LOW-VOLTAGE ARC SUSTAINABILITY

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Abstract – Arc Flash in low voltage equipment (480 volts and below) is a safety issue that can impact work practices for electrical workers. When estimating incident energy for low voltage equipment, the duration of the arc is typically the driving factor. This paper summarizes previous testing results that establish arc sustainability for various equipment configurations, when trip devices do not operate. In some cases, arc duration is limited by the physical conditions of the enclosure and by the driving voltage and current available. Using the maximum duration for arc sustainability can provide more realistic estimated incident energies than using the two-second self-extraction time cited in IEEE 1584-2002. Consequently, required levels of personal protective equipment can be reduced while still providing adequate protection to the worker.

Index Terms — Arc flash, safety, personnel protection, low voltage.

I. INTRODUCTION

Incident energy analysis for low-voltage enclosed equipment sometimes produces very high calculated values. The standard accepted method (formula) for performing this calculation is IEEE 1584-2002 [1]. While this formula does have differences imbedded in the factors for basic categories of equipment for arc gap and arcing current magnitude relative to bolted fault current magnitude, it relies on the user to determine the duration of the arcing event.

In low-voltage scenarios, the ratio of arcing fault to available bolted fault current can vary significantly. IEEE 1584 calculates these ratios to vary from 88% to 19% for 208-V three-phase arcs as currents vary from 1 kA to 106 kA. For 480-V three-phase arcs, these ratios vary from 97% to 43% in the same current range. IEEE 1584 generally predicts the ratio to get smaller as the current increases and to get smaller as the arc gap increases. This has been generally confirmed with actual testing on real equipment. In addition, testing on real equipment has shown that the heat flux rate (cal/cm^2/sec) predicted by IEEE 1584 to conservatively envelope the measured values. Because of the low value of actual arcing current, upstream trip devices can take a few seconds (or longer) to clear faults of these low magnitudes, resulting in very high estimated incident energies. However, testing in real equipment shows that many low-voltage arcs will self-extinguish prior to protective device operation. This paper summarizes the results of many different tests cover arc sustainability.

In this paper, test results will be shown for arc sustainability in low-voltage equipment in mainly utility equipment. This expands on other work in the industry with arc flash tests in actual low-voltage equipment [2 – 6].

II. ELECTRODE CONFIGURATION

Electrode configurations are known to impact incident energies from arc flash events. Wilkins et al. [7] and Stokes and Sweeting [8] showed the impact of horizontal electrodes on incident energies and the directionality of the resulting fireball. Wilkins et al. [9] demonstrated the effect of barriers on arc sustainability and incident energies. Nelson et al. [5] showed that electrode configurations in motor-control centers can cause an arc to move away from the enclosure opening.

For arc sustainability, the following general characteristics of equipment have notable impacts.

Electrode Spacing. Electrode spacing translates into arc gap. Longer arcs result in larger voltage drop across the arc resulting in not only lower arcing current but also directly impact the ability of the arc to self-sustain.

Thicker Electrodes. In many cases, arc duration is determined by the time it takes to vaporize all of the electrode mass. Smaller conductors and bus bars vaporize quicker. Thicker bus bars and larger conductors are supported with more robust structural members, so they not only offer more mass to burn, they are strong enough to remain intact against the large magnetic forces generated by the arc. This results in the arc gap maintaining for the duration of the arc event. However, smaller bus bar and smaller conductors are less well supported. The strong magnetic forces break the support structure allowing the arc gap to naturally increase as the electrodes are forced away from each other. This arc becomes unable to sustain after the electrodes are free to move.

Confined Space. Confinement of the arc inside an enclosure allows the ionized gasses to remain near the electrodes for longer periods of time. Presence of the ionized gas supports arc sustainability by allowing the arc to reignite after a zero voltage crossing. The smaller the space around the electrodes, the more likely is arc sustainability. Conversely, large enclosures with open space around the electrodes are more likely to self-extinguish.

End Barriers. Barriers are particularly important near the ends of the electrodes. Magnetic forces push arcs away from the source, often causing arcs to jet out of the ends of electrodes. If there is a barrier beyond the ends of the electrodes, this barrier will trap hot gasses and help sustain arcing. If the barrier is conducting, it will also provide a path to connect arcs. Barriers less than ten inches (25 cm) from the tips of the electrodes may sustain arcing, even with wider electrode spacing.

Parallel Bus Bars. With rectangular bus bars in parallel, arcing is more likely to sustain if the wide parts of the bus bars are facing each other. If the narrow parts are facing, the arcs will tend to run to the edges of the bus bars, and this increased space may not sustain arcing.

Three-Phase Arcing. Three-phase arcing is more likely to sustain because of multiple arcs and higher voltages (480 versus 277 V). With multiple arcs, when one arc extinguishes temporarily at a voltage zero, there are still adjacent arcs generating heat and ionized gas.

Arcing Current Magnitude. While counterintuitive, in several pieces of equipment with borderline arc sustainability, higher fault currents caused arcing to self-extinguish faster. Higher currents burn electrodes more quickly (as the current squared). Many times as the electrodes vaporize, spacing between electrodes increases. The increased magnetic fields also propel arcs faster. In absence of end barriers, these forces can blow the arcs off the ends of the electrodes so quickly there is not enough ionized vapor to support arc reignition.

III. 240-V EQUIPMENT

A. Staged Arc Gap Testing

The industry has long recognized the issue of arc sustainability. Wagner and Fountain [10] reported on a total of 21 tests of single-phase and three-phase faults at 250 V with 4-in (10-cm) bus spacing where all of the faults self-extinguished within two cycles. The authors cautioned that more sustainable faults may occur at tighter bus spacing. Fisher [11] reported that at test voltages from 120 to 277 V, arcing time was highly variable with ½ and 1-in (1.3 and 2.5 cm) gaps between electrodes. These faults self-extinguished prior to 15 cycles in most cases.

Wilkins et al. [9] showed that insulating barriers greatly improve the odds of sustaining arcs at 208 V. With an insulating barrier, they were able to sustain arcs at 208 V with a gap of 1.25 in (3.2 cm) with 10 and 22 kA of bolted fault capability.

A major utility performed a series of arc duration tests for the configuration shown in Figure 1. See Figure 2 for test results at 208 V [12]. At 208 V, arcs did not sustain for more than one half cycle above an arc gap of 0.5 in (1.3 cm) for this configuration. At a one-half-inch arc gap, faults cleared within 10 cycles. Because the bus bars are arranged so that the three phases are pointing at each other, it is a severe test. Arcs are more likely to self-sustain because the magnetic fields force the arcs towards the center of this arrangement. In parallel bus arrangements (as found in real equipment), the magnetic forces propel the arcs and hot gases away from the source, making it more likely that arcs will self-extinguish.

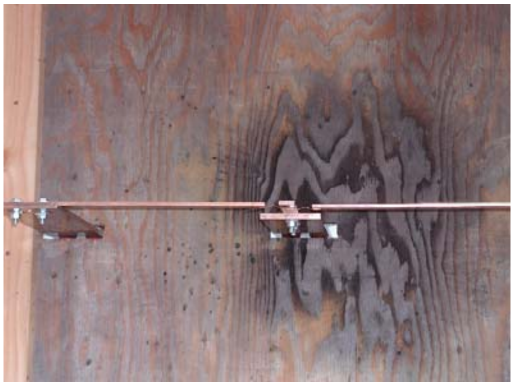

Fig. 1 Electrode configuration for duration tests

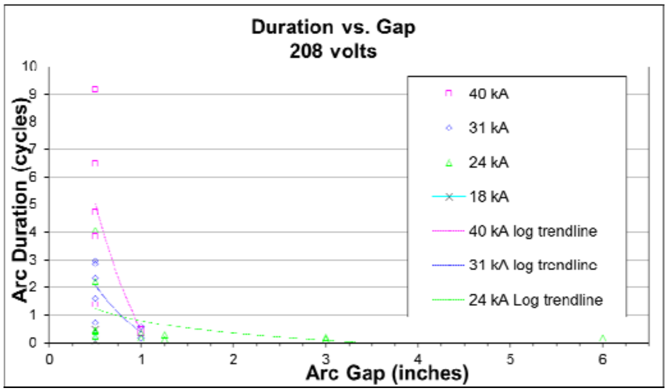

Fig. 2 Duration vs arc gap

B. Meter Sockets

Arc flash in self-contained meter sockets was tested with a 120/208-V supply. Faults were initiated in the self-contained meter base by jumpering between all three phases with a #12 copper wire (worst case initiation). See Figure 3 for an example test.

Fig. 3 Example fault on 120/208-V meter socket

See Table 1 for a summary of the test results. The longest duration recorded was 1.6 cycles. The maximum incident energy measured at 18 inches was 0.2 cal/cm^2.

TABLE I

SUMMARY OF 208-V SELF-CONTAINED METERS

Duration (cycle)	Bolted Fault kA	Incident Energy Peak cal/cm^2
1.0	14.9	0.0
1.1	14.9	0.0
1.6	14.9	0.1
1.0	30.7	0.2
0.9	30.7	0.1
0.6	30.7	0.1
0.3	40.4	0.1
0.5	40.4	0.2
0.2	40.4	0.1

C. *Network Protectors*

Tests were performed on two different network protectors with a 120/208-V supply at two bolted fault currents, 30.7 kA and 40.4 kA [12]. Unit #1 was physically smaller and had been previously tested for smoldering faults. Consequently, Unit #1 had the internal components significantly covered by soot and represents worst case. Testing was conducted primarily to determine arc sustainability; however for Unit #2, incident energy measurements were also made. Figure 4 shows a typical event.

Fig. 4 Example fault on a 208-V network protector

Table 2 shows a summary of the 14 tests on the two network protectors. All measured incident energies were very low. The most extreme case had approximately 12 cycles of arcing current. Even though the incident energy was not measured on this particular event. It is estimated that this event would not have exceeded 4 cal/cm^2 by extrapolating similar events imitated in similar locations i.e. 3.79-cycle event. Additionally, this event was created by wedging a vice grip inside the back of the protector in such a way that the magnetic forces could not dislodge the tool. This initiation does not represent any possible real condition that workers could duplicate in the field. Figure 5 shows the vice grip for this event.

IV. 480-V EQUIPMENT

A. *Staged Arc Gap Testing*

Arc duration tests were conducted similar to those reported in Section III but this time a 480-V source was used. See Figure 6 for test results at 480 V. At 480 V, arcs did not sustain when initiating arc gaps increased beyond 6 in (15 cm). When initiating arc gaps are 1.5 in (4 cm) or less, arcs are most likely to sustain. At arc gaps of 3 in (8 cm) and larger, the magnetic forces sometime blows the arc out for even the highest tested currents.

TABLE 2

SUMMARY OF 208-V NETWORK PROTECTORS

Unit #	Duration (cycle)	Bolted Fault kA	Incident Energy Peak cal/cm^2
1	0.39	30.7	
1	0.39	30.7	
1	0.96	30.7	
1	0.36	30.7	
1	0.52	40.4	
1	11.5	40.4	
2	0.36	40.4	0.15
2	0.36	40.4	0.01
2	0.29	40.4	0.02
2	3.79	40.4	0.10
2	2.34	40.4	0.01
2	0.14	40.4	0.00
2	4.89	40.4	0.06
2	0.62	40.4	0.01

Fig. 5 Vice grip wedged AΦ – BΦ in back of the protector

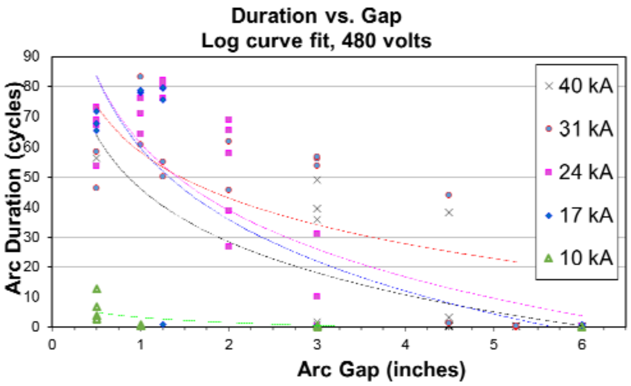

Fig. 6 Duration vs arc gap for staged tests

B. Previously Reported Results

This testing on low-voltage equipment was previously reported in [3,12,13].

Padmounted transformer secondary compartments self-extinguished in two cycles or less with incident energies measured at much less than 4 cal/cm^2. This is primarily due to the electrode spacing being very large and the compartment being fairly large and open. Even artificially reducing the arc gap to under 2 in (5 cm) between phases failed to produce a sustainable arc. See Fig 7.

Fig. 7 Padmounted transformer secondary compartment

Ringed self-contained meter sockets, style 16S, were able to sustain arcs. See Fig. 8. The tight confinement of the enclosure, close electrode spacing, and three-phase arcing combined to allow the arc to sustain until the metal jaws were vaporized and incoming 1/0 conductors melted beyond the attachment point allowing them to swing away from each other. Higher currents were found to reach this point quicker than lower currents, making 12-kA bolted faults capable of delivering more incident energy than 44 kA (20 cal/cm^2 vs 6 cal/cm^2 respectively). 12-kA faults took up to 60 cycles to self-extinguish while 44-kA faults took less than 10 cycles. Additionally, larger current more consistently deliver incident energy while currents 12 kA only delivered significant energy 50% of the time. Even lower currents of 6 kA delivered measurable incident energy 20% of the time.

Conversely, transformer rated meter sockets style 9S shown in Fig. 9 and test switch blocks were unable to sustain an arc. Even though this equipment has the tight spacing and confinement of a self-contained meter socket, the power is delivered by a small conductor (#10 AWG). The wire melts and behave like a fuse, terminating the arc event.

Large panelboards, as shown in Fig 10, have prime conditions for sustained arcing: large electrodes with robust supports, tight electrode spacing, facing electrodes, and a conducting barrier at the top that confines the fireball and provides a conducting path for current. Equipment with these conditions can have arcs that will sustain for as long as it takes to vaporize the entire length of bus bar i.e. many seconds. Incident energies are best estimated with IEEE 1584 formulas and actual circuit clearing times or the two-second assumed self-extraction time of the worker, if appropriate. In the test case, measured heat flux rates exceeded 60 cal/cm^2.

Fig. 8 Ringed self-contained meter socket

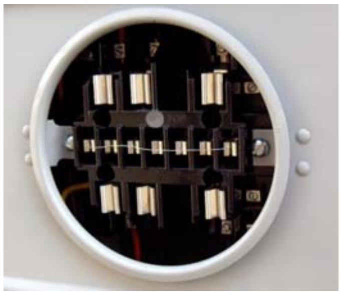

Fig. 9 CT-rated meter socket

Conversely, small panelboards with 50-A and 100-A ratings, as shown in Fig 11, had arcing faults that self-extinguished. Primarily, the arc ended when the mechanical forces to the bus bars pushed the bus bars apart. On these, the bracing is not sufficient to hold together the bus bars for longer-duration faults. These bus bars were not facing, another factor reducing the likelihood of sustained arcing. Average incident energy measurements were under 8 cal/cm^2.

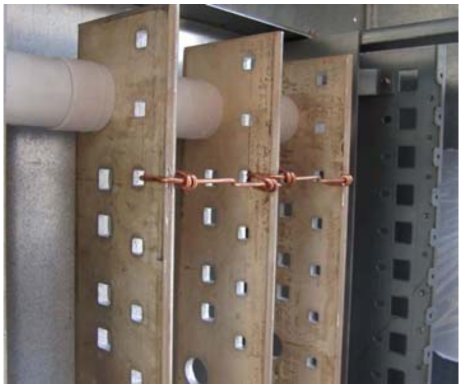

Fig. 10 Large panelboard, 250-A rating

Fig. 11 Small panelboard, 50A-100A

Simulated arcing the back bus bar of a network protector was created by gutting a network protector and installing a conductive back plate one inch (2.5 cm) away. In addition a conductive bottom plate was installed to mimic the conditions of the bottom back of the network protector. See Fig 12.

Fig. 12 Network protector testing-simulated back bus bar

Because the bus bars are flat rather than facing, arcs tend to separate. Arcing sustains because the back and bottom plates provide confinement and conductive arc paths. Equipment with these conditions can have arcs that will sustain for as long as it takes to vaporize the entire length of bus bar i.e. many seconds. Incident energies are best estimated with IEEE 1584 formulas and actual circuit clearing times or the two-second assumed self-extraction time of the worker, if appropriate. In the test case, measured heat flux rates exceeded 60 cal/cm^2.

C. New Testing and Results

After the original rounds of testing, more questions emerged about extrapolation of these results to other equipment and with different configurations. Additional testing was conducted to answer these questions.

Outdoor overhead secondary quadraplex cable was tested. See Fig. 13. Although these have tight spacing, there is no arc confinement. In addition, faults were started either as phase to neutral or phase to phase. In both cases, there is just a single arc with no propagation to adjacent phases. Arcs generally self-extinguish on the first zero crossing and have minimal measured incident energy.

Fig. 13 Overhead quadraplex cable

Meter sockets and CT cabinets were tested of different types and configurations. Results were highly variant. Ring-less meter sockets, see Fig. 14, were not able to sustain arcing as long as the ringed meter sockets. The ring-less design has less confinement, but even with fairly tight electrode spacing, arcs self-extinguished fairly quickly with generally low incident energies when arcs were initiated inside the meter socket. Arc initiated at the incoming terminations or on the load side terminations with the meter bypass switch engaged did last longer and have incident energies measured as high as 14 cal/cm^2. The other main difference between ringed meter sockets and ring-less meter sockets is focusing of the incident energy. The enclosure geometry is the main reason for the peak incident energy to be higher for the ringed design. With the cover off on the ring-less design, the arc energy is much less directed. In addition, the ring-less design is a larger enclosure and since the cover will be off, the fireball expands in many directions. Fig. A-1 in Appendix A shows the pattern of incident energy between these two types of meters.

Because there is wide variability in the design of meter socket enclosures, additional testing was performed with meters that had more internal bus bar. Meter sockets that have bypass switches or meter sockets with bottom entry and exit are much more likely to have this additional internal bus bar. Fig. 15 and Fig. 16 shows two additional single meter base enclosures that were tested. While the meter socket in Fig. 15 had a maximum measured incident energy less than 8 cal/cm^2, the meter socket shown in Fig. 16 experienced one test that continued to re-ignite many times until finally the lab circuit protection de-energized the test specimen at two seconds. In this event, peak incident energy was measured 87 cal/cm^2. Fig A2 in Appendix A compares the damage post arc-event between these two test specimens.

Fig. 14 Ring-less meter socket with cover removed

Fig. 15 200-A meter socket with bottom entry and exit

Fig. 16 320-A meter socket with bypass switch

Multi-bank meter sockets have much more robust electrodes than the single-meter sockets above. With the robust electrodes, tight spacing, and enclosure confinement, and close proximity to the conductive back plate, faults can arc for long durations. See Fig. 17. Tests on these indicate that arcs will not self-extinguish. Incident energies will be dependent on circuit protective devices or worker self-extraction. Post-test photos can be seen in Fig. A-3 in Appendix A.

Fig. 17 Multi-bank meter sockets

As can be seen by these results, incident energy is highly dependent on the internal configuration. Meter sockets rated above 200 A or constructed with large amounts of exposed bus bar, will likely not self-extinguish. Incident energies will be dependent on circuit protective devices or worker self-extraction. Post-test photos can be seen in Fig. A-4 in Appendix A.

A CT cabinet was also tested. See Fig. 18. As with meter socket enclosures, CT enclosures can be widely variant in internal configuration. However, limited resources were available for this destructive testing. For the CT enclosure configuration shown, testing with initiating points reasonable replicable by field personnel self-extinguished quickly (under five cycles). However, CT cabinets with tighter spacings, smaller cabinets, and/or larger cable or bus bar could reproduce arcs that would not self-extinguish.

Lessons learned from testing show that changing design or installation techniques may help reduce the magnitude of the possible incident energy. These include but may not be limited to:

- Taping or insulating crimped connector as much as possible to minimize the arc initiation points.
- Keep CT's centered vertically to maximize phase to enclosure distances.
- Keep CT's phase-to-phase separations as large as possible.

Fig. 18 CT enclosure

While the worst case condition for network protectors (NP) was discovered with previous testing i.e. when the back bus bar is energized meaning the transformer that feeds the NP is still energized, other maintenance activities were presenting a high degree of difficulty for workers to perform. Additional testing was conducted inside an intact NP with the back bus bar de-energized but the outgoing load side still energized. Most NPs are arranged in multiple sets, with all network protectors ganged together on the output. Customer connections are made to the load side ring bus that connects all the NPs together. This is great for reliability, but almost impossible to completely de-energize. Fuses are used between the circuit breaker inside the NP and the ring bus either inside the NP or in separate enclosures at the top of the NP. Typical maintenance activities would include:

- Removing fuses
- Adding customer connection to ring bus
- Removing cable terminations to allow NP replacement

Extensive testing at the internal fuse terminations shown in Fig. 19 discovered that arcs will self-extinguish in under two cycles [14]. The majority of events self-extinguished in under one cycle, see Fig. 20. Testing was done with two 250kVA transformers in parallel feeding the tested NP which resulted in over 5 kA of available bolted fault current. Specific examples of initiation points is shown in Appendix A.

Keeping in mind the requirements for sustained arcing identified in the previous section, arc initiations near the top of the NP have robust electrodes and tight spacing that would permit arc sustainability. However, there is large gaps to sides of the equipment, flat electrodes not facing each other, and not enough confinement to keep the ionized gases dense enough to allow arc re-ignition at this location inside the NP.

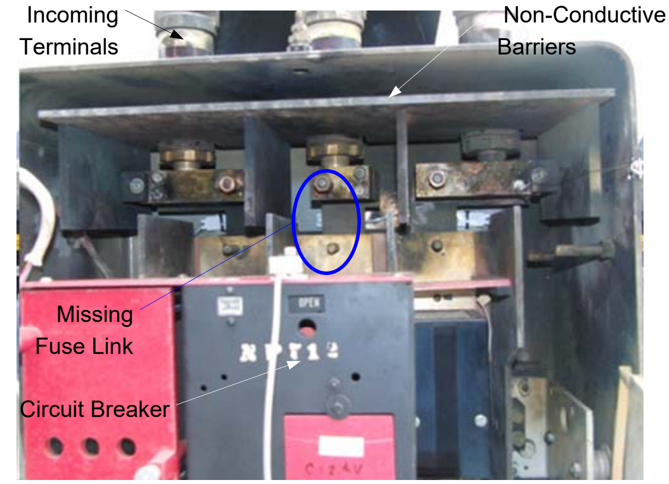

Fig. 19 Network protector- inside top

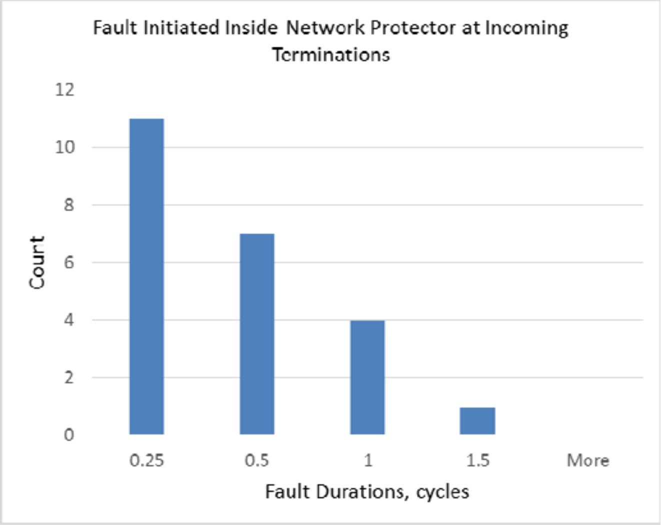

Fig. 20 Network protector- inside arc durations

Some NPs have external fuse compartments, see Fig. 21. Testing at these locations result in arcs that self-extinguish in under one cycle. Even arc initiations that could not realistically be duplicated by a worker (phase to phase to phase to ground) would not sustain.

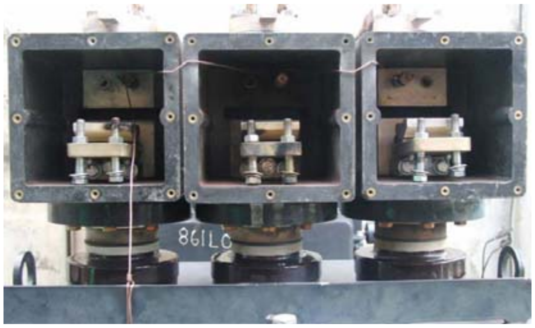

Fig. 21 Network protector external fuse- 3φ initiation

To simulate removal of a termination from the top of an NP further tests were performed. Simulations for tool contact between the phase and the case or adjacent phases along with loose terminations coming into contact with adjacent phases. See Fig. 22 and Fig. 23. In all cases the arc self-extinguished in under four cycles with almost negligible measured incident energy.

Additional tests were done to simulate arc in the areas around the common bus, both in cable trays and in simulated ceiling mounted bus bar. The insulation was removed in windows on the conductors and the expose conductors were tie-wrapped to force contact with the grounded tray or with adjacent exposed conductors. This physical constraint represents severe conditions. In real world scenarios, the cable would be free to move and the arc would not last as long .See Fig. 24 and Fig. 25. For the cable tray, all the arcs self-extinguished again in under four cycles.

Fig. 22 NP Tool placed phase to phase- 2.65 cycles

Fig. 23 Loose termination phase to phase- 1.09 cycles

Ceiling mounted bus bar, was simulated by attaching bare conductors to the bottom of a non-conductive surface (in this case wood), supporting them as rigidly as possible and ending them at a barrier. Arcs were initiated at the barrier end (which would be worst case, and changing the barrier from conductive to non-conductive material. See Fig. 26. In these cases, all the arcs self-extinguished in under two cycles.

Fig. 24 Phase to ground in cable tray- 3.52 cycles

Fig. 25 Phase to phase in cable tray- 1.54 cycles

Fig. 26 Simulated ceiling bus bar- 1.92 cycles

V. CONCLUSIONS

Much of the testing presented in this paper serves as the basis for the National Electric Safety Code [15], Table 410-1, *Clothing and clothing systems (cal/cm2) for voltages 50 V to 1000 V (ac),* which recommends minimum levels of arc protection for various utility equipment.

Some equipment behaves so consistently that general conclusions can be drawn e.g. 240 V and below cannot sustain arcs beyond two cycles. While other equipment is highly variable, and conclusions only apply to equipment that matches the equipment configuration tested.

Table 3 summarizes equipment categories for 480-V equipment that has enough testing and consistent behavior. Most equipment fully sustains or has low sustainability. Equipment with low sustainability generally has electrode spacings and/or box spacings that are large enough that arcs become too long to sustain at 480 V. Equipment with high sustainability generally has thick electrodes with tight spacings or confinement necessary to sustain arcing. Equipment with medium sustainability generally has tight enough spacings to sustain arcing, but the electrodes and supporting structures are small enough that arcing will self-extinguish once the electrodes burn sufficiently or the supporting structures break.

Table 3 does not cover all low-voltage equipment presented. For example, CT cabinets are not listed because only one sample configuration was tested. The CT cabinet in Fig. 18 is in the low-sustainability category, but CT cabinets with tighter electrode or box spacings may be high sustainability. When considering arc sustainability, the electrode size, electrode spacings, and the box spacings are critical parameters. The spacings at the ends of electrodes are particularly important. If these create a barrier effect, arcs are more likely to sustain.

TABLE 3
SUMMARY OF SUSTAINABILITY

Low sustainability (less than five cycles)
All equipment at or below 240 V
Open air
Single-phase equipment
Padmounted transformers
Insulated cables in a tray
CT-rated meter sockets
Network protectors with the transformer de-energized
External fuse links and external terminations on network protectors
Ceiling-mounted bus bar with >8 in (20 cm) spacing
Medium sustainability (up to 90 cycles)
Self-contained meter sockets like 16S style fed by 1/0 AWG cables
Small power panels with no flat facing bus bar
High sustainability (indefinite clearing)
Self-contained meter sockets with large terminals or large amounts of bus bar, including sockets rated above 200 A
Network protectors with the transformer energized
Large power panels, particularly with flat facing bus bar

Note: applies to 480 V unless otherwise noted

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VII. VITA

Marcia L. Eblen graduated from University of Colorado–Boulder in 1982 with a BSEE degree. She is recently retired from Pacific Gas & Electric where she worked for almost thirty years. Since 2002 she served as the Principle Grounding and Arc Flash Engineer. She is a member of the IEEE Substation Safety, IEEE ESMOL subcommittee, IEEE 1584 subcommittee, ASTM F18 Committee, and has been a voting member to the NFPA70E technical committee since 2010. She is a registered professional engineer in the state of California. She currently consults in arc flash and grounding through MLE Engineering, Inc.

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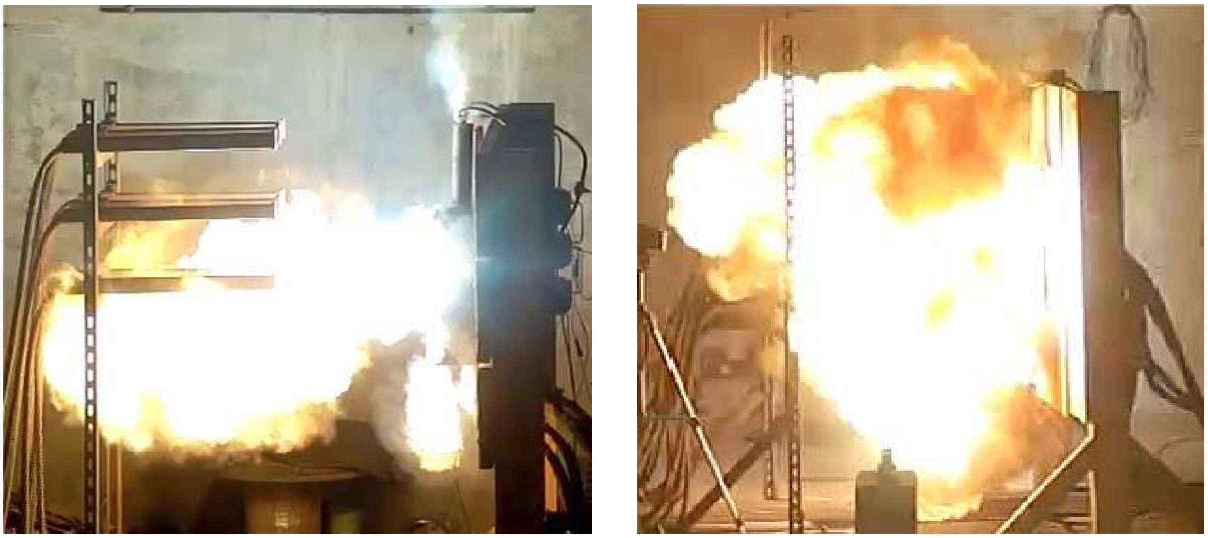
APPENDIX A

ADDITONAL TEST EQUIPMENT PHOTOS



Ringed Meter Socket

Ring-less Meter Socket

Fig. A-1 Comparison of Energy Pattern Between Ringed and Ring-less Meter Sockets

Test Specimen from Fig 15 Post-Test

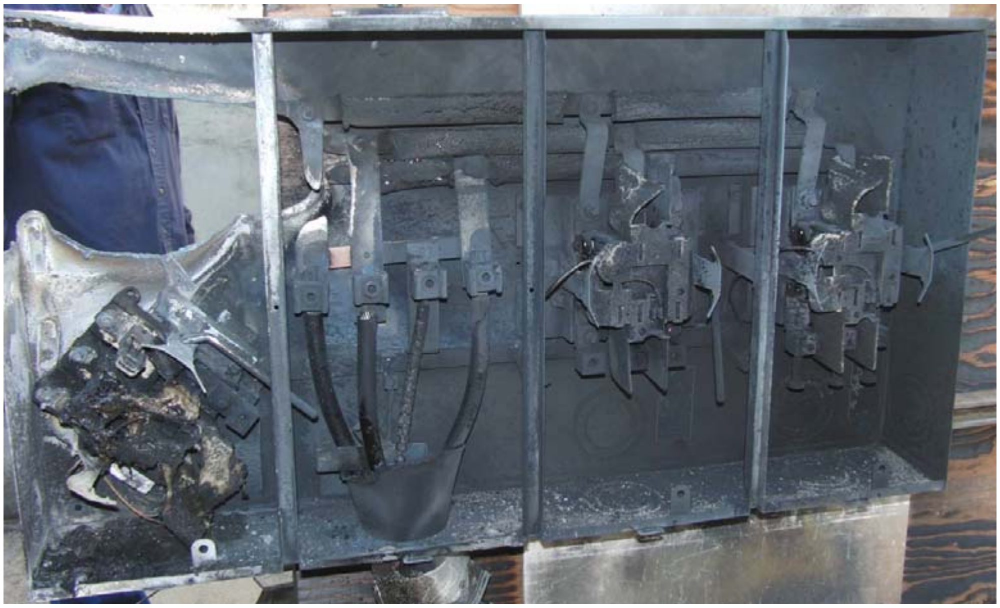
Test Specimen from Fig. 16 Post-Test

Fig. A-2 Post-Test Damage of Meter Sockets Shown Fig. 15 and Fig. 16

APPENDIX A

ADDITONAL TEST EQUIPMENT PHOTOS

Multi-Meter Sockets Post-Test

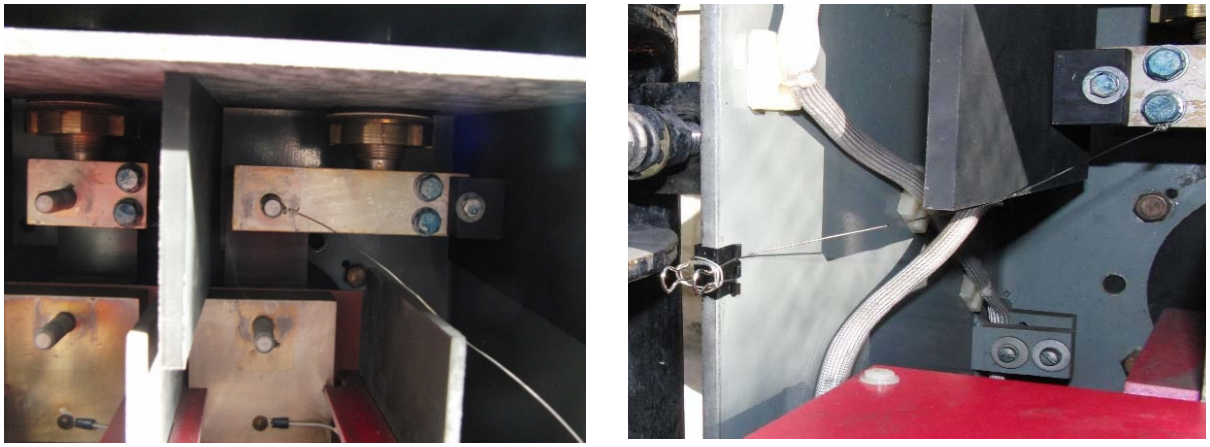


Multi-Meter Sockets Post-Test (Covers Removed)

APPENDIX A

ADDITONAL TEST EQUIPMENT PHOTOS

Fig. A-3 Multi-Meter Socket Panel Post Test with and without covers

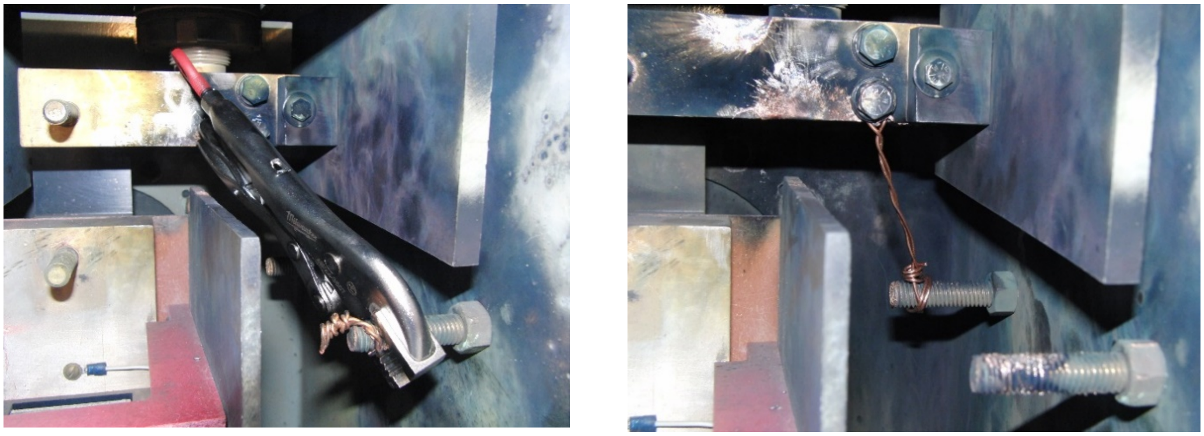


Test 13: AΦ to Case - 20 AWG - 0.14 cycles

Test 33: CΦ to Case - 20 AWG - 0.17 cycles

Test 15: AΦ to Case - 2-#14 - 0.35 cycles

Test 16: AΦ to Front Bolt - #14 - 0.41 cycles



Test ID 18: AΦ to Front Bolt- Vise Grip - 1.5 cycles

Test ID 23: AΦ to Back Bolt- 2-14 AWG - 0.55 cycles

Fig. A-4 Six Example Network Protector Arc Initiation Points