Investigation Of Factors Affecting The Sustainability Of Arcs Below 250V.

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Abstract. **Recent testing with various electrode configurations and insulating barriers suggests that 250V equipment omitted from arc flash hazard analyses has the potential for burn injury. Research into the sustainability of arcs at these voltages shows assumptions about the magnitude of these hazards need to be revised. This research enhanced the work of previous efforts by focusing on the sustainability of arcs with fault currents lower than 10kA. Gap lengths between electrodes, electrode shape, electrode material and voltage variations were studied for their effects on arc sustainability. A modified barrier design, representative of the space around panelboard bus bars was also studied.**

Index Terms — **Arc fault sustainability, arc flash hazard testing, effect of insulating barriers, plasma, terminated vertical conductors, terminated vertical electrodes, vertical conductors, vertical electrodes.**

I. INTRODUCTION

Current standards [1] [2] allow for the exclusion of some 208V circuits from arc flash studies. The exclusion applies to equipment fed by low impedance transformers less than 125kVA. This implies that it is impossible for an arc flash event to pose a hazard to a worker in close proximity to the equipment. However, if an arc were to occur and sustain for sufficient time in these applications, arc flash incident heat energies could exceed levels required to burn exposed flesh or ignite conventional clothing.

Arc flash energies are largely determined by the arc current and the arc duration. Since the transformer is just one component of the circuits being studied, there is no knowledge of the actual values of these determining variables. However, under these standards, arc flash hazard analyses are required for equipment on circuits fed by larger transformers even if the available fault current calculated at this equipment is lower than that from excluded transformers and circuits. The ambiguity created by excluding circuits based on the transformer's power rating could be reduced by identifying current levels below which arcs would self-extinguish before hazardous energy levels were reached.

Tests used to develop IEEE 1584[TM]-2002 [1] resulted in arcs self-extinguishing for available fault currents of 20kA on 208V systems. These tests were performed on vertical open tip configurations as described in [3]. Subsequent testing with vertical electrode configurations terminated in insulating barriers [4], showed arcs sustaining at much lower fault currents with 12.7mm gaps.

In this paper, the authors report on tests used to investigate the sustainability of arcs on 208V systems using additional gaps, a different electrode shape, a modified barrier construction, a 5% overvoltage and aluminum electrodes. Since an 112.5kVA with 2% impedance is capable of delivering near 15kA to a 208V circuit, tests were focused on levels below this. Observations from a limited number of tests with actual equipment are also presented.

II. CODE AND STANDARDS DISCUSSION

A. IEEE 1584[TM]-2002

The widely used empirically derived incident energy equations of the IEEE 1584 standard were developed with data from numerous tests with open tip vertical electrodes in empty enclosures. With this configuration of electrodes the arcs, initiated on the tips with a trigger wire, would try to form arc plasma jets downward and away from the tips. For 208V tests with low fault currents, the arc would not re-ignite after a zero crossing of the current because the recovery voltage was inadequate for the level of ionization remaining in the region between the electrodes. The equation for calculating the 208V incident energy predictions was created by extrapolating from data at higher test voltages.

Calculations using the IEEE 1584 equations for a 208V panelboard are plotted in Fig. 1 for fault currents below 15kA. When using the upper 2-second limit suggested in section B.1.2 of IEEE 1584, incident energy calculations exceed 8 cal/cm² for available fault currents as low as 2kA. Clearing time (arc extinguishment) must be below four cycles for this entire current range to limit incident energies to below the 1.2 cal/cm² threshold where arc rated personal protection equipment (PPE) is indicated.
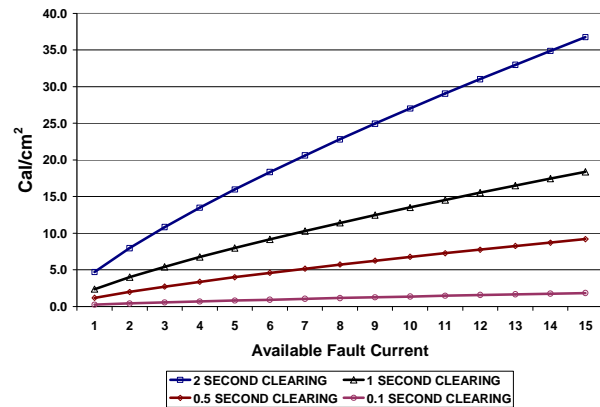

Fig. 1. Incident Energy Calculations for 208V Panelboards using IEEE 1584 equations.

The following statement concerning the need for study of the arc flash hazard at 208V is contained in 4.2 of IEEE1584:

> "Equipment below 240 V need not be considered unless it involves at least one 125 kVA or larger low impedance transformer in its immediate power supply."

It appears that the standard's intention is to neglect the arc fault hazard for fault currents below the abovementioned 15kA level. If fault currents below this level do not pose an arc flash hazard, the standard should clarify the need for calculations when the source consists of a larger transformer and significant conductor impedances.

B. NFPA70E-2009

The widely used safety standard in North America, NFPA70E-2009 [2] requires an arc flash hazard analysis before exposing workers to electrical hazards for the purpose of determining proper work practices and selecting adequate PPE. However, an exception to 130.3 of NFPA70E does not require analysis if all the following conditions exist:

1. The circuit is rated 240V or less.
2. The circuit is supplied by one transformer.
3. The transformer supplying the circuit is rated less than 125 kVA.

This exception does not direct workers to wear arc rated PPE for protection. It implies that there is no arc flash hazard because arc faults would either self-extinguish on such circuits or have insufficient incident energy to cause burns or ignite clothing. Note also that NFPA70E includes circuits rated 240V.

NFPA70E allows for two approaches to PPE selection: a calculation approach such as that of IEEE 1584 or a table approach. In the latter approach, workers would select a Hazard/Risk category from Table 130.7(C)(9) based on specific tasks to be performed on energized equipment identified in the table. The requisite PPE would then be selected from Table 130.7(C)(10).

Table 130.7(C)(9) calls for Hazard/Risk Category 0 or 1 PPE for work on energized equipment rated 240V or less depending on the task. The limits of use for this table are a maximum available short current of 25kA and a maximum clearing time of 0.03 seconds. This approach directs workers to arc rated PPE for certain tasks if the equipment is fed from a transformer larger than 125KVA. Even with low fault currents, workers are directed to wear arc rated clothing.

A power panel rated at 208V with an available fault current of 5kA and a clearing time of two seconds would need an arc rated PPE system rated greater than 16 cal/cm^2 if using the IEEE 1584 equations. However, if the equipment were fed by an 112.5KVA transformer, no analysis would be required and the worker might not wear arc rated clothing. If workers use the table method without knowledge of the clearing time of the upstream overcurrent protective device they may be wearing cotton clothing or PPE with an arc rating of 4 cal/cm^2. The lack of data on sustainable arcs affecting equipment rated 240V and below is at the heart of this ambiguity. Coinciding with this paper, a proposal to replace this exception from the standard with a note referring to other standards such as IEEE 1584 is being processed.

III. OVERVIEW OF PREVIOUS TEST FINDINGS

A. IEEE 1584-2002 Test Program for 208V

The purpose of this testing was to develop equations that would adequately predict arc current, incident energy and the arc flash protection boundary. The tests covered a range of voltages from 208V to 15,000V and fault currents up to 100kA. The program used test fixtures chosen to simulate real equipment. The low voltage tests were run using 3 phase vertical electrodes as shown in Fig. 2 with arcs initiated on the open tips

Fig. 2. Vertical Electrode configuration

Although the working group reported that arcs were sustained in only one case (87kA), they state that future testing at 208V would be worthwhile considering that arc injuries have occurred at this voltage [3]. The reported tests used vertical electrodes with gaps of 12.7mm.

B. Barrier Testing

After the release of IEEE 1584, tests were performed with an insulating barrier [4] attached to the bottom of the electrodes as shown in Fig. 3. The tests for that paper examined the effect of a barrier on incident energy and arc current level as compared to 1584 equations. Similar to IEEE 1584 tests and [5], these tests used a 508mm x 508 mm x 508 mm enclosure with a 32mm gap between electrodes for 208V, 480V and 600V systems.
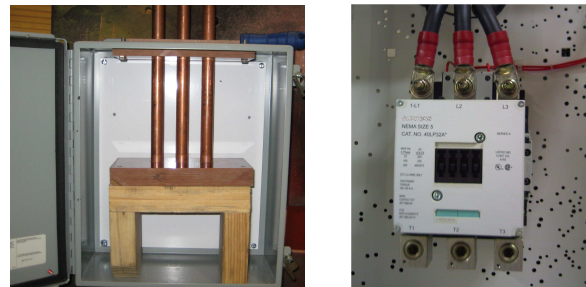

Fig. 3. Barrier configuration is used to simulate conductors on top fed equipment shown at right.

Tests performed with gaps of 12.7mm and 50.8mm compared the results with open tip tests to determine the effect of gap and X/R ratio on arc sustainability and incident energy with the barrier in place. Testing at progressively lower currents revealed the barrier configuration's ability to reliably sustain arcs for more than one second with a 12.7mm gap at 4kA and 208V. The 32mm gap performed intermittently at the lower values. Although these tests gave good insight into the arc's behavior with the barrier, [4] identified the need for more testing "with lower bolted-fault currents to determine the critical levels, below which sustained arcing is not possible" with common 208V equipment conductor spacing.

IV. SUSTAINABILITY OF LOW VOLTAGE ARCS

Factors that may not be significant for arc sustainability for high current arcs on 480V and higher systems need to be considered for low current arcs on 208V systems. Re-ignition of an a-c arc after a zero crossing of the current can be classified as dielectric or thermal. The degree of ionization in the space between electrode conductors,

the electric field strength about the electrodes, the temperature of the electrodes and the recovery voltage can affect the re-ignition process. After a zero crossing of the current, the dielectric strength between the electrodes begins to increase. If the recovery voltage grows to a value greater than the dielectric recovery strength, dielectric re-ignition will occur. Factors that affect the intensity of the electric field at the cathode such as sharp edges on the electrode material can assist in freeing electrons and re-igniting the arc. When the electrode and the arc achieve sufficient temperatures, it is possible for thermal re-ignition to occur at voltages lower than that required for dielectric re-ignitions. As cooling of the arcing area occurs, the ionization between electrodes will diminish rapidly and will require higher voltage to re-establish the arc. If the a-c voltage does not increase fast enough the arc will not reignite and is considered self-extinguished [6].

For a single phase a-c arc the current flow between two electrodes will go to zero at the end of each half cycle and deionization begins. The race between deionization and recovery voltage determines if the arc re-ignites. In a three phase arcing event, current flow through an arc will always be present. When one phase passes through a natural zero crossing the other two phases will continue to conduct. Hence plasma generated by these two phases can affect the re-ignition of the arc from the third phase. In high current arc faults where the plasma has been electromagnetically driven from 'open tip' electrodes, it is possible for re-ignition to occur near the location of the of the arc channel when extinction occurred. Higher voltages would be required to reignite the arc along this longer path.

If the plasma and hot gases from an arc fault are confined in a small location, a higher degree of ionization can be maintained about all electrodes by the two remaining conducting phases. In some configurations, it may be possible for the arc to re-strike upstream from the last location of the cathode prior to the arc extinguishing. Fig. 4 is a photograph of the bus bar erosion where an arc had been established between the aluminum bus bars just above an insulating support. With the air ionized above the top arrow, it is possible for the arc to re-strike at the smaller gap. Electromagnetic forces would drive the arc back to the barrier where it would burn for ½ cycle. The consumption of the aluminum electrode near the insulator is similar to that of a barrier configuration and suggests that the arc resides here for most of the burning time.

Fig. 4. Erosion of aluminum busbars from panel arc fault.

Single phase tests of open tip and barrier configurations were run to provide better insight into sustainability by looking at the relationship between the arc voltage and arc current.

The trace shown in Fig. 5 is from a single phase vertical open tip test in a 508mm x 508mm x 508 mm steel enclosure. The test was run at 480V, 23.6 kA and a X/R of 7.6. Note that after the first zero crossing, current flow is effectively zero for 2.1 milliseconds until the system voltage recovers to -536V. This indicates that dielectric re-ignition occurred as discussed above. After the second zero crossing, the arc does not re-ignite. It is postulated that the ionized gas was driven away from the tips, rapidly de-ionizing the area between the electrodes. The voltage could not recover fast enough to cause re-ignition in the gap or the longer arc path just prior to the current zero.
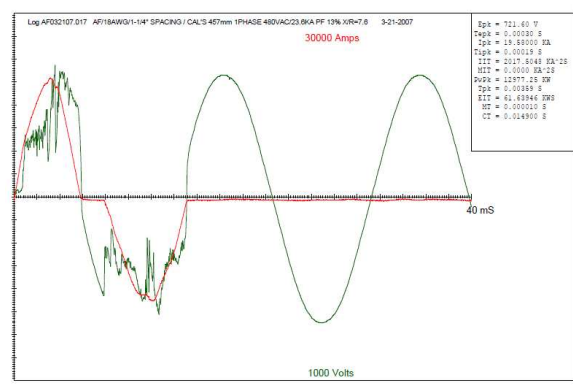

Fig. 5. Trace from 480V single phase open tip test.

The trace shown in Fig. 6 is from a repeat of the previous single phase vertical open tip test 23.6 kA. Note that at the beginning of the 2nd cycle the traces indicate dielectric re-ignition. After the zero crossing of current the arc is extinguished and current flow is effectively zero. The voltage recovers to 616V, the arc re-establishes and the arc burning voltage is determined by the path and current magnitude. At the beginning of the 3rd cycle, re-ignition occurs at a lower voltage and the current reaches a higher level for subsequent peaks. By the start of the sixth cycle the recovery voltage is only 172V and current flow resumes almost immediately after the zero crossing. It appears that a different re-ignition mechanism has occurred, most likely due to the increasing ionization within the large enclosures.
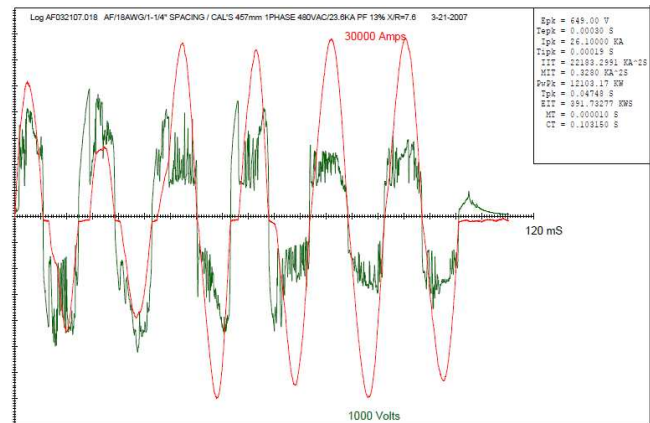

Fig. 6. Trace from 480V single phase open tip test.

The trace shown in Fig. 7 is from a single phase vertical electrode configuration terminated in an insulated barrier. This test was performed at 480V, 11.4 kA and X/R of 7.6. Note that after the beginning of the event, when the trigger wire melted, the current always resumes almost immediately after the zero crossings, suggesting thermal re-ignition. Highly ionized gas between the electrodes may play a bigger role with this barrier configuration than the open tip configuration and may help to explain the sustained arcs at 208V and low fault currents. Pyrolysis of the insulating barrier may also contribute to sustainability of the arc.
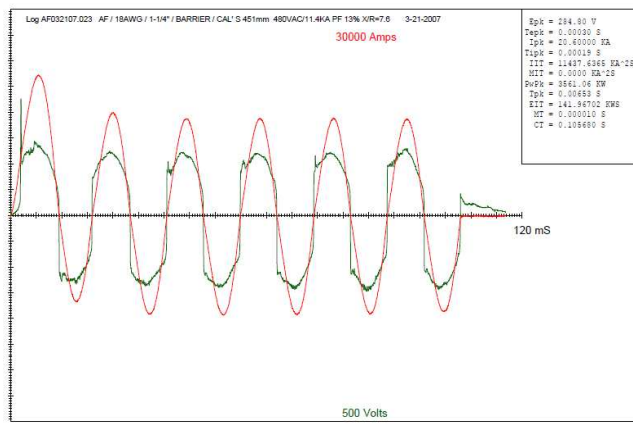
Fig. 7. Trace from 480V single phase barrier test

V. TEST OVERVIEW

Low voltage equipment was examined to identify features that may aid dielectric re-ignition and/or may be better suited to thermal re-ignition than the test configurations previously investigated. The following factors were incorporated into test set-ups and evaluated for their effect on arc sustainability on 208V power systems with low fault currents.

A. Gap

Prior barrier configuration tests [4] at 208V used gaps of 12.7mm, 32mm and 50.8 mm. These gaps were initially used to investigate their effect on power transfer for 480V and 600V systems. They were used on 208V tests out of convenience. To more effectively evaluate arc sustainability on 208V systems the authors conducted additional testing with insulating barriers and electrode spacing of 19mm and 25.4mm between electrodes. These gaps are more representative of 250V rated equipment [7] [8].

B. Electrode Shape

Prior barrier configuration tests used 19mm diameter copper rods for electrodes to compare results with the initial IEEE 1584 developmental tests. This shape might be considered to be representative of cable. Bus bars sized at 12.7mm x 25.4mm were added to the test series. This is believed to be representative of vertical conductors in power panels commonly in use in North American facilities. Tests were run to determine if the higher electric field strength at the sharp edges of the bus bars aided arc re-ignition.

C. Configuration Design

One characteristic of the barrier configuration is the ability to sustain arcs at lower available fault currents. Fig. 8 shows 2 frames from a high speed video sequence of an 'open-air' barrier test at

208V. As discussed in [4], the plasma flow from this configuration is along the plane of the barrier and perpendicular to the plane of the electrodes.
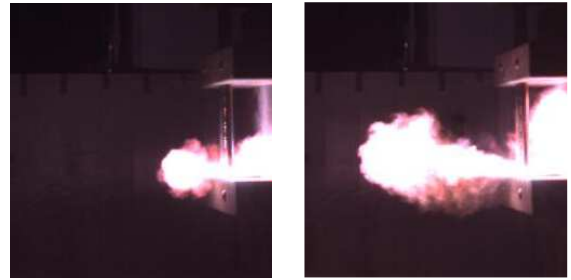

Fig. 8. 208V barrier test in open air – 2ms and 6ms into event.

Since this test set-up has a back panel 4" behind the electrodes, the plasma flow away from the rear of the barrier is reflected back between the electrodes. Once an arcing condition is established in an enclosure, this should have the effect of ensuring that the gases between the conductors to the electrodes are more highly ionized than with the open tip configuration, where the ionized gases are driven away from the electrodes. Re-ignition can occur along a much shorter path and require a lower recovery voltage for re-ignition. As the arcing progresses, greater ionization will make it easier for re-strikes to occur anywhere along the length of the conductors above the barrier.

To simulate the space around the bus bars behind molded case circuit breakers in panelboards, a modified barrier arrangement, shown in Fig. 9, was used. A 203 mm x 25mm x 76mm block of phenolic material was attached along the front and back of the insulated barrier used in prior testing. Investigations were made to determine whether the front barrier diverted the outward flow of plasma upward and increased ionization levels between electrodes during the arc event with the lower fault currents. The results of these tests are reported as the chamber configuration.
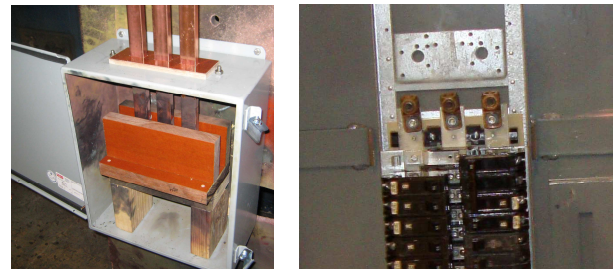

Fig. 9. Chamber Configuration. This is intended to simulate the tight space behind the breakers and around the bus bars in the panelboard shown at right.

D. Electrode Material

All prior barrier tests were performed with copper conductors (electrodes). A review of power panels showed that most 208V and 240V panels in service use aluminum bus bars. Tests were performed to determine whether the physical properties of aluminum [9] would enhance re-ignition at lower fault currents. The minimum limit of arc sustainability with aluminum bus bars was compared to that of copper bus bars for various test set-ups.

E. Available Fault Current (I_{BF})

I_{BF} values, ranging from 2 kA to 15.6 kA were used to compare the performance of the variables in their ability to sustain arcs. Each

configuration was tested to find the value at which arcs would not sustain for more than three cycles.

F. Voltage

The majority of tests were run with a system voltage of 208V. When the limit of sustainability was found with any configuration, additional tests were run at 218V (+5%). If there was no increase in arcing activity, the fault current was identified as the bottom limit of that test condition.

A limited number of scouting tests at 250V provided more insight into the impact of voltage on sustainability at low fault current levels.

VI. TEST RESULTS AND FINDINGS

The following sections discuss results from 89 tests, at 208V, 218V and 250V, with vertical electrode gaps of 19mm and 25.7mm and bolted fault currents near to 2kA, 4kA, 6kA, 8kA and 15.6kA (the precise levels being dependent on the voltage chosen). The electrodes were placed in a test enclosure with dimensions of 305mm x 355mm x 152mm and were 63.5 mm from the back panel of the enclosure. Fifty-six of these tests used an insulating barrier shown in Fig. 3, while the chamber of Fig. 9 was used in the remainder. All tests were done with a low source X/R (<2). Four calorimeters were located at a distance of 305mm (12") from the electrodes.

A. Sustainability Findings

Each configuration was tested with progressively lower I_{BF} until they failed to sustain arcs for at least three cycles. The station breaker was set to limit each event near to 1 second. Fig. 10 shows the longest duration arcs obtained with configurations using 25.4mm gaps and various test variables. From the limited number of scouting tests it appears that the abovementioned factors are significant in determining arc sustainability for I_{BF} below 10kA. These test findings are discussed in the sections below. In the plots of sustainability, the data points indicate the longest duration observed. The lines between the data points are drawn for clarity and do not reflect results for values between the test currents.
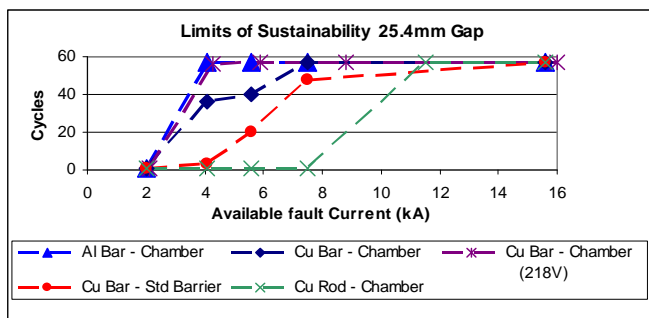

Fig. 10. Longest duration arcs obtained during scouting tests.

Effect of gap. Unlike the open tip configuration, the gap width is a critical variable in sustaining current flow during a low current arcing event with both the barrier and chamber configurations. At higher currents, arcs were easily sustained for the gaps tested; the size of the gap affected the amount of power transferred into the arc and the magnitude of the arcing current. Fig. 11 shows a comparison of the number of cycles sustained for the 208V tests performed with

the chamber configuration at 0.75" and 1.0" gap spacing. Notice the difference in arc duration for the 4.1kA and 5.6kA tests.
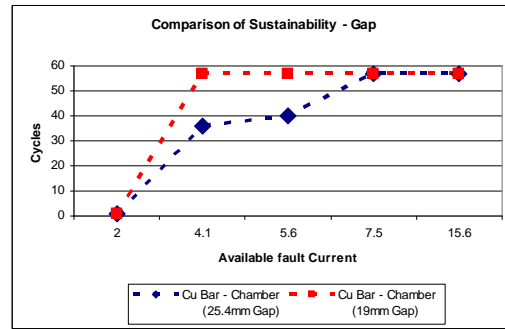

Fig. 11. Results of chamber configuration tests at 208V.

The test duration for both tests was 57 cycles. A comparison of current waveforms is shown in Fig.12. At 19mm gap and I_{BF} of 5.6kA, the arc is established when the trigger wire melts and maintains current flow through the arc for the entire test duration. With a 25.4mm gap the arc quickly extinguishes but restrikes later in the test at a low level of arc current. Approximately 18 cycles after the re-strike, the arc currents in all 3 phases look very stable; B phase current is about 10% lower than the test with the 19mm gap. Similar performances occurred with other test configurations.
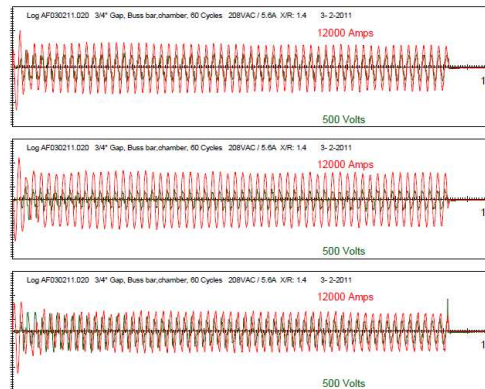

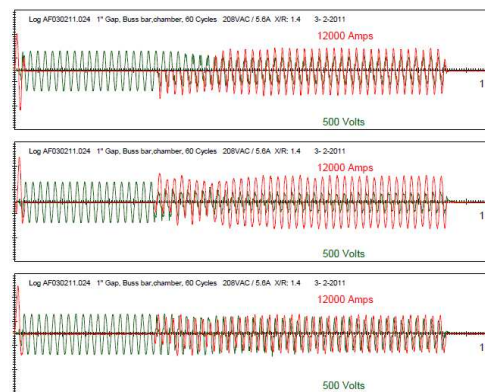Fig. 12a Chamber test at 208V, 5.6kA and 19mm gap.

Fig. 12b Chamber test at 208V, 5.6kA and 25.4 mm gap.

Effects of Electrode Shape. When 12.7mm x 25.4 mm Cu bus bars were used as the electrodes, it was possible to sustain arcs at much lower available fault currents as compared to 19mm copper rod

electrodes. As noted earlier higher electric fields at the sharp edges likely aided arc sustainability. See Fig. 10 for a comparison of the number of cycles sustained for the 208V tests with 19mm rods and the bus bars performed with the chamber configuration at 25.4mm gap.

Effects of Voltage. Minor changes in voltage had a dramatic effect on arc sustainability for some low fault currents used during these scouting tests as shown in Fig. 10. For the 218V tests the I_{BF} was 5% higher than the 208V tests. At higher test currents, the influences of small voltages appeared to have minimal effects on sustainability, power transfer into the arc and the magnitude of the arcing current.

Fig.13 shows results of a 218V test tests performed with the chamber configuration at 25.4mm gap spacing and I_{BF} of 5.9 kA. The arc, initiated when the trigger wire melts, becomes firmly established in the next two cycles and maintains current flow through the arc for the entire test duration. Arc current levels are relatively stable and a slightly higher percentage of I_{BF} than the 208V test shown in Fig.12b.
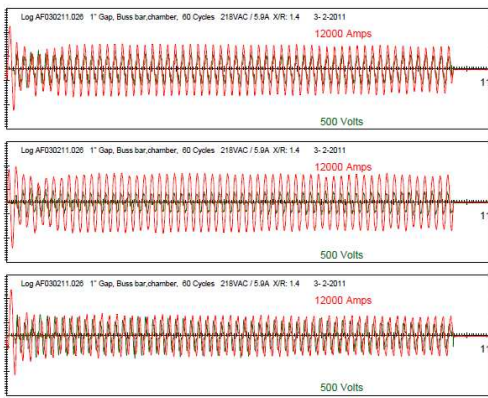

Fig. 13 Chamber test at 218V, 5.9kA and 25.4 mm gap.

Tests run at 250V showed even more dramatic effects on arc sustainability. The trace shown in Fig. 14 is from a single phase vertical electrode configuration terminated in an insulated barrier with a gap of 19mm. This test was performed at 250V, 4kA and X/R of 1.6. Note that after the trigger wire melted the arc never extinguished until the station breaker opened. Arc re-ignition after each zero crossing is similar to that of Fig. 7 for most cycles.
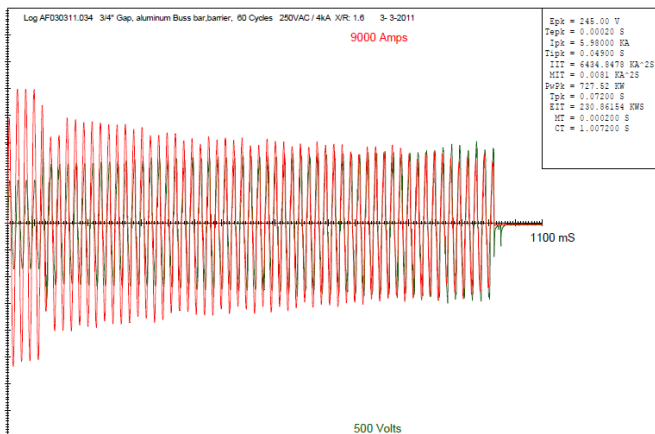

Fig. 14. Traces from 250V, 4kA single phase test barrier test with 19mm gap.

Effects of Configuration. Test results for the new 'chamber' design show arcs re-ignited easier, were more stable and had larger currents when compared to the insulating barrier. See the graph in Fig. 10 comparing the number of cycles sustained for the 208V tests performed on the chamber configuration and on the barrier configuration with 1.0" gap spacing.

Effects of Aluminum Electrodes. The change to aluminum bus bar had a dramatic effect on arc sustainability for the current levels used during these scouting tests as shown in Fig. 10. At higher currents, arc sustainability appeared similar to copper.

Comparing the current waveforms shown in Fig. 15 for the chamber tests at 4.1kA, it appears that aluminum electrodes help facilitate a more stable arc. With copper bus bar, the arc quickly self extinguished but re-struck several cycles later. C phase current is intermittent throughout the subsequent arcing period. Ionized gases from the arcing between A phase and B phase are likely responsible for the re-strikes of C phase during this period. With aluminum bus bars, the arc is intermittent at first but quickly stabilizes and maintains throughout the entire test period. The arc currents in A and B are near 10% higher; C phase is more stable.
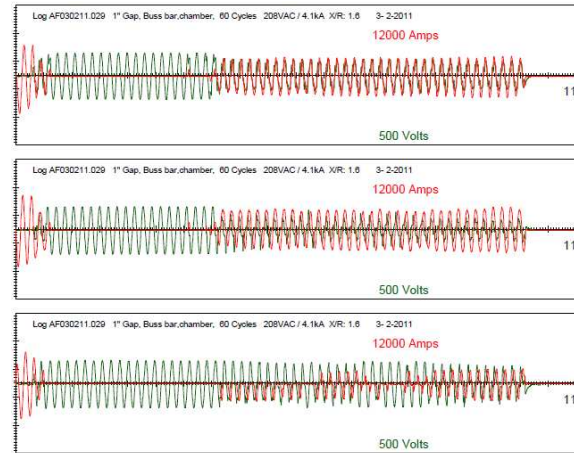

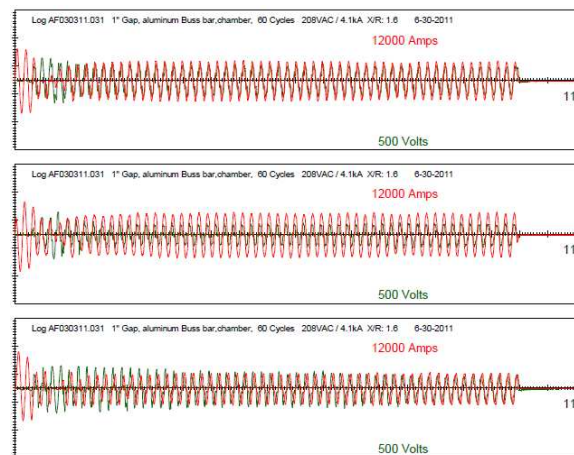Fig. 15a: 25mm Gap, 4.1kA, 208V and copper bus bars.

Fig. 15b. 25mm Gap, 4.1kA, 208V and aluminum bus bars.

B. Incident Energy Findings

In most of the tests where less than 57 cycles were reported, the arcs extinguished but re-struck and burned until the end of the test

period. See Fig. 12b as an example. It is highly likely that these arcs would have burned longer than the allotted test time. Most of the reported incident energy for these tests was generated after the re-strikes. For this reason, incident energy results are normalized to 30 cycles based on the number of cycles of conduction on B phase not on the duration of the test. More data points at the low end will be needed to help develop a reliable predictive equation.

For all chamber configuration tests, the incident energy was less than predicted by the IEEE 1584 equations. Results are shown in Fig. 16. Where arcs were sustained, tests with the standard barrier, had measured incident energy closest to the IEEE 1584 predictions. Fig. 17 highlights a few cases where incident energy was higher than IEEE 1584 predictions.
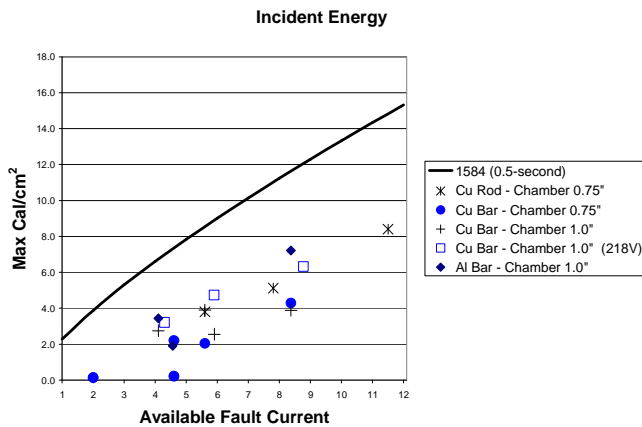

Fig. 16. Plot of incident energy normalized to 30 cycles.
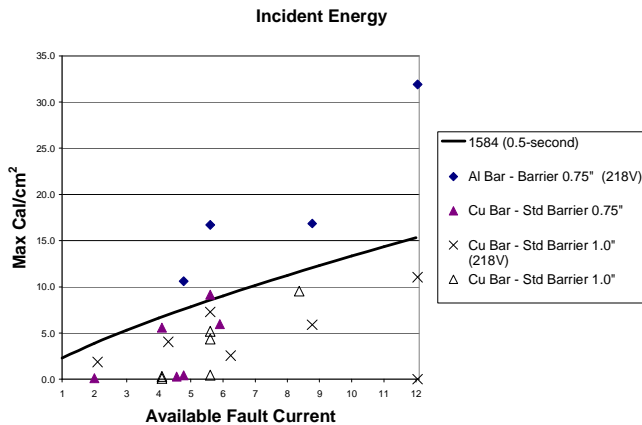

Fig. 17 Plot of incident energy normalized to 30 cycles.

The higher incident energies of the barrier configuration can be attributed to the outward plasma flow shown in Fig. 8 and described in [4]. The lower incident energy from the chamber configuration can be attributed to the upward deflection of the horizontal plasma flow by the front barrier as shown in Fig. 18. The greater distance between the conducting channel and the calorimeters allows the plasma cloud to cool before reaching the calorimeters.

The limited results from tests with aluminum electrodes appeared to be significantly higher than those of copper when arcs were sustained for both materials in the barrier configuration. In cases

where the aluminum helped support current flow better than the copper, measured incident energy was obviously higher.
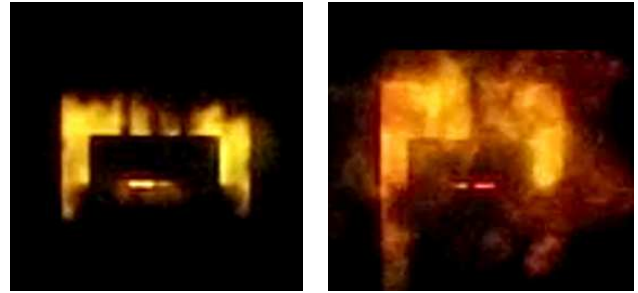

Fig. 18. Front view photos from chamber test.

C. Arc Current

For all tests above 7.6kA, the measured arc current of B phase exceeded that predicted by the IEEE 1584 equations. However, below this level some configurations had arcing currents lower than predictions. Fig. 19 shows the average current after any re-strike.
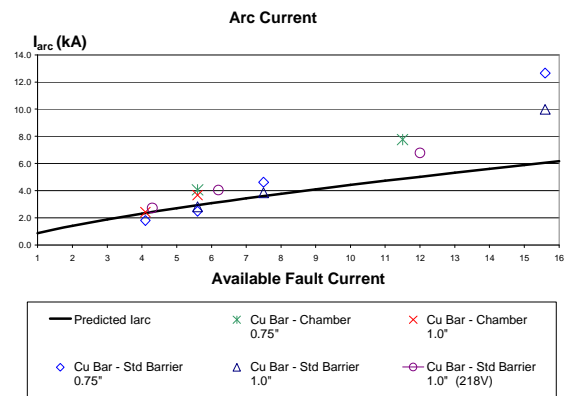

Fig. 19. B-Phase arc current plotted versus IEEE 1584 predictions.

Although the incident energy with the chamber configuration was significantly lower than with the barrier configuration and IEEE 1584 predictions, it performed better in maintaining fairly steady arc currents at these low fault currents. Results from the limited number of chamber configuration tests always had B phase current higher than IEEE 1584 predictions. Tests with the standard barrier however, resulted in lower-than-predicted arc currents when available fault current was below 7.6kA. The barrier configuration appears to have allowed for longer arc lengths and resultant lower currents than the chamber configuration.

Currents were always imbalanced as discussed in [4]. At the lower fault currents, intermittent currents were sometimes observed on A or C phase. See Fig. 15a for example. To properly assess overcurrent protective device performance, it may be necessary to predict B phase and average arc fault current.

The ratio of I_{arc} to I_{BF} at the low fault current levels was observed to be slightly higher at 218V when compared to 208V for those tests where the arc was sustained. When developing incident energy models, this will be an issue that needs to be addressed to better select clearing times of overcurrent protective devices. If arcs can be sustained at 208V, the lower arc current needs to be used; if the arcs can only be sustained at 218V, the higher current would be more appropriate.

D. Fuse Performance

Previous works [10] [4] showed that UL Class RK-1 fuses would limit incident energies to less than 0.5 cal/cm^2 at 18" when the arc current was greater than the fuse's threshold value. To confirm energy limitation from RK1 fuses, 200A and 400A Class RK1 Nontime Delay fuses were evaluated with 4kA and 5.6kA available fault currents. At 4kA, even the 400A fuse opened before the #12 AWG trigger wire could melt.   Since no arc was established, measured heat was negligible.

E. Equipment Tests Results

The authors evaluated three 250V panels to determine what locations within the panel were most likely to sustain arcs at low fault currents and which were most likely to create outward plasma flows. Fig. 20 highlights what are believed to be different electrode configurations within typical panels. The area labeled A would be similar to the barrier test configuration. Area B behind the circuit breakers would be like the chamber configuration with respect to ionization between electrodes. The feed through lugs near C on the panel in the right photo might be similar to the vertical open tip configuration.
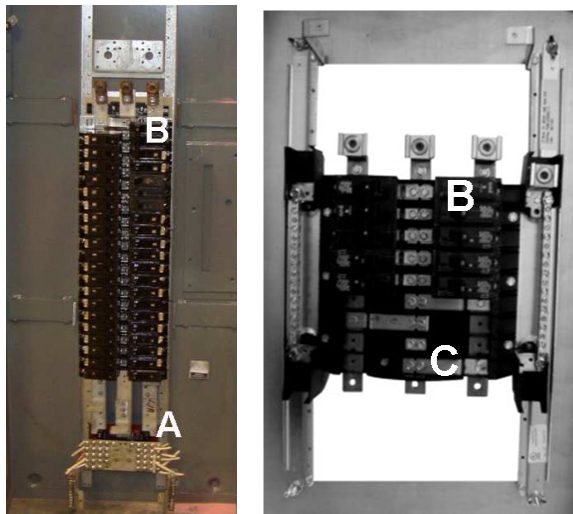

Fig. 20. Multiple electrode configurations in panels

An arc was initiated above position B in the panel of Fig. 20. The test circuit was set at 250V and I$_{BF}$ of 6.5kA. Spacing between the aluminum bus bars of this panel was 19mm. The arc was electromagnetically driven downward to a location behind the circuit breakers. Results are shown in Fig. 21 and Fig. 22. Note the amount of burning aluminum that was ejected. As shown in the trace, the arc self-extinguished and re-struck 18 cycles later. This trace closely resembles results shown in other figures for a chamber configuration test. The arc burned for a total of 1.6 seconds and appears stable at the end of the 2 second test period when the station breaker opened the circuit. The measured incident energy was 15.7 cal/cm^2 at 457mm. The IEEE 1584 prediction for 2 seconds is 20.6 cal/cm^2 and 16.9 cal/cm^2 for 1.6 seconds.
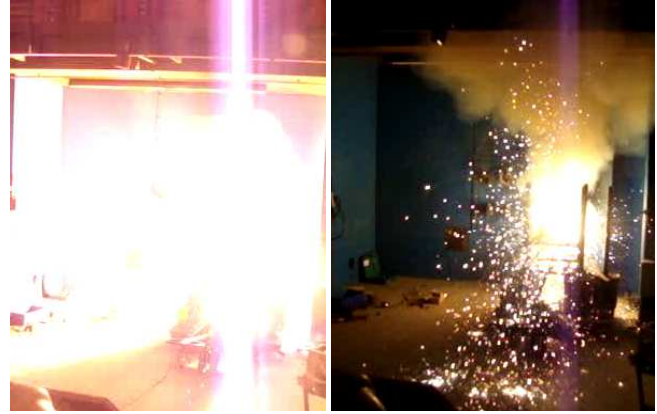

Fig. 21. Photos of panel with arc flash test at 250V and 6.5kA
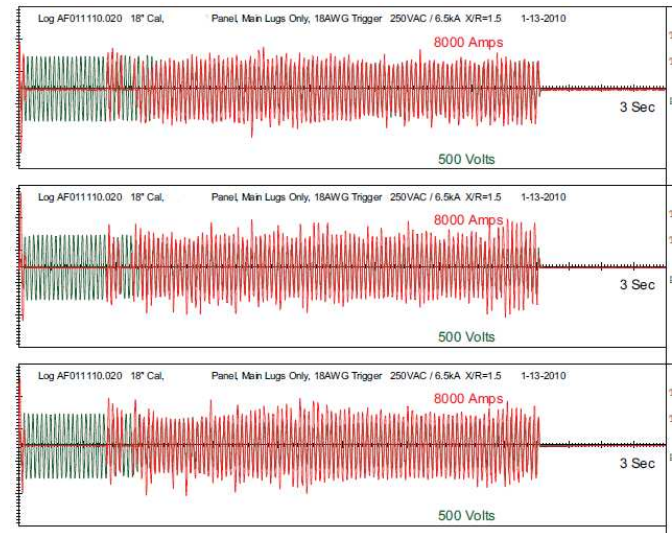

Fig. 22. Traces from Panel arc flash test at 250V and 6.5kA

Limited testing at 208V, due to lack of equipment, was inadequate to confirm the applicability of the barrier and chamber configurations for further model development. More equipment testing with low voltage equipment is critical in refining predictive equations. The above mentioned results, strongly implies that exclusions of circuits 240V from analyses could lead to serious injuries and needs to be revised.

F. Other Observations

Contaminants on insulating surfaces could affect arc sustainability and should be considered before omitting a piece of equipment from an arc flash study. In some tests, the insulating support at the top entry of the bus bars into our test boxes was not cleaned prior to several early tests at 4kA. Tests, re-run after cleaning and meggering the insulator, yielded different results for some configurations. Tests with the contaminants appeared more likely to re-strike and establish stable arcs at the lowest currents tested. The material and condition of insulators in the field may have a similar effect.

Effective arc gap distance could be less than equipment gap distance during equipment failure or introduction of a foreign object into the gap between conductors. If foreign objects enter into the space between conductors, they could remain as a conductor in the

arc circuit and effectively reduce the arc gap. As shown above and in previous work with 12.7mm gaps [4], reducing gap size can have a dramatic effect on arc sustainability.

The performance of overcurrent protective devices in the presence of intermittent fault currents may need further evaluation for cases where such devices are not expected to open in their short circuit mode. Test setups may need to use smaller trigger wire sizes to ensure the wire melts and starts an arc before the protective device operates. If arcs cannot be established with smaller wire, mechanical means of establishing an arc could be evaluated.

Arc rated PPE would be needed for workers at these lower currents if durations were greater than a few cycles. For example, if these limited results are typical and incident energies are somewhat linear over time, arc rated PPE would be needed for fault currents of 5.6kA if clearing times were greater than three cycles. For extended arcing times, the outward convective flow of the barrier configuration could have additional effects on PPE selection [11].

VII. CONCLUSIONS

The testing discussed in this paper shows that sustained arcs are possible at 208V even at relatively low fault currents but are dependent on several factors including voltage variations, conductor material, the configuration of conductors and the presence of insulating barriers. The challenge to industry is to advance the research identified in the references, do additional testing on a variety of low voltage equipment and incorporate those findings into improved standards. These test strategies must consider all practical locations within the equipment where arcs may occur; within all equipment is the possibility for different electrode orientation.

Enhanced models for various equipment is essential to moving forward and improving incident energy predictions, work procedures and effective mitigation actions. The test configurations discussed may require new equations in the IEEE 1584 standard. The work of the IEEE/NFPA Collaboration on Arc Flash Hazard Phenomena Research Project remains critical to advancing the level of protection against arc fault hazards.

An underlying tenet of electrical safety is that equipment is not in an electrically safe condition until proven that is safe. Exceptions in standards for equipment rated 240V and below need to be reconsidered. The uncertainty discussed in this paper and elsewhere [11], indicates revisions to these standards should include clarity on PPE requirements and minimum fault currents instead of transformer power ratings for any exclusion to arc flash hazard analysis requirements. It would be prudent to consider 208V equipment as having potential arc flash hazards when performing hazard analyses for facilities. With an arc flash hazard prediction for this equipment, mitigation efforts and improved practices can be added to the electrical safety program. De-energizing equipment (0 cal/cm^2 and 0 volts) prior to work remains the best way to hedge bets on workers' health.

VIII. ACKNOWLEDGEMENTS

IX. REFERENCES

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X. VITA

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