for point contact arcing than that observed for carbonized path arcing (Table 3). This lowered peak arcing current therefore likely prevented accurate prediction of circuit breaker behavior, since the majority of arcing events fell below the assumed level of 80% of short-circuit current. Though this is the issue, the root cause of this deviation needs to be identified before a decision can be made on whether the mathematical relationship needs to be modified.

Table 3. Recalculated values for the 1000A arcing tests conducted in Part I, 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 was discussed in Part I, 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 (80%) of arcing half-cycles occurs during the ±90° voltage cycle when arcing current is expected to be at a maximum (Figure 6 is an updated chart that includes data from Part II). 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 small[6]). Furthermore, 42% of all arcing half-cycles for the Section 40.3 carbonized path arcing

[6] More accurately, the probability of all eight point contact arcing half-cycles to not occur during 90° phase angle is $(0.203)^8 = 2.88 \cdot 10^{-6}$, or 2.9 in 1 million. For Section 40.4 carbonized path the probability is $(0.106)^8 = 1.59 \cdot 10^{-8}$, or 16 in 1 billion. These values are in contrast to 40.3 arcing tests, where there is a 0.1% probability for eight arcing half-cycles to all occur outside 90° phase angle.

did not occur at ±90°, and this group of tests showed peak currents at or exceeding 80% of short-circuit current.

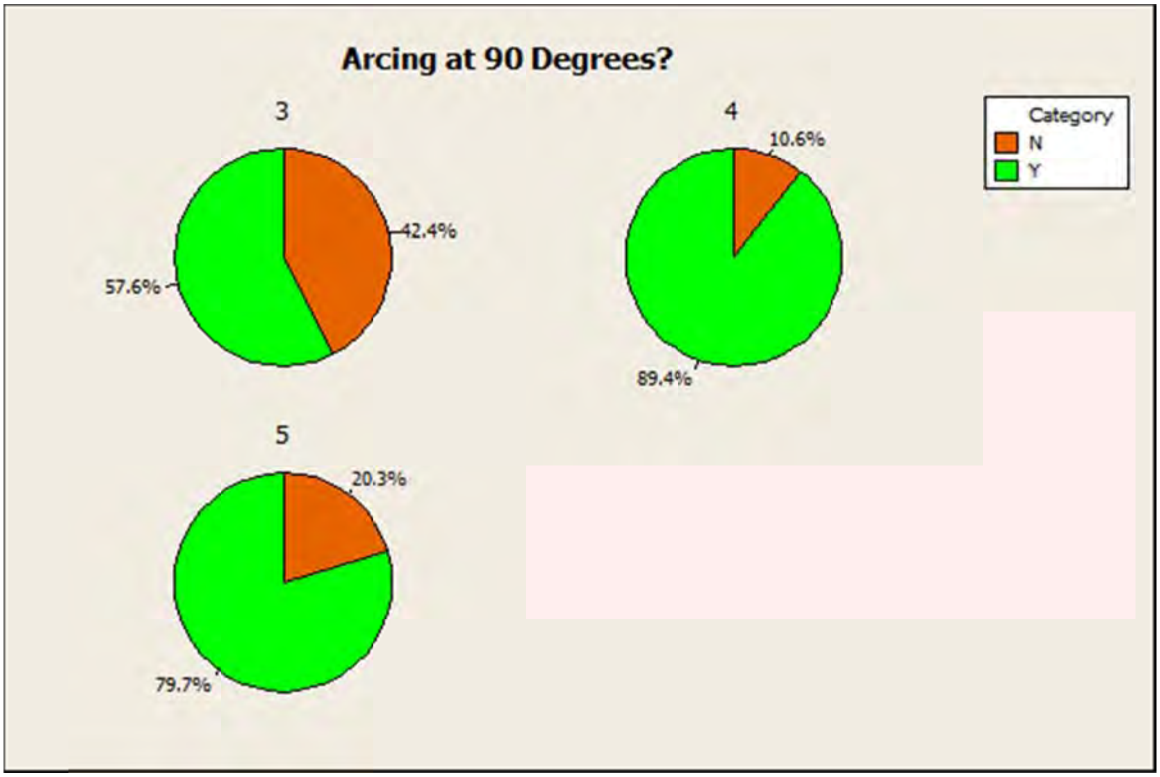

Figure 6. Pie charts showing fraction of arcing half-cycles that occur during the voltage maxima at ±90°. Analysis includes arcing data from Parts I and II.

Another potential issue that was identified was different impedances that may exist between the point contact and carbonized path arcing tests. These were addressed in Part II through modification of the point contact test apparatus to utilize the same NM cable, connecting it directly to the test sample though new, clean screw terminals, as was used for the carbonized path tests. In addition, the short-circuit current was tested for each run length and test method to monitor consistency among tests. The short-circuit currents were tested through true bolted-fault conditions, with a circuit breaker in the circuit. The resulting waveform typically included a small number (less than 10) of shorted half-cycles for evaluation. Cable temperature was monitored during each test to ensure that the cable temperature did not deviate outside the 20°C to 30°C test condition. The measured short-circuit values are listed in Table 4.

Table 4. Measured short-circuit values (in Amperes rms) for each arcing test. Values in parentheses were obtained from shorted half-cycles that are measured during point contact arcing tests.

Test Method	*L* = 15 feet	*L* = 30 feet	*L* = 40 feet	*L* = 50 feet (500A)	*L* = 50 feet (1000A)
40.3	377.6	294.3	259.5	234.3	299.2
40.4	388.6	309.2	272.3	238.7	304.8
40.5	386.3 (352.3)	311.1 (304.1)	270.8 (268.5)	247.8 (241.8)	–
R_C (see text)	30 mΩ	8.9 mΩ	3.8 mΩ	12 mΩ	

The data in Table 4 show that the short-circuit current values among different arcing tests was maintained consistently. For the point contact short-circuit data, two sets of values were measured: one where a bolted fault was placed across the sample location, and a second set that were extracted from the arcing waveform data where the guillotine blade shorted the two conductors together. In all cases, the values obtained from the arcing tests showed a lower current than the bolted fault tests. It is also observed that the data where the short was created by the guillotine blade deviate further from the bolted fault values as the short-circuit current increases, while the bolted fault values remain consistent at all current levels. This suggests that the contact resistance between the guillotine blade and the NM cable adds an additional resistance in series that lowers the available short-circuit current. An estimation of this contact resistance can be made using Ohm's Law:

$$R_C = V\frac{(I_A - I_C)}{I_A I_C}$$

where I_A is the short-circuit rms current measured using the bolted fault method, I_C is the rms current when the guillotine blade shorts the sample, V is the circuit rms voltage (assumed here to be 120 V), and R_C is the estimated blade contact resistance. The last row in Table 4 shows the calculated values for R_C using this method. Note that the values can only be used as an estimation, since the contact resistance will depend on the cleanliness of the guillotine blade, the chemical composition of the contact area, and the cable and blade temperature. However, the calculations show values consistent within an order of magnitude, and show that blade contact resistance is a potential explanation for this drop in short-circuit current during point contact tests. This effect of contact resistance is explored further in the next Task.

Task 2 – Arcing Tests and Peak Current Analysis

In this Task, arcing tests are to be performed and the peak current threshold used in the mathematical relationship relating magnetic trip level to run length and available panelboard current will be reevaluated. This Task therefore addresses the following issues:

- Determine whether there is a difference between arcing peak current behavior between point contact and carbonized path tests.
- Reevaluate threshold peak arcing current value used in calculations, in an earlier work this threshold value was set to 80% of short-circuit current.[7]

In this Task, circuit breakers that have been characterized in Part I are placed into a simulated “home run” environment that has an arcing fault present.

As was discussed in the prior study (Ref. 7), the current at the panelboard and the run length govern the expected fault current at the parallel arcing fault, was expected to be related 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 Part I it was found that this equation was not able to accurately predict circuit breaker performance for point contact arcing, and suggested that the 0.8 factor used in the equation may need to be lowered. Therefore, this value will be recalculated using data from the prior study (Ref. 7), as well as data from Part I of this study. Additional data using different home run lengths with 500A available at the panelboard were collected in this Part of the study, and is combined with the earlier data for analysis. Point contact data from Part I was redone using the improved sample contacts and cable lengths to match the carbonized path experiments.

[7] 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.[8] Statistical justification of this can be found in a 2009 study by UL,[9] 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. 7. 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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[8] "UL Standard for Safety for Arc-Fault Circuit-Interrupters," UL 1699, April 2006, Section 40.4, p. 40.

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

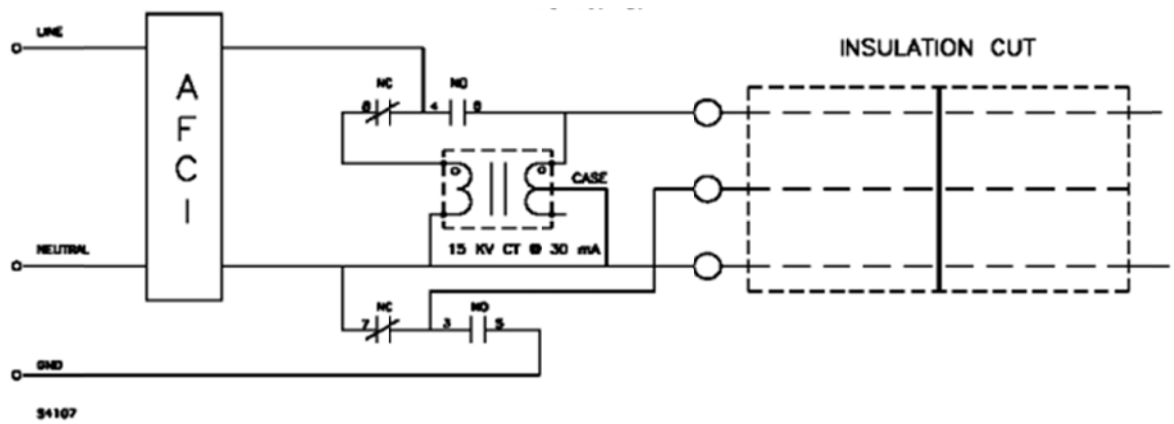


Figure 7. Carbonized path arc interruption test apparatus, as specified in UL 1699, Section 40.3.

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.[9] 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.

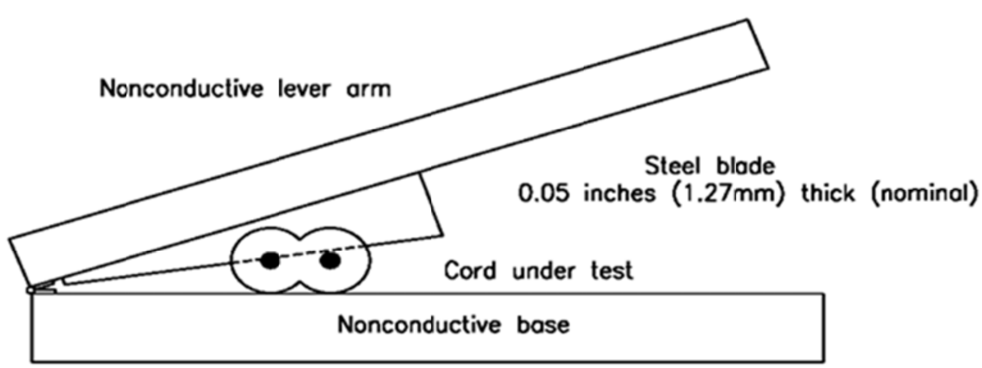


Figure 8. Point contact test apparatus (“guillotine”), as specified in UL 1699, Section 40.5.

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 9), 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.

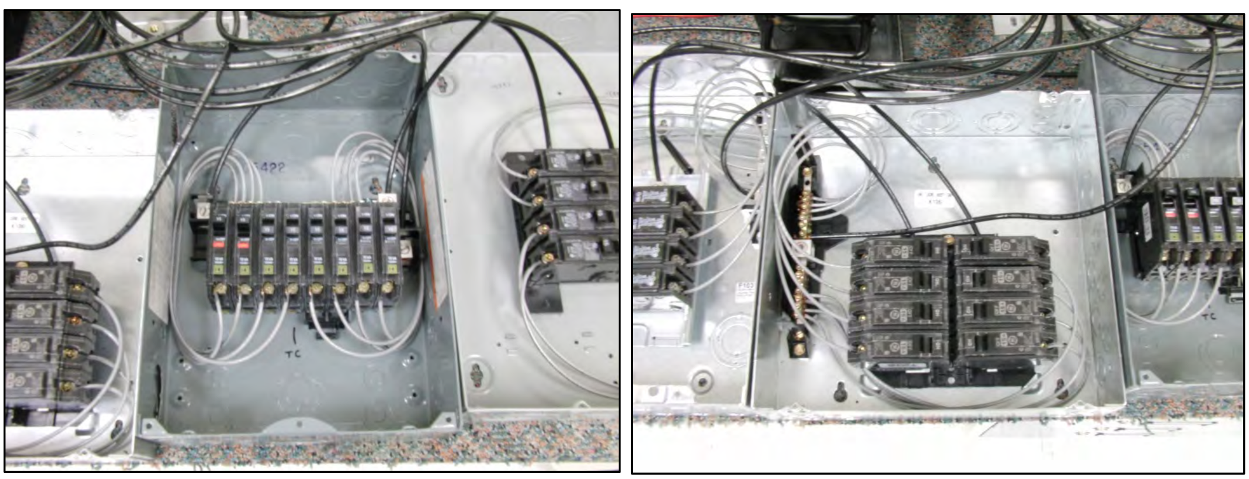


Figure 9. Representative photos of the circuit breakers under test mounted into commercially available electric panels.

The home run was simulated with an unbroken run at lengths of 15, 30, 40, and 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°C to 30°C, 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 10.

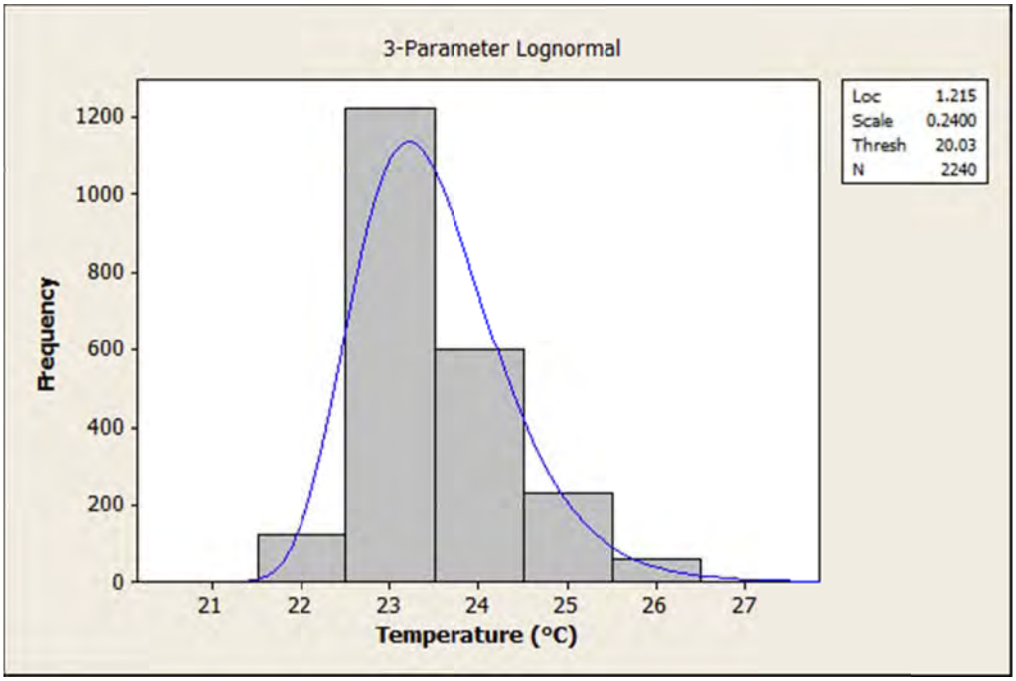


Figure 10. Distribution of cable temperature for all arcing tests (Parts I and II), which was specified to be maintained between 20°C and 30°C.

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.

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).

Data Analysis

Analysis of Circuit Breaker Performance Normalized to Magnetic Trip Level

As is known from the circuit breaker calibration discussed in Part I, the circuit breaker response time is dependent on the magnetic trip level of that particular circuit breaker. Furthermore, it was observed that two breakers despite being of the same model from the same manufacturer may exhibit different magnetic trip levels. Therefore further analysis would benefit using a “normalized” magnetic trip current, defined as:

$$\bar{I}_{mag} \equiv \frac{\left|I_{ssc(rms)}\right|}{\left|I_{mag(rms)}\right|}$$

where I_{ssc} is the short-circuit current and I_{mag} is the magnetic trip level of the circuit breaker. Defining this normalized magnetic trip current allows circuit breakers possessing different magnetic trip levels to be compared together. Using this normalized current and key test parameters, the correlation of each key variable can be analyzed using ANOVA. Table 5 contains the results of this analysis. The results show that the number of arcing half-cycles and the total arc energy released are strongly linked to one another, suggesting that analyses using these two attributes will correlate highly with one another. This is supported in the fact that the R_{sq} values of other test variables are similar between the arcing energy and number of arcing half-cycles. The strongest correlations are related to whether the breaker trips and whether the circuit breaker passes the UL1699 criterion, however, these are not variables that can be directly tied to a specific circuit breaker. The magnetic trip level is a value that can be measured in a circuit breaker, and therefore is used as the primary variable in assessing a circuit breaker’s ability to

mitigate arcing half-cycles and arc energy release. Manufacturer is found to have minor correlation to circuit breaker performance, but this simply reflects the fact that breakers from different manufacturers tend to have different magnetic trip levels. Among the variables that show little significance include run length and available panelboard current. Though this is not intuitive at first, observation of Figure 11 shows why the R_{sq} value is relatively low: The relationship of arc energy and number of arcing half-cycles is more strongly dictated by magnetic trip level rather than by circuit parameters alone. Though having an influence on trip behavior, the magnetic trip level (as well as normalized trip level) is far stronger predictors of circuit breaker performance. Breaker position and test iteration number show no correlation, meaning that performance does not vary among breakers of the same model type and position in the panelboard, and that successive tests of the same circuit breaker give repeatable results. The moderate value for the influence of test type (UL1699 Section 40.*x*) reflects the fact that 40.3 carbonized path tests tend to result in shorter arcing events than 40.4 and 40.5 tests.

Circuit Breaker Performance Relative to Magnetic Trip Level

From the statistical analysis of the arcing behavior, most test variables can be eliminated from consideration, including circuit breaker position, manufacturer, age, iteration number, and absolute magnetic trip level. As the analysis shows, the short-circuit current is the dominant variable controlling circuit breaker magnetic trip level. Therefore, to be able to compare performance between circuit breakers with different magnetic trip levels, the normalized current will be used as defined earlier. A normalized current of 1.0 denotes operation at the circuit breaker magnetic trip level; values less than 1 denote operation below the magnetic trip level (operating in the thermal trip regime); and values greater than 1.0 denote operation above the magnetic trip level. As it has already been discussed that specific arcing behavior is independent of the test variables (except for time), and thus only the number of arcing events and their occurrence in time are considered for the remainder of this work.

As can be seen in each plot in Figure 11, though arcing greatly diminishes when the magnetic trip level is reached, significant arcing may occur at or below a normalized current above 1.0. As can be seen, at or even slightly above the magnetic trip level, arcing can be significant and of a very long duration.

Table 5. ANOVA analysis showing effect of test variables on number of arcing cycles and energy release, includes data for 500A and 1000A available current for run lengths of 15 feet to 50 feet.

Effect of	**On**	R_{sq}, %	$R_{sq(adj)}$, %	P	N
Number Arcing Half-Cycles	Total Arc Energy Release	90.64	90.52	0.000	2239
Breaker Pass/Fail	Number Arcing Half-Cycles	75.10	75.08	0.000	2239
Breaker Pass/Fail	Total Arc Energy Release	69.26	69.23	0.000	2239
Norm. Mag Trip Level	Total Arc Energy Release	63.44	59.95	0.000	2239
Norm. Mag Trip Level	Number Arcing Half-Cycles	57.00	52.89	0.000	2239
Breaker Trip	Total Arc Energy Release	31.25	31.22	0.000	2239
Breaker Trip	Number Arcing Half-Cycles	36.93	36.90	0.000	2239
Magnetic Trip Level	Number Arcing Half-Cycles	25.07	24.63	0.000	2239
Magnetic Trip Level	Total Arc Energy Release	23.87	23.42	0.000	2239
Short-Circuit Current	Total Arc Energy Release	21.38	20.92	0.000	2239
Manufacturer	Number Arcing Half-Cycles	20.07	19.96	0.000	2239
Manufacturer	Total Arc Energy Release	19.00	18.89	0.000	2239
UL 1699 Sec 40.X	Total Arc Energy Release	17.52	17.45	0.000	2239
Short-Circuit Current	Number Arcing Half-Cycles	17.66	17.18	0.000	2239
UL 1699 Sec 40.X	Number Arcing Half-Cycles	9.51	9.43	0.000	2239
Home Run Length	Number Arcing Half-Cycles	4.15	4.02	0.000	2239
Home Run Length	Total Arc Energy Release	1.71	1.57	0.000	2239
Avail Panelboard Current	Number Arcing Half-Cycles	0.37	0.33	0.004	2239
Avail Panelboard Current	Total Arc Energy Release	0.26	0.21	0.017	2239
Breaker Position	Number Arcing Half-Cycles	0.51	0.20	0.123	2239
Breaker Position	Total Arc Energy Release	0.50	0.19	0.131	2239
Test Iteration No	Number Arcing Half-Cycles	0.14	0.00	0.525	2239
Test Iteration No	Total Arc Energy Release	0.13	0.00	0.586	2239

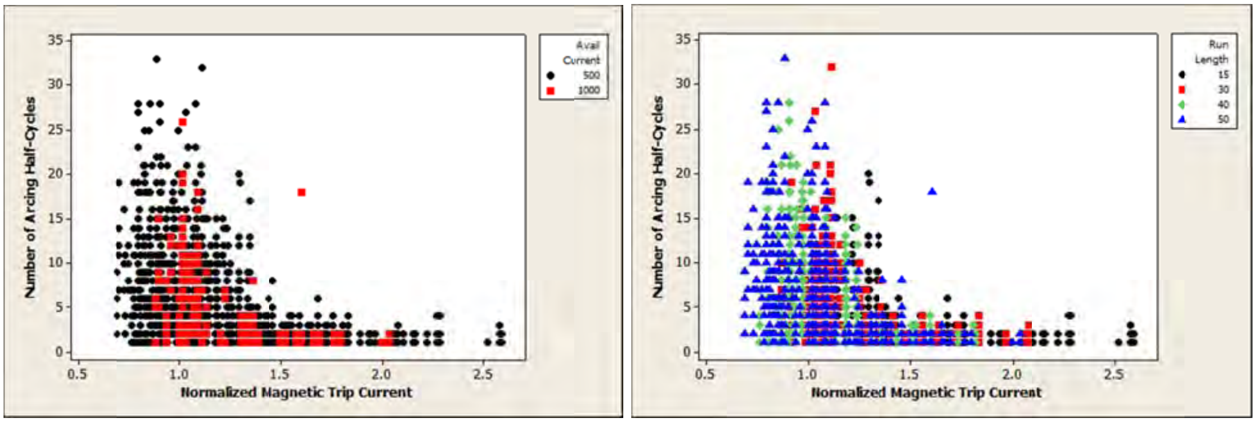


Figure 11. Number of arcing half-cycles as a function of normalized magnetic trip current. (*Left*) indexed to available fault current; (*Right*) indexed to home run length. Data from Parts I and II only (500A and 1000A available).

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 6.

Table 6. 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 6, as can be seen in Table 7 and Figure 12 (*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 12, (*right*).

Table 7. Results from all arcing tests (Parts I and II), 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	246	101	131	478	Inconclusive
Yes	Pass	523	523	368	1414	Pass
No	Fail	29	171	133	333	Fail
Yes	Fail	2	5	8	15	Fail (rare case)

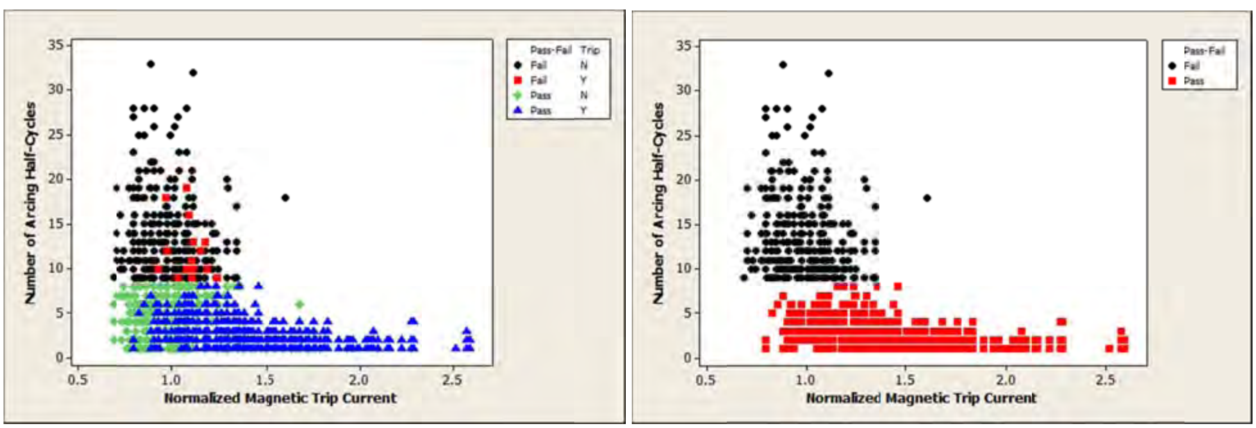


Figure 12. Scatter plots showing circuit breaker performance for all arcing tests, based on number of arcing half-cycles. (*Left*) Data coded by the four criteria as described in Table 6. (*Right*) Data marked pass/fail only, with inconclusive data (less than eight arcing half-cycles but no trip) removed.

The data in Figure 12 show that a threshold value for normalized magnetic trip current can be set to ensure a high probability that the circuit breaker will trip within eight arcing half-cycles. However, more

than one approach can be used for this. The simplest approach is to identify the largest normalized magnetic trip value where circuit breakers fail to trip within eight arcing half-cycles, and set the threshold at or above this value. Reviewing Figure 12 (*right*), with the exception of a single outlier point (the results of this outlier will be discussed in a later section), there were four tests at $\bar{I}_{mag}$ = 1.34 where the circuit breakers failed to trip within eight half-cycles. Above this level (again, neglecting the single outlier point) all breakers tripped in time. Therefore, the threshold criterion can be set to a value at 1.34, which would imply that the short-circuit current needs to be greater than 1.34 times that of the magnetic trip level of the circuit breaker. Inversely, this would also suggest that the magnetic trip level needs to be set at 1/1.34 = 75% of short-circuit current to be effective. Another approach would be to observe that one could fit an exponential-decay curve along the upper bound of data points, effectively resulting in a curve that would result in a function relating $\bar{I}_{mag}$ to number of arcing half-cycles. Such a curve would pass through a data point at $\bar{I}_{mag}$ = 1.46, where a circuit breaker tripped in exactly eight arcing half-cycles. Therefore, such an approach would suggest that the short-circuit current would need to be 1.46 times that of the breaker magnetic trip level, again inversely this suggests that the magnetic trip level of a circuit breaker would need to be 1/1.46 = 68% of short-circuit current. Though the 68% value would add conservatism, it would likely result in far too much since no arcing test fell below 75%. Considering also that additional factors will be added that will have the effect of making the final relationship more conservative, 75% is therefore concluded to be the threshold.

Energy Release and Normalized Magnetic Trip Level

An approach to refine the threshold value of $\bar{I}_{mag}$ is to evaluate the amount of total arcing energy release for each arcing event and find where this total energy release approaches zero. This approach would build in a second layer of confidence in the choice for the threshold value, since material ignition relies on the transfer of arcing energy, and selecting an operating regime where this approaches zero would suggest a high probability of mitigating risk of fire due to arcing. The relationship of energy release to normalized magnetic trip level is shown in Figure 13.

The data show an upper bound that can be characterized by a linear relationship, as is shown in Figure 14. This relationship for the upper bound of energy release is the following:

$$E_{arc}(\bar{I}_{mag}) = 27479 - 19312 \cdot \bar{I}_{mag}$$

Note that this is a fit of the upper bound of data points. Solving for E_{arc} = 0:

$$0 = 27479 - 19312 \cdot \bar{I}_{mag}$$

$$\bar{I}_{mag} = \frac{27479}{19312} = 1.42$$

This result suggests that zero energy release is approached when the normalized magnetic trip level reaches 1.42, which implies a magnetic trip level equal to 1/1.42 = 70%. This value is in between the range 75% and 68% that was found when considering arcing half-cycles, and therefore is consistent with that result.

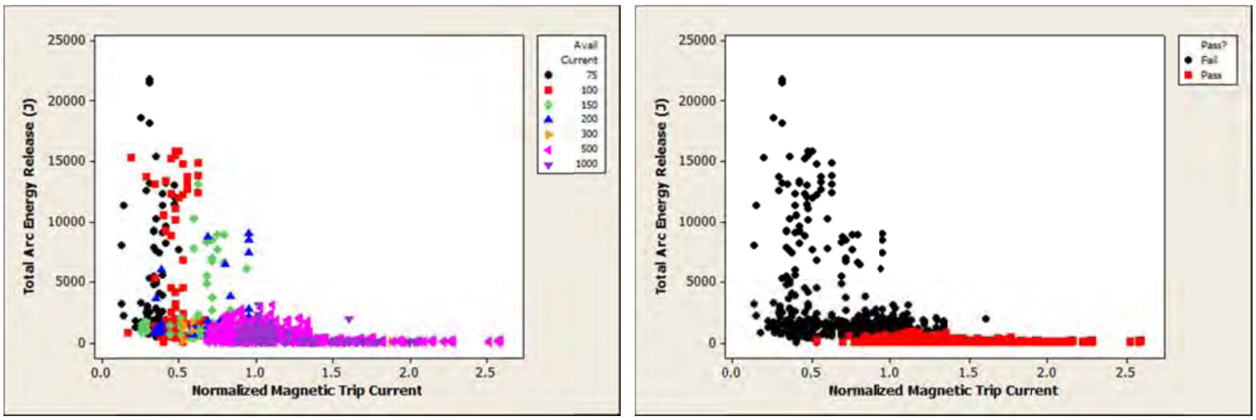


Figure 13. Relationship of total arcing energy released to magnetic trip level. (*Left*) Indexed by available fault panelboard current.[10] (*Right*) Indexed by pass/fail criterion per UL 1699. Data from Ref. 7, and Parts I and II of this study are all included.

Though the goal of zero theoretical energy release would be preferable, it is likely that it is adding too much conservatism into the calculations, considering again that none of the circuit breakers exceeding the eight half-cycle criterion exceeded 75% normalized magnetic trip current. The result does show that 68% is likely too conservative; since it exceeds the limit of zero theoretical energy release at 1/1.33 = 70% normalized magnetic trip level. Conversely, using a limit of 75% suggests a nonzero upper theoretical limit on energy release: using the relationship above the maximum energy release can be calculated:

$$E_{arc}\left(\bar{I}_{mag} = 1.33\right) = 27479 - 19312(1.33) = 1730\ \mathrm{J}$$

[10] Note that the use of the term “available current” is mixed in Figure 13 (*left*). For available currents from 75A to 300A, “available current” is defined as the short-circuit rms current. For 500A and 1000A, the “available current” is that measured at the panelboard, and varies between 234A and 389A (per Table 4). Note that this mix of data gives a uniform relationship for total arc energy release and normalized magnetic trip level, suggesting that the upper bound applies at minimum from 75A to 389A available.

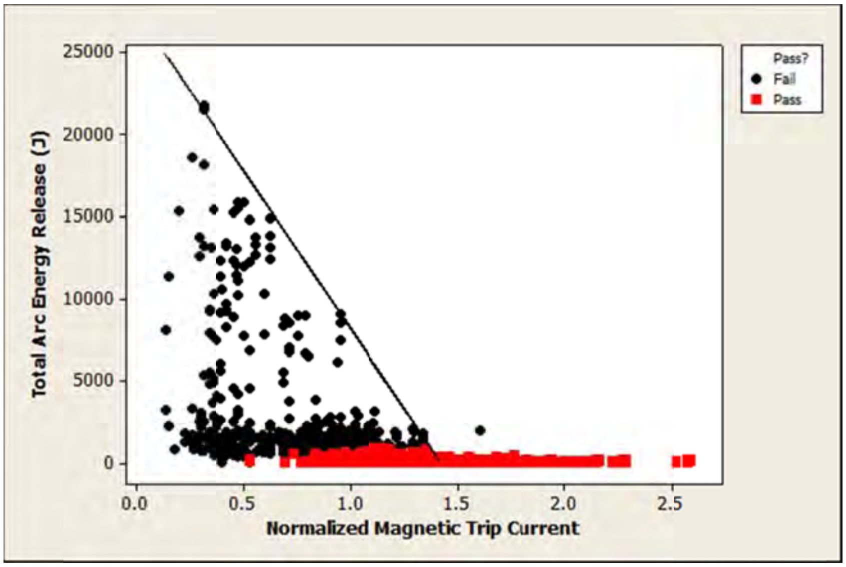


Figure 14. Energy release data with linear curve fit shown. Zero intercept is located at $\bar{I}_{mag}$ = 1.42.

Therefore, it is calculated that at a 75% normalized magnetic trip level it is expected that total arc energy release will not exceed 1730 J. From previous work,[11] the upper bound of probability of ignition for this energy level is 19%. Note that this is a theoretical maximum: the data in Figure 14 and Table 10 from Ref. 11 show that circuit breakers with $\bar{I}_{mag}$ at 1.33 (75%) that pass the eight half-cycle criterion are expected to release 1 kJ or less energy, depending on available short-circuit current, or a probability of ignition at or below 10%.

Normalized Peak Current and Test Type

In Task 1 it was shown that a contact resistance is present for point contact arcing tests, which has a negligible effect at lower available short-circuit currents (for example, when there is 500A available at the panelboard and a 50-foot home run length in place), but becomes more significant as short-circuit current increases. As can be seen in Figure 15 and Table 8, the distribution in normalized current remains around the 0.75 value calculated before, which suggests that a threshold of this value will result in tripping of the circuit breaker within a few half-cycles (statistically, there is a 50% probability of tripping on a single half-cycle if the median value is equal to 0.75). However, if the distribution falls below 0.75, as is seen as the point contact test short-circuit current increases; the probability of an arcing half-cycle to exceed this threshold of 0.75 begins to diminish (again statistically, the probability of tripping on a single half-cycle

[11] Value is derived from Figures 21 and 26, and Table 10 from P. Brazis and F. He, “Effectiveness of Circuit Breakers in Mitigating Parallel Arcing Faults in the Home Run,” UL Corporate Research Report, January 2012.

falls to 25% if the upper quartile is equal to 0.75). Once the distribution falls sufficiently far from 0.75, a circuit breaker with a magnetic trip level set according to the mathematical relationship will fail the eight arcing half-cycle criterion. Furthermore, it can be seen that the point contact arcing test consistently has statistical values less than the carbonized path tests; therefore, any corrective factor will be based on data from point contact arcing. As seen in Figure 15 (*right*), the normalized current distribution for point contact arcing remains consistent with the carbonized path arcing if data are normalized to short-circuit values measured through the guillotine blade. This shows that the drop in normalized current seen for increased I_{ssc} is due to series resistance through the guillotine blade and related contact resistance.

Table 8. Normalized peak arcing current statistics, with respect to UL1699 Section number and short-circuit current.

UL1699 40.*x*	I_{ssc} (A)	Panelboard Current (A)	Run Length (ft)	Normalized Current				
				Median	Mean	Upper Quartile	Lower Quartile	*N*
3	377.6	500	15	0.724	0.712	0.839	0.629	206
	299.2	1000	50	0.785	0.750	0.848	0.676	305
	294.3	500	30	0.767	0.741	0.822	0.691	340
	259.5	500	40	0.750	0.719	0.815	0.643	179
	234.3	500	50	0.824	0.797	0.880	0.734	531
4	388.6	500	15	0.722	0.697	0.751	0.667	256
	309.2	500	30	0.718	0.709	0.764	0.662	539
	304.8	1000	50	0.719	0.653	0.779	0.657	613
	272.3	500	40	0.742	0.731	0.781	0.694	806
	238.7	500	50	0.783	0.765	0.838	0.724	976
5 (Bolted Short)	386.3	500	15	0.628	0.589	0.697	0.510	464
	311.1	500	30	0.704	0.664	0.743	0.621	755
	270.8	500	40	0.728	0.685	0.763	0.645	861
	247.8	500	50	0.730	0.695	0.764	0.665	1189
5 (Blade Short)	352.3	500	15	0.689	0.646	0.765	0.559	464
	304.1	500	30	0.720	0.679	0.760	0.635	755
	268.5	500	40	0.734	0.691	0.770	0.650	861
	241.8	500	50	0.749	0.713	0.783	0.681	1189
Average	297.8			0.734	0.702	0.787	0.652	627

Figure 16 shows graphically the drop in the statistical values for the point contact arcing, suggesting that a correction factor is needed for more accurate prediction of the normalized magnetic trip level that is needed for predicting circuit breaker performance. This plot shows that adjusting the normalized magnetic trip level as a function of short-circuit current will add considerable complexity to the mathematical relationship. However, the discussion about short-circuit current in Task 1 suggests that this drop could be characterized by a contact resistance value that would be reasonably independent of I_{ssc}. Therefore, the point contact effect is incorporated into the mathematical relationship by adding an additional resistance, R_C, to the factors for home run cable resistance and available current at the panelboard:

$$R = 2\rho_L L + \frac{V_{rms}}{I_{pssc}} + R_C$$

This new equation for circuit impedance will be used for a revised calculation for the mathematical relationship between run length, available current at the panelboard, and breaker magnetic trip level.

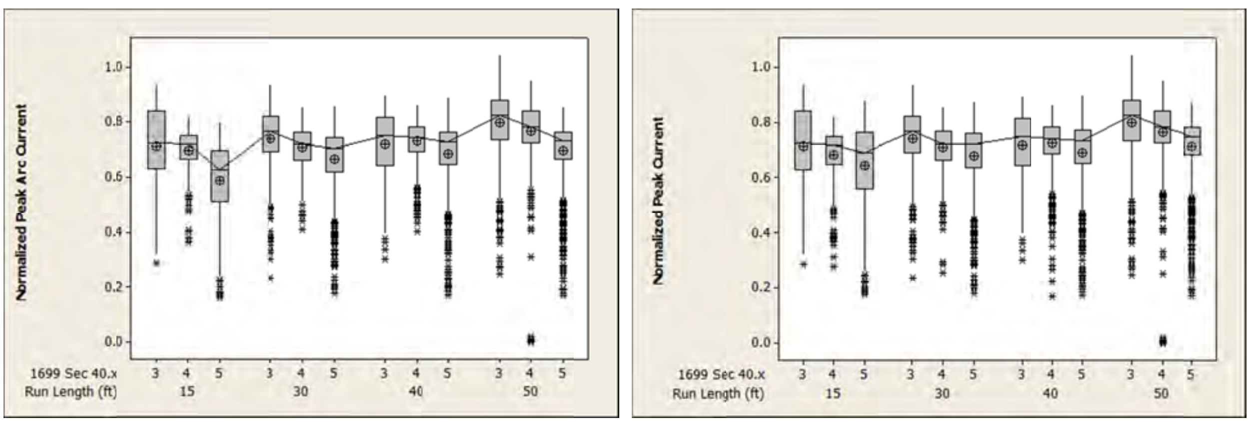


Figure 15. Boxplot of normalized peak arcing current by run length and UL1699 Section number (40.*x*). All data shown are for 500A available at the panelboard. (*Left*) Data for point contact (Section 40.5) normalized to bolted-fault I_{ssc} value. (*Right*) Data for point contact normalized to blade short-circuit values.

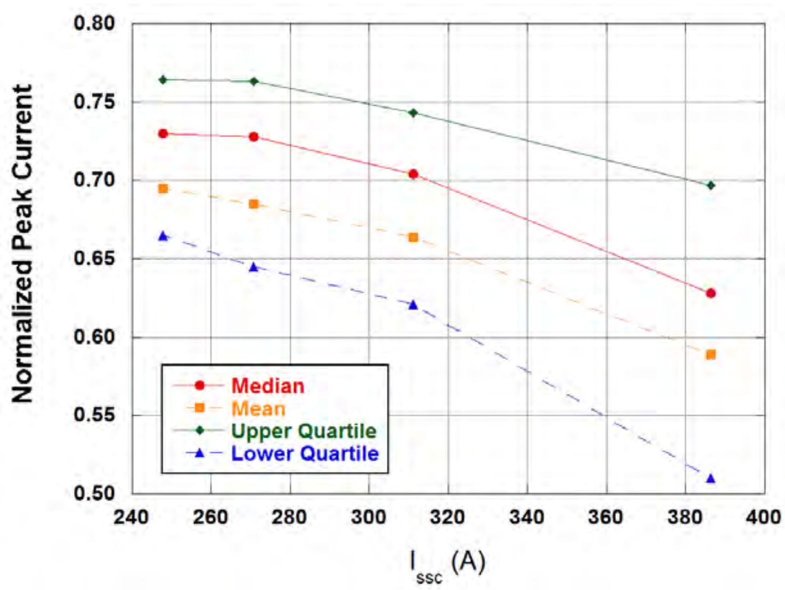


Figure 16. Statistical distribution of normalized peak current for point contact arcing (UL1699 Section 40.5), as a function of short-circuit current.

Updated Formula for Predicting Circuit Breaker Behavior

The results from this Task have resulted in the following information:

- The analysis of the arc energy release and number of arcing half-cycles shows that the normalized magnetic trip level needs to be set to 1.33, or a threshold of 75% of short-circuit current. This is slightly lower than the previous result of 80%, but is based on a much larger sample size.
- Due to the series resistance of the guillotine blade, a correction factor is added to compensate for reduced fault current as the short-circuit current increases. This is applied for all arcing situations since it is not clear what type of arcing will be encountered, and point contact arcing is found to be consistently lower than carbonized path arcing.

Starting with the first bullet point, the short-circuit current must exceed the magnetic trip level of the circuit breaker by a factor of 1.33:

$$\frac{I_{max}}{I_{mag}} > 1.33$$

Solving for I_{max},

$$I_{max} > \frac{I_{mag}}{0.75}$$

The short-circuit current is related to the wire impedance and supply voltage by Ohm's Law:

$$V_{rms} = I_{max} \cdot R$$

The resistance *R* is governed by the resistivity of the cable, the available current at the panelboard, plus a series contact resistance:

$$R = 2\rho_L L + \frac{V_{rms}}{I_{pssc}} + R_C$$

where *L* is the length of the home run in feet, ρ_L is the resistivity of the cable in ohms/foot, I_{pssc} is the available current at the panelboard, and R_C is the series contact resistance from point contact arcing. The factor of 2 is added to incorporate the resistance of the supply and return cables (this assumes the return path is of the same wire gauge as the supply gauge, generally true for NM cable). Combining these equations results in the inequality:

$$V_{rms} > \frac{I_{mag}}{0.75}\left(2\rho_L L + \frac{V_{rms}}{I_{pssc}} + R_C\right)$$

$$\frac{0.75V_{rms}}{I_{mag}} > 2\rho_L L + \frac{V_{rms}}{I_{pssc}} + R_C$$

$$2\rho_L L < \frac{0.75V_{rms}}{I_{mag}} - \frac{V_{rms}}{I_{pssc}} - R_C$$

$$\rho_L L < \frac{V_{rms}}{2}\left(\frac{0.75}{I_{mag}} - \frac{1}{I_{pssc}} - \frac{R_C}{V_{rms}}\right)$$

The last equation above is the same that was derived in Ref. 7, but with a lowering of the arc current threshold to 75% of short-circuit current from 80%, and an added term that compensates for contact resistance that becomes significant when short-circuit current increases during a point contact arc. Though this last term applied to a point contact arcing scenario, the last term can be left in for carbonized path arcing, resulting in a conservative value for maximum run length. However, the last term can be neglected in calculations exclusively focused on carbonized path arcing events.

Task 3 – Verification of Formula Using Arcing Data

The goal of this Task is to use the formulation derived in Task 2 to verify whether the relationship accurately predicts the magnetic trip level of a circuit breaker to pass the UL1699 eight half-cycle criterion. Solving for I_{mag}:

$$I_{mag} < 0.75 \cdot V_{rms} \left(2\rho_L L + \frac{V_{rms}}{I_{pssc}} + R_C \right)^{-1}$$

To solve for I_{mag} for known values of I_{pssc}, V_{rms} (here, 120 V_{rms}), and L, values for ρ_L and R_C are needed. For ρ_L, cable resistance per unit foot is based on 14 AWG copper NM cable at room temperature (20°C to 30°C), conditions that were used in the experimental work. In this case, ρ_L is 2.575 mΩ/ft. With regards to R_C, the maximum (*i.e.*, most conservative) value calculated in Task 1 at a relatively high I_{ssc} was 30 mΩ.

Table 9. Comparison of maximum value of I_{mag} and the arcing test results shown in Figure 17. Values in parentheses next to predicted values show deviation from the actual threshold value.

I_{pssc} (A)	L (ft)	I_{ssc} Range (A)	Predicted I_{mag}, 75% with R_C (A)	Predicted I_{mag}, 80% with R_C (A)	Predicted I_{mag}, 75%, no R_C (A)	Predicted I_{mag}, 80%, no R_C (A)	Actual I_{mag} (A)
500	50	235-248	172 (–18)	184 (–6)	183 (–7)	195 (+5)	190
500	40	260-272	191 (–14)	203 (–2)	204 (–1)	217 (+7)	200-210
500	30	294-311	214 (–21)	228 (–7)	230 (–5)	245 (+10)	230-240
1000	50	299-305	224 (–31)	239 (–16)	242 (–13)	258 (+3)	250-260*
500	15	378-389	260 (–20)	278 (–2)	285 (+5)	304 (+24)	280

*Range excludes single outlier, this outlier is discussed further in Appendix A.

Table 9 shows the results of the predicted threshold values for I_{mag} necessary to satisfy the UL1699 eight half-cycle criterion, compared to the actual results as shown in Figure 17. Four calculations were conducted, using either 75% or 80% of short-circuit current at the threshold, as well as presence or absence of the point contact resistance, R_C. The results show that the original formula derived in Ref. 7 fails to accurately predict the maximum magnetic trip level required for passing UL1699. As was observed in Part I, the formula tends to break down as available fault current increases for point contact arcing tests as I_{ssc} increases. Changing the threshold to 75% also fails to compensate for this contact resistance. The values for the calculations that incorporate R_C show that the effect is a constant deviation of the predicted and actual results, showing that the proposed value of 30 mΩ for R_C compensates for the contact resistance. Therefore, the value for R_C is observed as necessary for accurate prediction of a maximum value for the magnetic trip level of a circuit breaker.

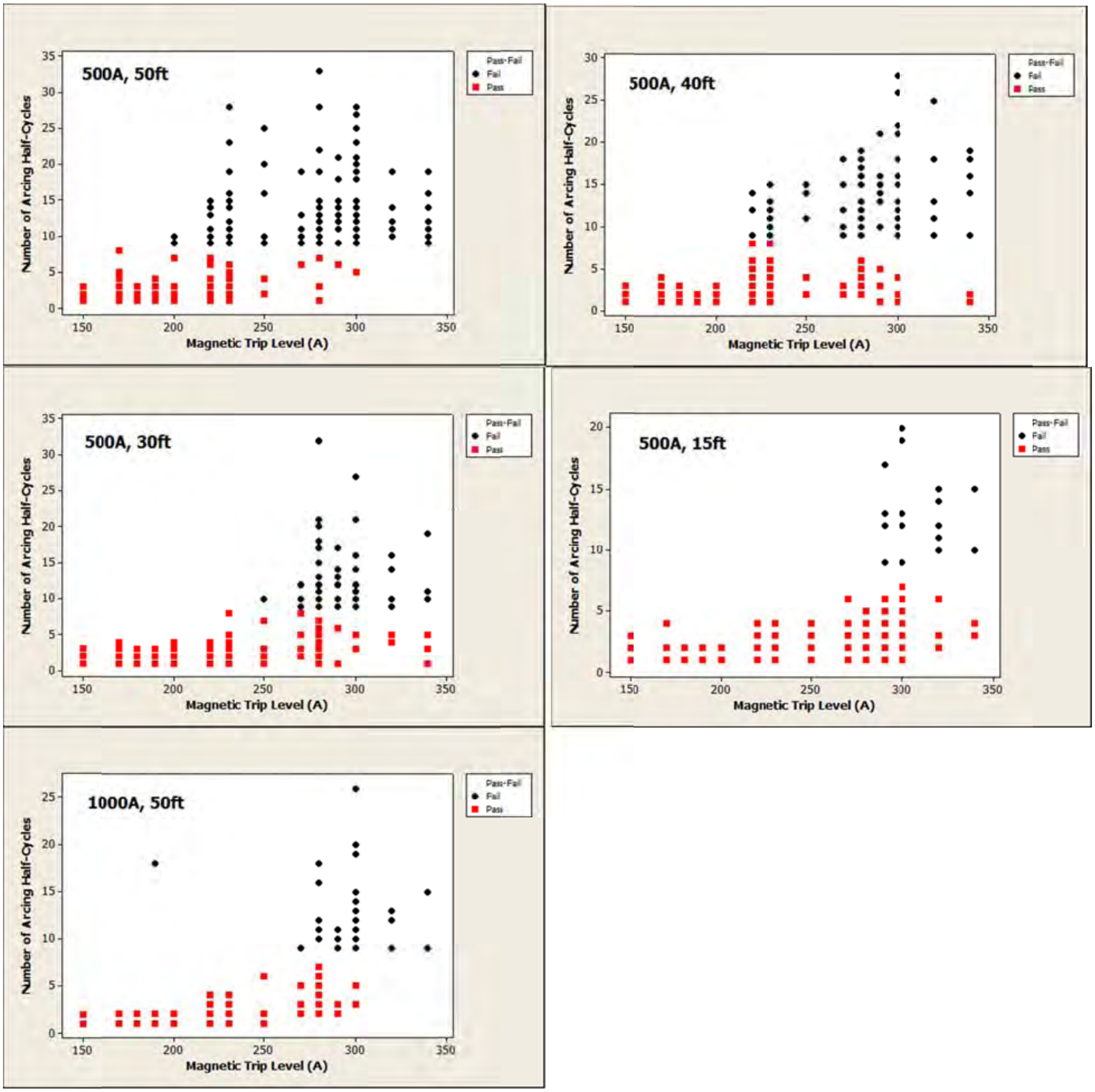


Figure 17. Pass/fail data based on the UL1699 eight half-cycle criterion, with respect to available panelboard current and home run length.

The calculations combining R_C and the new threshold value of 75% of short-circuit current shows values that are approximately 20A lower than the actual threshold. These calculations suggest that both lowering the threshold value to 75% and adding the R_C value doubly compensates for the point contact resistance: though the assessment shown in Figure 12 shows threshold of 75%, this does not consider any additional term for R_C, which has the effect of lowering all predicted values. Therefore, adding R_C to the formula compensates for the needed reduction in the threshold, without a need to also reduce the threshold from 80% to 75%. Calculations using 80% and R_C substantiate this, as shown in Table 9.

Conclusions

The results of Part II were intended to address the following concerns:

- Evaluate and/or correct differences in circuit impedance among different arcing tests, particularly potential apparatus issues in the point contact arcing test.
- Determine whether any additional changes were needed to the mathematical relationship relating breaker magnetic trip level, available panelboard current, and run length.
- Reevaluate mathematical relationship with added experimental data that incorporates varying run lengths from 15 to 50 feet.

Circuit Impedance Considerations

The short-circuit current results shown in Task 1 suggest that the impedance of each test type (the point contact arcing test as well as the two carbonized path arcing tests) were successfully matched to one another so that accurate comparisons between each could be made. Modifications to the point contact arcing test apparatus were made to remove any additional contact resistances in the circuit, specifically aged or differing terminal styles. Subsequent results showed that the point contact arcing test continued to exhibit an additional series resistance that was absent in the carbonized path arcing tests. Comparison of the short circuit current data between bolted fault shorting and shorts created using the guillotine blade show that the additional series resistance is due to the guillotine blade and/or the contact resistance between the blade and the conductors. Though there was variability in the calculated contact resistance, this variability was within an order of magnitude. A final decision was made to use 30 mΩ as the contact resistance value (denoted as R_C in this work). This was found to be the largest calculated value; therefore a level of conservatism is gained using this value. Additionally, the 30 mΩ value was found at the highest short-circuit current test conditions used in this work (500A available and 15 foot home run length), where the series contact resistance would have the greatest influence on circuit behavior.

Changes to Mathematical Relationship

The additional testing completed in Part II of this work resulted in a large data set of more than 2,200 individual arcing tests, spanning a larger range of fault currents than in the previous works. Considering also that data in Part I showed that the mathematical relationship derived in Ref. 7 failed to predict circuit breaker performance for some point contact tests, there was a need to reevaluate the assumptions used in the derivation of the relationship. Therefore, circuit breaker performance in terms of normalized magnetic trip current (the ratio of short-circuit current to the magnetic trip level of the circuit breaker) was evaluated against number of arcing half-cycles and total energy release. This analysis suggested the magnetic trip level needs to be set so that it is a factor of 1.33 above that of the short-circuit current. Conversely, this means that the peak arcing current is expected to be 75% of peak short-circuit current.

Comparison of Calculated Results to Arcing Data

Combining this new threshold with the contact resistance R_C, a new mathematical relationship was derived. Using the 75% threshold and R_C resulted in predictions that were 20A lower than the actual threshold values. This added conservatism can be explained by the fact that the evaluation of the threshold value utilized data without consideration of the additional contact resistance. When the contact resistance is added in, this has the effect of further lowering the calculated value for I_{mag}, for both carbonized path and point contact arcing, and at all current levels. Therefore, the 5% lowering that was calculated can be obtained through the added value for R_C, and therefore the originally proposed threshold value of 80% can be maintained. A calculation using the 80% value with the added contact resistance value results in predicted I_{mag} values that are consistently within 10A of the actual value. Considering that the magnetic trip level of each breaker was calculated to ±5A, these values can be considered as accurately predicting circuit breaker performance.

Summary

In summary, the following key points are a result of this work:

- Point contact arcing introduces an additional series resistance that tends to reduce the available short-circuit current. Short-circuit tests both with the guillotine blade and using a bolted fault show that this contact resistance is estimated to be between 5 and 30 mΩ. Though this series resistance is not present in carbonized path arcing, it is recommended it be used for all calculations since the type of arcing occurring during a fault will not likely be known in a real-world situation.

- The final mathematical relationship is the following, using the 80% threshold as before, but with an added term to compensate for point contact resistance:

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

  or in terms of run length:

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

  In this work, an R_C of 30 mΩ was found to accurately match the point contact results.
- This revised mathematical relationship was found to accurately predict the ability of a circuit breaker to mitigate a parallel arcing fault in the home run. This was proven for available panelboard currents of 500A and 1000A, with home run lengths from 15 feet to 50 feet. It is anticipated that this relationship will apply for other panelboard currents, home run lengths, and cable gauges.
- Temperature considerations are not included in these calculations; the effects of temperature were covered in Part I of this work and still apply.

Appendix A – Discussion of Breaker Outlier Data

Out of 2,239 individual arcing tests conducted in Parts I and II of this work, the results of a single test fell significantly outside of the analysis. Therefore, the data from that test were removed from consideration and details included here so that further failure analysis can be conducted. Note that in Part I several other circuit breaker tests were identified as anomalous: however, the results from Part II show that all but the single event included here were either erroneously identified due to the shortcomings of the prior mathematical relationship (for example, the point contact resistance R_C was not included and the threshold was set to 80% of short-circuit current, not 75%), or were identified as faulty due to instrumentation issues. The improvements in experiment and analysis described in Part II of this work show that the results of only one test remain unexplained.

Description of Test

The single test that falls outside the analysis was encountered with a single circuit breaker from Manufacturer A. The breaker was identified as Breaker No. 14 and was observed on Iteration No. 4. The test conditions were 1000A available panelboard current and 50 foot home run length. The test type was the modified UL1699, Section 40.4 arcing test. The magnetic trip level of the circuit breaker was 190 A_{rms} (269 A_{peak}) and the I_{ssc} for the test was 304.8A ($\bar{I}_{mag}$ = 1.60, or 1/1.60 = 63%). These values predict that the circuit breaker will trip within the eight arcing half-cycle criterion, but 18 arcing half-cycles were recorded. Total arc energy released was 1979 J, or a 23% probability of cable insulation ignition. This circuit breaker passed the other nine arcing tests at the same I_{ssc}, as shown in Table 10.

Table 10. 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

Table 11. Parametric data on each arcing half-cycle for Manufacturer A, Breaker 14, Iteration 4, 40.4 Test for 1000A available and 50 foot run length.

Half-Cycle Number	Strike Angle (deg)	Stop Angle (deg)	Strike Voltage (V)	Stop Voltage (V)	Arc Energy (J)	Peak Current (A)	Voltage at Peak Curr (V)	Duration (ms)
1	29.53	174.38	146.50	20.98	72.88	332.47	88.89	6.706
2	37.41	176.77	98.46	19.92	131.48	370.62	94.53	6.452
3	28.94	176.78	80.31	20.16	137.90	376.29	93.36	6.844
4	34.88	176.52	93.40	21.01	133.98	372.95	93.86	6.557
5	21.89	174.49	59.97	27.30	138.92	365.47	95.53	7.065
6	33.53	174.36	85.87	26.98	133.59	366.76	93.79	6.520
7	28.70	172.25	78.35	35.72	134.87	372.04	92.50	6.646
8	28.30	175.56	75.86	24.07	134.75	344.77	99.59	6.818
9	35.72	171.67	92.23	36.50	129.86	353.82	96.11	6.294
10	39.34	174.33	102.43	27.65	128.59	356.59	95.88	6.250
11	99.90	174.41	160.68	26.93	48.19	301.07	85.20	3.450
12	111.80	174.54	149.74	27.14	31.29	257.90	76.16	2.905
20	87.07	173.95	158.82	29.06	69.12	334.05	90.25	4.022
23	75.10	171.34	150.71	39.34	87.27	345.24	94.93	4.456
25	59.57	173.49	136.14	30.27	108.98	347.31	97.66	5.274
26	64.75	172.53	142.41	33.96	100.94	349.18	94.99	4.990
27	37.67	174.86	95.29	25.28	127.39	340.93	99.79	6.351
28	31.86	172.09	89.84	34.72	128.86	329.01	100.77	6.492

Table 12. Parametric data on each arcing half-cycle for Manufacturer A, Breaker 14, Iterations 1, 2, 3, and 5, 40.4 Test for 1000A available and 50 foot run length.

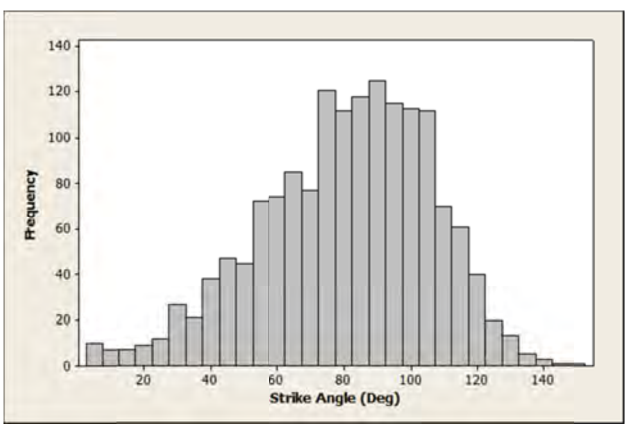
Iteration No	Half-Cycle No	Strike Angle (deg)	Stop Angle (deg)	Strike Voltage (V)	Stop Voltage (V)	Arc Energy (J)	Peak Current (A)	Voltage at Peak Curr (V)	Duration (ms)
1	1	97.87	172.42	143.84	33.11	52.60	235.78	92.29	3.451
1	2	41.42	175.60	86.56	34.62	125.16	332.34	100.72	6.212
2	1	59.89	168.35	127.22	47.07	104.68	341.19	96.75	5.021
3	1	0.67	166.07	11.88	25.06	24.56	224.33	73.33	7.657
3	2	36.19	176.88	82.63	20.81	129.94	356.54	95.20	6.513
5	1	15.82	169.86	112.12	26.76	13.76	176.10	60.10	7.131
5	2	66.85	175.69	138.04	32.19	96.35	351.76	94.81	5.039

Appendix B – Additional Statistical Data for Arcing Tests

This section includes additional statistical information on the arcing tests used in this analysis. These data show the statistical differences between the two carbonized path arcing tests, as well as the differences of point contact arcing.

Strike and Stop Angle

Strike angle is defined as the phase angle where the arcing current begins, defined at the maximum value of *di*/*dt*. Phase angle is defined relative to the voltage supply waveform, with the zero crossings defined at 0 and 180 degrees. Detection is automated through LabVIEW software. Stop angle is detected and defined the same as strike angle, but designates the phase angle where the arcing current ends. Figure 18, Figure 19, and Figure 20 show the strike and stop angle distributions for the UL1699, Sections 40.3, 40.4, and 40.5 arcing tests, respectively. Strike angle for carbonized path tests show a threshold value, reflecting the need for a minimum voltage to be attained before an arc will strike. Note that this voltage threshold in more defined in 40.4 tests than 40.3 tests. 40.3 data may be more spread due to the shorter duration of their occurrence, and the fact that the carbonized path is less defined and shorter-lived for 40.3 arcing events than for 40.4 events. The point contact arcing strike voltage (40.5) show an absence of this threshold voltage, since the arc strike is dependent on the guillotine blade establishing a point contact, which is independent of supply voltage. The stop voltage for point contact arcing is also more widely distributed, again affected by removal of the guillotine blade, or from damage/destruction of the blade at the arcing contact point.



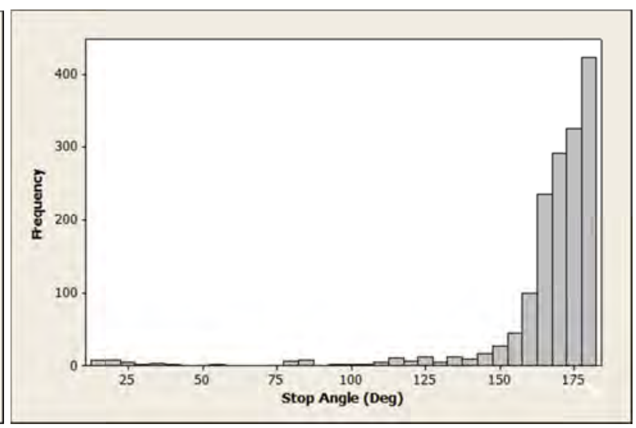


Figure 18. (*Left*) Strike angle and (*right*) stop angle for carbonized path arcing tests, conducted according to UL1699, Section 40.3.

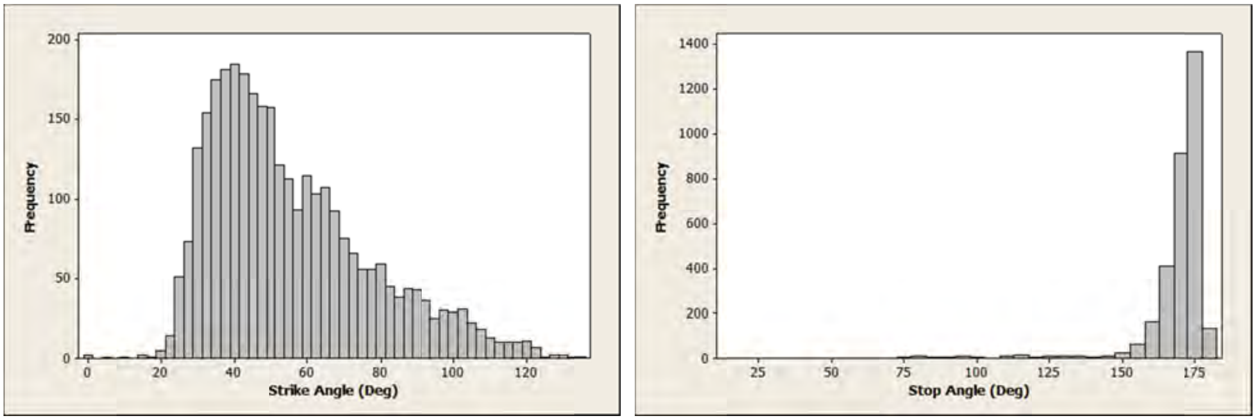


Figure 19. (*Left*) Strike angle and (*right*) stop angle for carbonized path arcing tests, conducted according to methods described in UL1699, Section 40.4. (Excludes the 1st arcing half-cycle, since the voltage was applied without phase angle control, influencing the measured strike angle.)

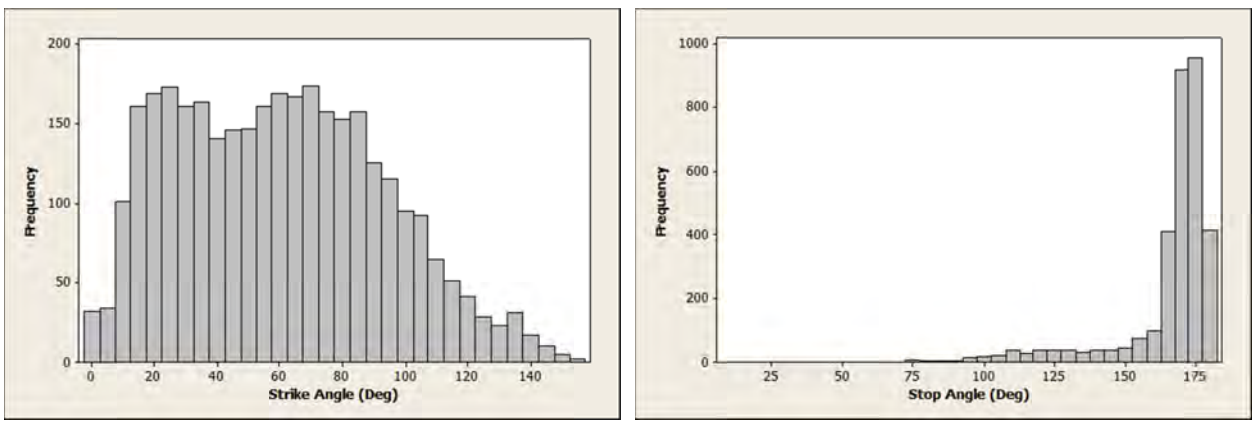
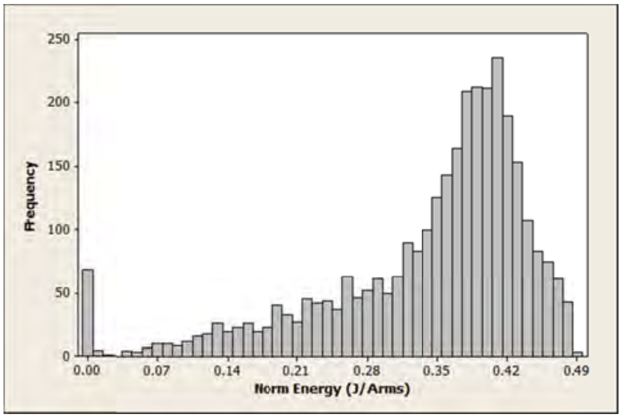


Figure 20. (*Left*) Strike angle and (*right*) stop angle point contact arcing tests, conducted according to UL1699, Section 40.5.

Arc Energy

Shown in this section is the arc energy per half-cycle, for the 40.4 and 40.5 arcing tests conducted in this work. There was an issue with the energy calculation for 40.3 tests, and therefore the data are not included here. The arc energy analyzed in this section were normalized per unit Ampere, based on the

short-circuit current, I_{ssc}. More details on the arcing energy behavior can be found in Ref. 7. This is shown in Figure 21. The point contact data show some bimodality, which is related to bimodality observed in the peak voltage values. However, the nature of this voltage effect was not investigated.



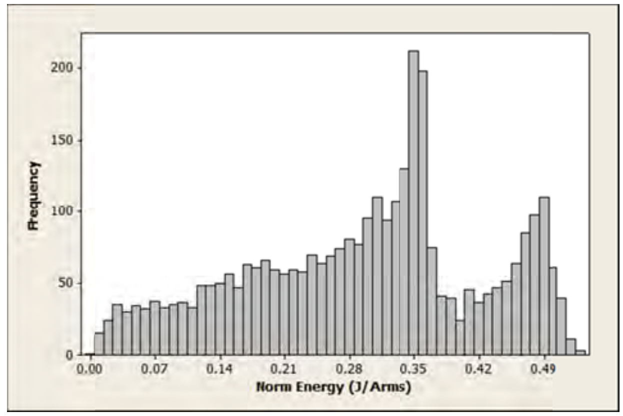


Figure 21. Normalized energy per arcing half-cycle. (Left) carbonized path arcing based on UL1699 Section 40.4 methods. (Right) point contact arcing according to UL1699, Section 40.5.

Normalized Peak Current

The normalized peak current is defined as the maximum current magnitude within an arcing half-cycle, normalized to the peak short-circuit current. Data are shown in Figure 22. The data show similar distributions for each of the three arcing types, with median normalized current values between 0.7 and 0.8. Additional values below the median are found for the point contact data relative to the carbonized path data, which is reflective of the series resistance attributed to the contact resistance of the guillotine blade.

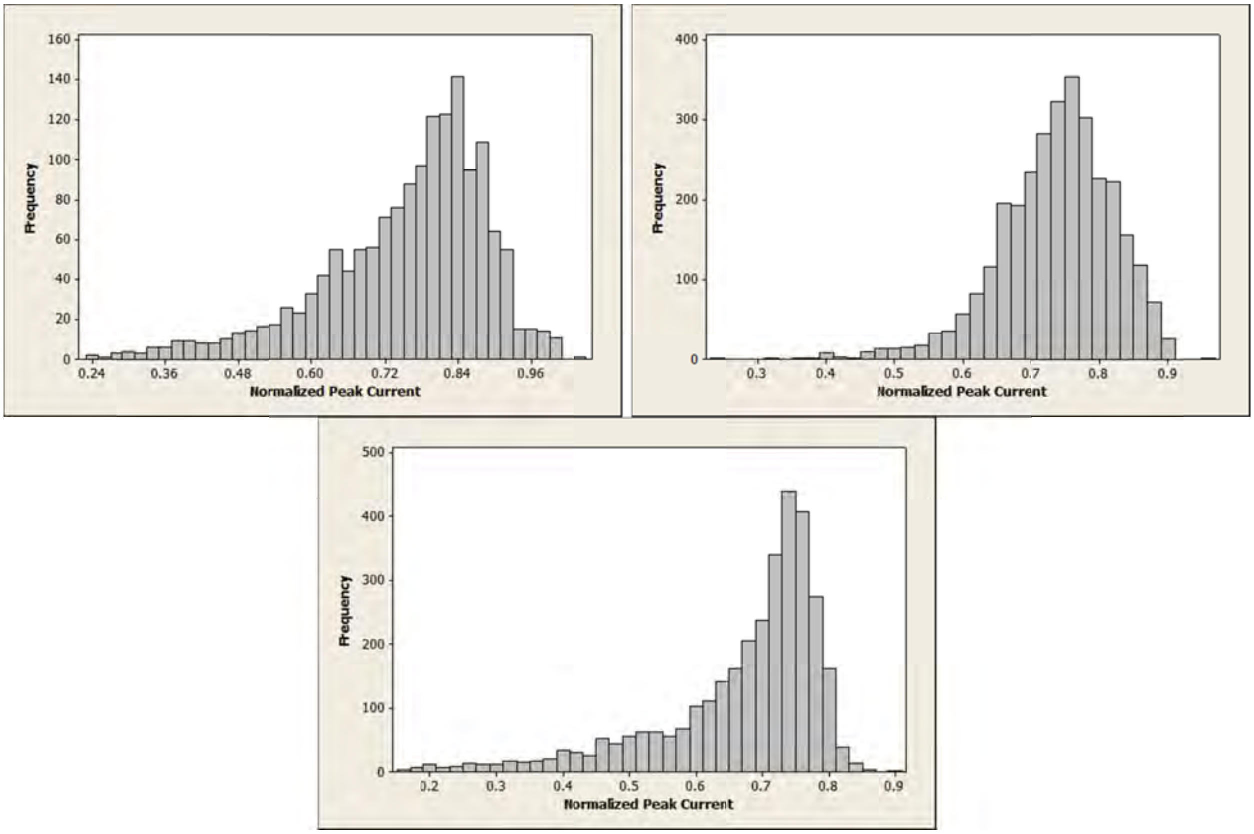


Figure 22. Peak current distributions for (*top left*) Section 40.3 carbonized path arcing test, (*top right*) Section 40.4 carbonized path arcing test, and (*bottom*) Section 40.5 point contact arcing test.

Appendix C – Temperature Considerations

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°C (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°C). Using this formula to solve for R_2, the equivalent resistance at 25°C can be adjusted to any desired temperature, for example for converting to 90°C:

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

Solving for R_2 gives a resistance of 3.157 mΩ/ft at 90°C 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.

Table 13. 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, °C	−35	−10	0	10	25	40	60	90
$\rho_L(T)$, mΩ/foot 14AWG	1.941	2.184	2.282	2.379	2.525	2.671	2.866	3.157
$\rho_L(T)$, mΩ/foot 12AWG	1.221	1.374	1.435	1.496	1.588	1.680	1.802	1.986

Appendix D – Table of Calculations for Mathematical Formula

Assumptions: R_C = 30 mΩ; V_{rms} = 120V; 14 AWG ρ_L at 25°C = 2.525 mΩ/ft, 12 AWG ρ_L at 25°C = 1.588 mΩ/ft , clean electrical-grade copper conductors, and varies according to the relationship in Appendix C (see Table 13).

Table 14. Predicted maximum magnetic trip level to meet UL1699 criterion, 14 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Run Length, ft**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
25	**0**	356	505	640	1067	1371	1778	2087	2286
	1	349	492	619	1010	1279	1626	1881	2040
	2	343	480	600	959	1199	1498	1711	1843
	5	325	446	548	833	1008	1211	1347	1428
	10	300	399	479	683	797	919	995	1038
	15	278	361	425	579	659	740	789	815
	20	259	330	382	503	561	619	653	671
	30	228	281	318	398	433	467	486	496
	40	203	245	273	329	353	375	387	393
	50	184	217	239	280	298	313	322	326
	75	148	169	182	205	214	222	226	228
	100	124	138	147	161	167	172	174	176
	150	93	101	106	113	116	118	119	120
	200	75	80	83	87	89	90	91	91
	500	34	35	36	37	37	37	37	37
40	**0**	356	505	640	1067	1371	1778	2087	2286
	1	349	491	618	1007	1274	1618	1870	2028
	2	342	478	597	953	1190	1484	1694	1822
	5	324	443	543	823	993	1189	1320	1397
	10	297	394	472	669	778	894	966	1006
	15	274	355	417	564	639	716	761	786
	20	255	323	374	488	543	597	628	645
	30	223	274	309	384	417	448	465	475
	40	198	238	264	316	338	359	370	375
	50	179	210	230	269	285	299	307	311
	75	143	163	174	196	204	211	215	217
	100	119	133	140	154	159	163	165	167
	150	90	97	101	108	110	112	113	114
	200	72	76	79	83	84	86	86	86
	500	33	34	34	35	35	35	35	35

Table 15. Predicted maximum magnetic trip level to meet UL1699 criterion, 14 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Run Length, ft**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
60	**0**	356	505	640	1067	1371	1778	2087	2286
	1	348	490	616	1003	1268	1607	1856	2011
	2	341	477	595	946	1178	1466	1671	1796
	5	321	439	537	809	973	1161	1286	1359
	10	293	388	463	652	754	862	929	967
	15	270	348	407	546	615	686	727	750
	20	250	315	363	469	520	569	598	613
	30	217	265	298	366	397	425	440	449
	40	192	229	253	301	321	339	349	354
	50	172	201	220	255	269	282	289	292
	75	137	155	166	185	192	198	202	203
	100	114	126	133	145	149	153	155	156
	150	85	91	95	101	103	105	106	106
	200	68	72	74	78	79	80	81	81
	500	31	31	32	32	33	33	33	33
90	**0**	356	505	640	1067	1371	1778	2087	2286
	1	347	489	614	997	1258	1592	1835	1987
	2	340	474	590	935	1162	1441	1637	1757
	5	318	433	529	790	945	1122	1238	1305
	10	288	379	450	627	721	820	880	913
	15	263	337	392	520	583	646	682	702
	20	242	304	347	444	489	533	557	570
	30	209	253	283	344	370	394	408	415
	40	184	217	238	280	298	313	322	326
	50	164	190	206	237	249	260	265	268
	75	129	145	154	170	177	182	185	186
	100	107	117	123	133	137	140	142	143
	150	79	84	88	93	94	96	97	97
	200	63	66	68	71	72	73	73	74
	500	28	29	29	30	30	30	30	30

Table 16. Predicted maximum magnetic trip level to meet UL1699 criterion, 12 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Run Length, ft**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
25	**0**	356	505	640	1067	1371	1778	2087	2286
	1	351	497	627	1030	1312	1679	1952	2125
	2	347	489	614	996	1257	1591	1834	1985
	5	336	466	579	907	1118	1374	1551	1659
	10	318	433	528	788	943	1119	1235	1302
	15	302	404	486	697	816	945	1025	1071
	20	288	379	450	625	719	817	877	910
	30	263	337	391	518	581	643	680	699
	40	242	303	347	442	487	530	555	568
	50	224	275	311	386	420	451	469	478
	75	189	224	247	293	311	329	338	343
	100	163	189	205	236	248	258	264	267
	150	129	144	153	169	176	181	184	185
	200	106	116	122	132	136	139	141	142
	500	52	54	55	57	58	58	59	59
40	**0**	356	505	640	1067	1371	1778	2087	2286
	1	351	496	626	1028	1309	1674	1945	2116
	2	347	488	613	993	1251	1581	1821	1970
	5	335	464	576	899	1106	1356	1529	1633
	10	316	429	523	777	927	1096	1206	1270
	15	300	399	479	684	797	920	996	1039
	20	285	373	442	611	700	792	848	879
	30	259	330	383	503	562	620	654	672
	40	237	296	338	428	470	510	532	544
	50	219	268	302	372	403	432	449	457
	75	184	217	239	281	298	314	322	327
	100	158	183	198	225	236	246	251	254
	150	124	138	147	162	167	172	175	176
	200	102	111	117	126	129	132	134	134
	500	49	51	52	54	55	55	56	56

Table 17. Predicted maximum magnetic trip level to meet UL1699 criterion, 12 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Run Length, ft**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
60	**0**	356	505	640	1067	1371	1778	2087	2286
	1	351	496	625	1026	1304	1667	1935	2105
	2	346	487	611	988	1243	1568	1804	1951
	5	333	461	571	889	1091	1333	1500	1599
	10	314	425	516	762	905	1066	1170	1230
	15	296	393	470	666	774	888	959	999
	20	281	366	432	592	676	761	813	842
	30	254	322	372	485	539	592	623	639
	40	232	287	326	410	448	484	505	516
	50	213	259	291	355	384	410	424	432
	75	178	209	228	266	282	296	304	307
	100	152	174	188	213	223	232	236	239
	150	118	131	139	152	157	161	164	165
	200	97	105	110	118	121	124	125	126
	500	46	48	49	51	51	52	52	52
90	**0**	356	505	640	1067	1371	1778	2087	2286
	1	350	495	623	1022	1298	1656	1921	2088
	2	345	485	608	980	1232	1550	1780	1922
	5	331	457	565	874	1068	1300	1458	1552
	10	310	418	506	740	875	1024	1120	1175
	15	291	385	458	642	741	845	909	945
	20	275	356	418	567	642	719	765	791
	30	247	311	357	459	508	554	581	596
	40	224	275	311	386	419	451	469	478
	50	205	247	275	333	357	380	392	399
	75	169	197	214	247	261	273	279	282
	100	144	163	175	197	205	213	217	219
	150	111	122	129	140	144	148	150	151
	200	90	98	102	109	111	113	114	115
	500	43	44	45	46	47	47	47	47

Table 18. Maximum run length to meet UL1699 criterion, 14 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Mag Trip, A_{rms}**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
25	**120**	105	121	129	141	145	148	149	150
	140	82	98	106	118	122	125	127	127
	160	65	81	89	101	105	108	110	110
	180	52	68	76	88	92	95	97	97
	200	42	57	65	77	81	84	86	87
	220	33	49	57	69	73	76	77	78
	240	26	42	50	61	65	69	70	71
	260	20	35	43	55	59	62	64	65
	280	14	30	38	50	54	57	59	60
	300	10	26	34	46	50	53	54	55
	320	6	22	30	42	46	49	50	51
	340	2	18	26	38	42	45	47	48
	360	–	15	23	35	39	42	44	44
	380	–	12	20	32	36	39	41	42
	400	–	10	18	30	34	37	38	39
40	**120**	99	114	122	133	137	140	141	142
	140	78	93	100	112	115	118	120	121
	160	62	77	84	95	99	102	104	104
	180	49	64	72	83	87	90	91	92
	200	39	54	62	73	77	80	81	82
	220	31	46	54	65	69	72	73	74
	240	24	39	47	58	62	65	66	67
	260	19	34	41	52	56	59	61	61
	280	14	29	36	47	51	54	56	56
	300	9	24	32	43	47	50	51	52
	320	6	21	28	39	43	46	48	48
	340	2	17	25	36	40	43	44	45
	360	–	14	22	33	37	40	41	42
	380	–	12	19	30	34	37	39	39
	400	–	9	17	28	32	35	36	37

Table 19. Maximum run length to meet UL1699 criterion, 14 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Mag Trip, A_{rms}**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
60	**120**	92	106	113	124	127	130	132	132
	140	73	86	93	104	107	110	112	112
	160	58	72	79	89	92	95	97	97
	180	46	60	67	77	81	84	85	86
	200	37	51	58	68	72	74	76	76
	220	29	43	50	60	64	67	68	69
	240	23	37	44	54	58	60	62	62
	260	17	31	38	49	52	55	56	57
	280	13	27	34	44	48	50	52	52
	300	9	23	30	40	44	46	48	48
	320	5	19	26	37	40	43	44	45
	340	2	16	23	34	37	40	41	42
	360	–	13	20	31	34	37	38	39
	380	–	11	18	28	32	35	36	37
	400	–	9	16	26	30	32	34	35
90	**120**	84	97	103	112	116	118	119	120
	140	66	79	85	94	98	100	101	102
	160	52	65	71	81	84	86	88	88
	180	42	54	61	70	73	76	77	78
	200	33	46	52	62	65	67	69	69
	220	26	39	45	55	58	61	62	62
	240	21	33	40	49	52	55	56	57
	260	16	28	35	44	47	50	51	52
	280	12	24	31	40	43	46	47	48
	300	8	21	27	36	40	42	43	44
	320	5	17	24	33	36	39	40	41
	340	2	15	21	30	34	36	37	38
	360	–	12	18	28	31	34	35	36
	380	–	10	16	26	29	31	33	33
	400	–	8	14	24	27	29	31	31

Table 20. Maximum run length to meet UL1699 criterion, 12 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Mag Trip, A_{rms}**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
25	**120**	167	192	205	224	230	235	237	239
	140	131	156	169	188	194	199	201	203
	160	104	129	142	161	167	172	174	176
	180	83	108	121	140	146	151	153	155
	200	66	91	104	123	129	134	137	138
	220	52	78	90	109	115	120	123	124
	240	41	66	79	98	104	109	111	113
	260	31	56	69	88	94	99	102	103
	280	23	48	61	80	86	91	93	95
	300	16	41	54	72	79	84	86	88
	320	9	35	47	66	72	77	80	81
	340	4	29	42	61	67	72	74	76
	360	–	24	37	56	62	67	69	71
	380	–	20	32	51	58	63	65	66
	400	–	16	28	47	54	59	61	62
40	**120**	158	182	193	211	217	222	224	226
	140	124	148	159	177	183	188	190	192
	160	98	122	134	152	158	163	165	166
	180	78	102	114	132	138	143	145	146
	200	63	86	98	116	122	127	129	130
	220	50	73	85	103	109	114	116	117
	240	39	63	74	92	98	103	105	107
	260	30	53	65	83	89	94	96	97
	280	22	45	57	75	81	86	88	90
	300	15	39	51	68	74	79	82	83
	320	9	33	45	63	68	73	76	77
	340	4	27	39	57	63	68	70	72
	360	–	23	35	53	59	63	66	67
	380	–	19	31	48	54	59	61	63
	400	–	15	27	45	51	55	58	59

Table 21. Maximum run length to meet UL1699 criterion, 12 AWG copper.

		Available Panelboard Current, A_{rms}							
Temperature, °C	**Mag Trip, A_{rms}**	**500**	**750**	**1000**	**2000**	**3000**	**5000**	**7500**	**10000**
60	**120**	147	169	180	197	203	207	209	210
	140	115	138	149	165	171	175	178	179
	160	92	114	125	142	147	151	154	155
	180	73	95	106	123	129	133	135	136
	200	58	80	92	108	114	118	120	122
	220	46	68	79	96	102	106	108	109
	240	36	58	69	86	92	96	98	99
	260	28	50	61	77	83	87	90	91
	280	20	42	54	70	76	80	82	83
	300	14	36	47	64	69	74	76	77
	320	8	31	42	58	64	68	70	72
	340	3	26	37	53	59	63	66	67
	360	–	21	32	49	55	59	61	62
	380	–	17	28	45	51	55	57	58
	400	–	14	25	42	47	52	54	55
90	**120**	133	154	164	179	184	188	190	191
	140	105	125	135	150	155	159	161	162
	160	83	103	113	128	133	137	139	140
	180	66	86	97	112	117	121	123	124
	200	53	73	83	98	103	107	109	110
	220	42	62	72	87	92	96	98	99
	240	33	53	63	78	83	87	89	90
	260	25	45	55	70	75	79	81	82
	280	18	38	49	64	69	73	75	76
	300	13	33	43	58	63	67	69	70
	320	8	28	38	53	58	62	64	65
	340	3	23	33	48	53	57	60	61
	360	–	19	29	44	50	54	56	57
	380	–	16	26	41	46	50	52	53
	400	–	13	23	38	43	47	49	50