Impact of Arc Flash Events With Outward Convective Flows on Worker Protection Strategies

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Abstract. Recent research into arc flash test configurations suggests that some equipment may have the potential for greater arc flash incident energy than predicted by IEEE 1584 due to outward convective flows associated with electrode orientation and configuration. This research suggests that lower arcing currents could lead to longer clearing time of protective devices and higher incident energies. Additional research also suggests that Flame-Resistant (FR) material used in electrical Personal Protective Equipment (PPE) may not provide the same protection levels as predicted by their arc rating when placed within these convective flows. The possible impact on protection requirements, work procedures and mitigation strategies of these findings is discussed. This paper looks at the impact of adjusting the C_f factor of the IEEE 1584 incident energy equation to accommodate test data from alternate configuration, using lower I_{ARC} and de-rating the arc rating of PPE.

Index Terms — Arc flash hazard testing, effect of insulating barriers, arc rating, effective arc rating, horizontal conductors, horizontal electrodes, personal protective equipment (PPE), plasma, terminated vertical conductors, terminated vertical electrodes, vertical electrodes, vertical conductors

I. INTRODUCTION

The widely used empirically derived incident energy equations of the IEEE 1584™-2002 [1] standard were developed with data from numerous tests with open tip vertical electrodes. Test results showed incident heat energy at the front opening of the test box up to 3 times that of comparable arcs in open air [2]. When published, the standard contained an incident energy equation with a calculation factor (C_f) of 1.5 for applications under 1000V to ensure that the equation would predict incident energies higher than most of the test results used to develop the equations [3].

It has been shown that arc development is downward within the enclosure with this electrode arrangement. Subsequent tests with electrodes in open air directed at the heat measuring devices and in an enclosure with electrodes entering from the rear of the enclosure indicated incident energies two to three times higher than the vertical electrodes [4] [5]. Arc currents were also significantly lower than predicted by the IEEE 1584 equations. If clearing times of upstream overcurrent protective devices are significantly higher at these lower currents, incident energy calculations will be greater than three times the existing IEEE1584 calculations. Additionally, tests with the vertical electrodes of the IEEE 1584 test configuration 'terminated' into an insulating barrier indicated higher than predicted incident energies [6]. It is postulated that the resultant outward plasma flows of these test configuration contributed to a greater convective heat transfer than previous configurations.

Early tests by Neal [7] suggested that PPE specimens placed in the outward convective flows of the abovementioned test configurations would have significantly different arc ratings than that determined by ASTM F1959 [8] and ASTM F2178 [9]. Face shields that were effective in blocking the convective flow would perform much better than their ASTM rating. However, fabric specimens placed in the convective flow exhibited significantly lower performance than their arc rating.

Part of the mission of the IEEE/NFPA Collaboration on Arc Flash Hazard Phenomena Research Project is to resolve the issues related to incident energy discussed above and to develop equations better suited for real world electrical equipment. The ASTM F18.65 Subcommittee has recently formed a task group to address the issues raised in Neal's paper. Until the work of these groups is complete, industry must deal with the uncertainty raised by the research on test configurations and PPE.

In this paper, the authors investigate the potential impact of higher incident energies on low voltage systems and reduced arc ratings of PPE on the safety programs of a large plant. This was accomplished by investigating the effects of increasing the C_f factor, doing a second calculation at 70% of I_{ARC} and using the recommendations in Neal's paper for "effective arc rating". The results of applying this approach at this plant has suggested changes in work procedures for several locations, additional mitigation efforts and a modified PPE strategy. Tests performed on actual equipment provided insight into issues related to the application of current models for equipment.

II. BACKGROUND

A. *Predictive Equations*

In 2002 IEEE 1584™-2002 was released with the following equation for incident energy:

$$E = 4.184\, C_f\, E_n\, (t/0.2)\, (610^x / D^x) \qquad (1)$$

Where:

- C_f - Calculation Factor of 1.5 for 1kV and below
- t - Arcing time
- D - Distance to worker
- X - A distance exponent.
- E_n - Normalized energy determined from the equation:

$$\log_{10} E_n = K_1 + K_2 + 1.081 \log_{10} I_{ARC} + 0.0011 g \qquad (2)$$

The calculation factor was added to shift the incident energy predictions upward to predict a value higher than most of the test results with the open tip vertical electrodes. The working group settled on a value of 1.5 to ensure proper selection of PPE for 95% of the test results used to develop the equation. Users can shift this value upward if they want to be more conservative[3].

Results from arc flash tests performed at 480V with vertical electrodes with and without an insulating barrier and horizontal electrodes described in [5] and [6] are presented in Figure 1. Results for tests at 208V are presented in Figure 2. The lines on the graph are the predicted values based upon equation (1) with various C_f when applied for switchgear (i.e. gap = 32mm). Test results for vertical electrodes without a insulating barrier are shown clustered around the line for the empirically derived incident energy formula with C_f = 1.0 and fall below the C_f = 1.5 line chosen by the IEEE 1584 committee. The results from alternate configuration testing are significantly above this line in several cases.

The arcing current (I_{ARC}) used in equation (2) was derived from measurements during the same tests used to measure incident energy. The empirically derived I_{ARC} equation, based upon the bolted fault current (I_{BF}) of the tests, is shown in equation (3).

$$\log_{10} I_{ARC} = 0.00402 + 0.983 \log_{10} I_{BF} \qquad (3)$$

Results for I_{ARC} from arc flash tests performed at 480V with vertical electrodes with and without an insulating barrier and horizontal electrodes described in [6] and [7] are presented in Figure 3. The lines on the graph are the predicted value, 85% of that value as recommended by the IEEE 1584 standard and a line at 70% of the predicted value. The 85% factor is used in the IEEE 1584 model for voltages less than 1000V to compensate for inaccuracies in impedances in the short circuit study that could lead to substantially longer clearing times of the overcurrent protection device [10].

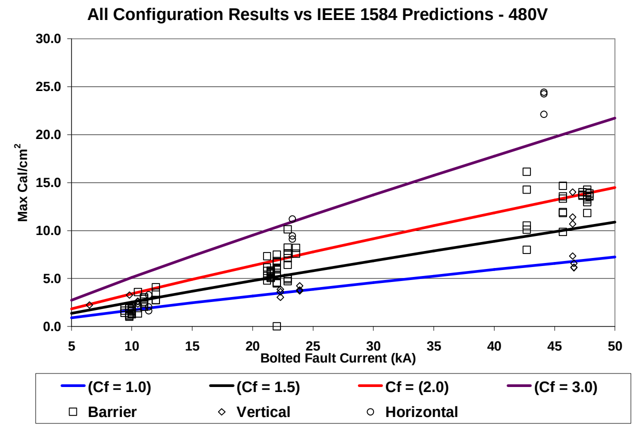

Figure 1. Maximum Incident Energy for Various Configurations at 480V. Results normalized for 0.1s.

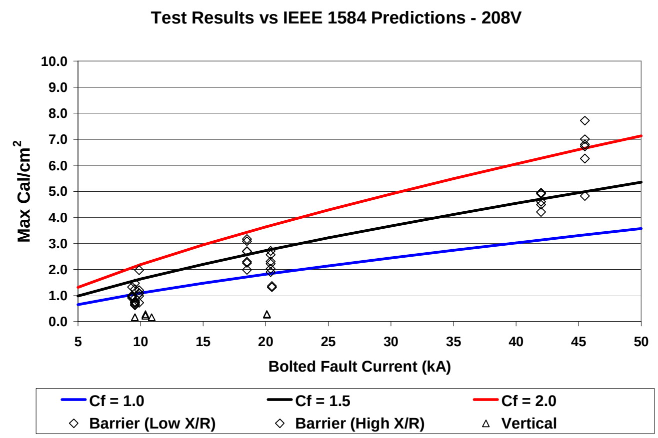

Figure 2. Maximum Incident Energy for Various Configurations at 208V Results normalized for 0.1s.

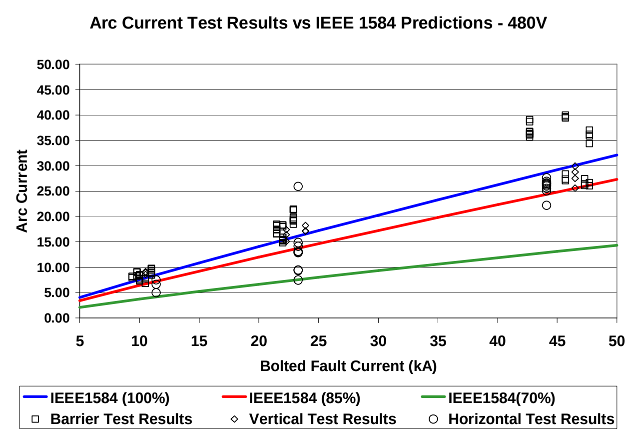

Figure 3. Arc Current I_{ARC} Average for Various Configurations tests at 480V.

The data points for the vertical electrodes tests cluster around the 100% line show comparable results to the data used to create the 1584 equation. The results for the barrier is equal to the vertical or higher in most cases. Although this implies a different relationship between incident energy and I_{ARC} than equation (2), this difference ensures that overcurrent protection devices will clear the arc in times equal to or less than the current model predicts. The data for the horizontal open tip is shown to be significantly lower than predicted. For equipment with similar conductor arrangements as this configuration, incident values could be much higher than 3 times if the lower current results in clearing times longer than predicted.

B. Effective Arc Rating of PPE

The arc flash heat energy transfer process through PPE can vary with the type of equipment configuration and the materials that are involved in the arc flash event. The relative levels of radiant heat energy and convective heat energy, the impact of direct plasma exposure in the main arc channel, and the heat transfer due to metal vapor/liquid/solid phase transition are among the primary causes for the differences in the heat transfer process through PPE. Radiant energy can only travel in a straight path while convective energy is not limited to a straight line path. The heated gases and plasma involved in convective energy transfer can move in any direction based on pressure gradients. Consequently, radiant energy is more effectively blocked by the permeable fibrous matrix which makes up FR clothing fabrics than convective energy which can move between and around the fibers within the fibrous matrix of FR clothing fabrics. On the contrary, impermeable faceshields and hood shield windows very effectively block convective energy while permitting a degree of radiant energy transmission due to the need for visibility through the faceshields and hood shield windows. This difference in the heat transmission mechanism between radiant energy and convective heat energy creates the need for a modified arc rating based on the type of energy exposure involved in an arc flash event. In this discussion, the term "effective arc rating" is used to indicate the rating of FR clothing fabrics or systems of fabrics and face protection relating to a specific test configuration. The "effective arc rating" is based on limited testing using arc-in-a-box conductor configurations described in [7] which tend to generate a high level of convective heat energy.

B. ASTM Arc Rating: The "ASTM arc rating" of arc flash Personal Protective Equipment (PPE) is determined by ASTM Test Method Standards F1959 for FR fabrics and F2178 for face protection [8] [9]. In these test methods, the arc rating is determined by exposing test specimens at a distance of 12 inches from a single phase, 8kA arc flash generated between opposing vertical stainless steel electrodes. With this electrode configuration, the arc flash is constrained between the two electrodes resulting in primarily radiant heat transfer to the FR fabric or face protection specimens.

C. *Arc-In-a-Box PPE Tests:* The The arc-in-a-box test configurations described above and in [2][4][5][6] and [7] consist of a 508 mm (20 inches) cubic box with the front surface open and with three vertical copper conductors with a diameter of 19 mm (0.75 inch) positioned in a linear array. The arrangement of array of three conductors can be horizontal with open tips, vertical with open tips or vertical with tips terminated into an insulating block. Tests were conducted with a system voltage of 480V and 600V and an arc fault current of 20kA to 50kA. In a few cases a smaller cubic box was also used. Specimens ranged from 305mm (12 inches) to 457mm (18 inches) from the conductors. In all arc-in-a-box configurations, the exposure consists of a high level of convective energy and a lower level of radiant energy. For the purposes of this discussion, convective energy includes heat transfer due to direct contact by plasma generated during the arc flash. Table 1 provides the "effective arc rating" for PPE exposed to these primarily convective energy exposures. The ASTM arc ratings are also provided in Table 2 for comparison. Due to the heat transfer process described above, the "effective arc ratings" of fabrics is significantly lower than the ASTM arc ratings, and the "effective arc ratings" of face protection is significantly higher than the ASTM arc ratings.

Material Type Weight oz/yd2 Air Permeability ft^3/min (cfm)	Arc Rating ASTM F1959-05b Test Method SS Electrodes cal/cm2	Est. Arc Rating Box Method Terminated Vertical Cu Electrodes cal/cm2	Est. Arc Rating Box Method Horizontal Cu Electrodes cal/cm2
HRC2, 1 layer Aramid, 8 oz/yd2 18 cfm	8 (20 Specimens)	7 (3 test panels)	7 (3 test panels)
HRC2, Aramid OU coated fabric 1 layer, 3.4 oz/yd2 0 to 1 cfm	11 (20 Specimens)	9 (2 test panels)	9 (3 test panels)
HRC4, 2 layers FRT cotton/nylon 19 oz/yd2, 5 cfm	41 (20 Specimens)	22 (4 test panels	21 (3 test panels
HRC4, 3 layers Aramid 12 oz/yd2, 84 cfm	49 (20 Specimens)	18 (3 test panels	18 (3 test panels
HRC4+ 5 layers 15 oz/yd2, 59 cfm	70 (20 Specimens)	27 (3 test panels)	35 (1 test panels)
HRC2 Faceshield 0.105 inch thickness Air Perm = 0	12 (20 Specimens)	>30 (2 test shields	>21 (1 test shield)

Table 1: Effective Arc Ratings of Hazard Risk Category 2 through 4+ with Three Arc Test Configurations

D. *Recommendations:* Based on test results published by Neal [7] FR fabric "effective arc ratings" are assigned as follows:

- For FR fabrics with an ASTM arc rating at 11 cal/cm^2, "effective arc rating" is 85% of the ASTM arc rating
- For FR fabric systems with an ASTM arc rating at 40 cal/cm^2 and above, "effective arc rating" is 50% of the ASTM arc rating
- For faceshields with a thickness greater than 0.10 inch and an ASTM arc rating from 8 to 12 cal/cm^2, "effective arc rating" is 150% of the ASTM arc rating

III. Modified Analysis

A. General Approach

The purpose of the modified analysis was to identify equipment where labels are indicating a level of PPE protection that would be predicted to be inadequate based on the research in [4], [5], [6] and [7]. A two step approach was utilized to select PPE based on higher than predicted incident energies and lower "effective arc ratings". In the first step the constant C_f was increased to 3.0 for 480V applications based on data shown in Figure 1 and to perform the second calculation at 70% of I_{ARC} instead of 85% as recommended by IEEE 1584. Similarly, C_f was increased to 2.0 for applications below 300V based on data shown in Figure 2. The calculated incident energy at each location was matched to the "effective arc rating" of the PPE to provide adequate protection. In the second step, those applications that 'jumped' to a higher PPE Hazard Rick Category (HRC) were further evaluated for the appropriateness of a higher C_f and lower I_{ARC}. If visual inspection indicated that there were no open tip horizontal conductors present in the equipment, the second evaluation was recalculated with 85% of I_{ARC}.

B. Facility background

A large manufacturing plant was chosen to assess the potential impact that higher energy predictions and reduced arc rating of FR fabric could have on their electrical safety program and PPE strategy.

This facility uses a three level PPE strategy corresponding to HRC0, 2 and 4. Worker PPE requirements had been determined by an arc flash study using the IEEE 1584 equations. The modified study of 869 buses covered only voltages ranging from 480V to 208V. The study included 39 MCC's, 11 substations, 19 power distribution boards, 25 lighting panels, several bus ducts and a variety of control panels on the low voltage system.

This facility's PPE strategy is highlighted in Table 2 with the number of applications falling within each grouping for their low voltage systems. This is compared to the breakdown of applications falling within each NFPA70E hazard risk category (HRC). Note that for this strategy, many of the locations already have a margin of extra protection built in. For example the 77 locations that would be classified as HRC1 (<4.0 cal/cm^2) by NFPA70E require workers to wear HRC2 PPE with coveralls rated at 11 cal/cm^2.

	NFPA 70E		Facility	
Cal/cm^2	HRC Category	Number	PPE Category	Number
0-1.2	0	645	0	645
1.2 - 4	1	77	–	–
4.0 - 8	2	29	2	106
8.0 - 25	3	79	–	–
25 - 40	4	13	4	92
>40	X	31	X	31

Table 2. Summary of PPE Requirements for LV systems.

The facility uses all PPE required by NFPA70E for each HRC. The following discussion is limited to the performance of the clothing relative to predicted incident energy.

Fabric specimens for the PPE systems used at the facility were tested in a manner described by Neal [7] to identify an "effective arc rating" of the clothing systems. When the specific FR fabric used by the facility is tested using a horizontal open tip conductor configuration or a vertical terminated tip conductor configuration, the convective heat transfer through the FR fabric reduces its protective capability and results in an "effective arc rating" lower than the ASTM arc rating. Conversely the face shields used by the facility exhibit higher "effective arc rating" than the ASTM arc rating.

Table 3 provides information on the FR fabrics used as part of each category at this facility. The "effective arc ratings" shown are predicted by the authors based on limited testing of FR fabrics in the outward convective heat flows using the test set-ups discussed in [7].

HRC	Material	ASTM ATPV	Estimated Effective Arc Rating
0	Cotton	-	-
2	FR Cotton	11 cal/cm^2	8 cal/cm^2
4	FR Cotton	40 cal/cm^2	20 cal/cm^2

Table 3. Estimated effective arc rating of PPE used at facility.

C. Step 1 Results

The impact on the distribution of HRC levels due to increased incident energy and lower effective arc ratings is shown in Figure 4. For the initial step of the modified analysis, there were 245 applications that had calculations above the effective arc ratings of the prescribed PPE. These applications are highlighted in Figure 4 and are the focus of the following discussion. For example, if the modified calculation was above the HRC4 "effective arc rating" of 20 cal/cm^2, that location was moved to HRC X.

With Modified Calculations and Effective Arc Ratings

with 1584 Calculations		HRC0	HRC2	HRC4*	HRC X
HRC 0	640	510	125	1	4
HRC 2	106		65	33	8
HRC 4	92			18	74
HRC X	31				31
		510	190	52	117

Figure 4. Redistribution PPE requirements due to increase in C_f and reduced I_{ARC} in Step 1.

** - HRC4 has an effective arc rating of 20 cal/cm^2*

D. Step 2- Analysis Refinements

The 245 locations identified in Step 1 as requiring higher-rated PPE were further analyzed to validate the need for a modification of the standard IEEE 1584 approach. The remaining 624 equipment locations were determined to have an adequate PPE strategy regardless of electrode (conductor) configuration.

The first group of locations evaluated were the 130 applications for which the HRC0 level was increased to HRC 2,4 or X. These 130 applications consisted of 53 at 480V and 77 at 208V or 240V.

Of the 53 locations at 480V, 31 had clearing times longer than the initial analysis due to calculation at 70% of I_{arc}. Of those determined not to have horizontal conductors projecting toward workers, 10 were returned to HRC 0 with calculations at C_f =3.0 and 85% of I_{arc} and removed from the list of concern. The remaining 43 application were designated to be at the higher HRC 2 protection level due primarily to the higher C_f value of 3.

Of the 77 locations at 208 or 240V, 64 had I_{BF} less than 10kA. Since test results for all electrode configurations conform to the IEEE 1584 model at these current ranges (see Figure 2), these locations were removed from the list of concern and returned to HRC0. The remaining 13 locations were evaluated similar to the 480V applications above; 4 remained at the new HRC 2 Level.

In summary, 47 of the 640 HRC0 locations were increased to HRC2 with the modified approach using a C_f = 3.0 for all 480V applications and C_f = 2.0 for lower voltage applications

In the second group evaluated there were 41 HRC2 applications that moved up to HRC4 and HRCX. Of the 37 locations at 480V, 20 had clearing times longer than the initial analysis due to calculation at 70% of I_{arc}. Eight locations were determined not to have horizontal conductors projecting towards workers, and were returned to HRC2 with calculations at C_f =3.0 and 85% of I_{arc}. Of the balance, 27 locations remained at the higher HRC4 protection level and 2 locations remained at HRCX. All 4 locations at 240V had I_{BF} less than 10kA. Similar to the discussion above, all were returned to HRC2.

In summary, 29 of the 41 HRC2 locations were increased to a higher HRC level with the modified approach using a Cf = 3.0 for all 480V applications. The calculation at 70% I_{ARC} required 2 of these locations to be classified as HRCX.

In the third group of HRC4 locations there were 74 applications that were moved beyond Category 4. Of these, 41 were 480V and 33 were 240V. Because the "effective arc rating" of the PPE clothing system for HRC4 was estimated to be 20 cal/cm^2 and the C_f increased to 3.0, 40 out of the 41 480V applications remained at HRCX. Likewise, because the "effective arc rating" for the HRC4 system was estimated to be 20 cal/cm^2 and the Cf increased to 2.0, 26 out of the 33 240V applications remained at HRCX

In summary, 66 of the 74 HRC4 locations were increased to a higher HRC level with the modified approach. An arc flash suit with an "effective arc rating" of at least 36 cal/cm^2, would provide protection for 42 of these 66 locations.

The revised distribution of PPE requirements in Figure 5 shows that only 16% of the locations had increases in PPE requirements with this modified analysis approach.

with 1584 Calculations		With Modified Calculations and Effective Arc Ratings			
		HRC0	HRC2	HRC4*	HRCX
HRC0	640	593	47	0	0
HRC2	106		77	27	2
HRC4	92			26	66
HRCX	31				31
		593	124	53	99

Figure 5. PPE requirements after refinements in Step 2.

** - HRC4 has an effective arc rating of 20 cal/cm^2*

IV. Action Items

Three actions would be considered for each location left on the list of locations of concern: changing PPE strategy, mitigating incident energies and changing practices (procedures). The top priority was to address the 68 locations where the modified incident energy calculation increased PPE requirements beyond the effective arc rating of the facility's HRC4 systems.

A. Revisions to PPE selections

Selecting a PPE system with an "effective arc rating" of at least 36 cal/cm^2 would provide adequate protection for 42 of the 68 locations that were increased to Category X. Fabrics rated above 70 cal/cm^2 would be needed to provide a protection level in this range.

B. Mitigating Incident Energies

The 26 locations not protected by the revised PPE were reviewed for energy reduction through revisions to the overcurrent protection. The incident energy calculations for eight (8) of these locations increased dramatically because of the calculation at 70% of I_{ARC} consistent with horizontal electrodes. Revised circuit breaker settings (2) and new trip units (6) could reduce clearing times and reduce energies below the effective arc rating of 36 cal/cm^2 for the HRC 4 system proposed above.

The remaining 18 locations moved beyond the effective arc rating of the HRC4 PPE due solely to the doubling of the C_f factor. Most of these locations would need new trip units in upstream circuit breakers to ensure protection by HRC 4 system proposed above.

C. Work Procedure Changes

All incident energy calculations at the substation mains doubled with the modified analysis. These were already classified as Category X. Installation of remote open and close circuitry should be investigated and then combined with de-energization of the source before racking in or out the breaker if applicable.

Where substations are not equipped with a main breaker or compartmentalized, all of the 480V breakers would be Category X. De-energization of the transformer feeding the substation should be considered before racking in or out the 480v breakers. Use of remotely located control devices should also be investigated to remove the electrical worker from within the arc flash boundary.

V. INSIGHTS

A. Equipment Model Development Issues

IEEE 1584 assigns different equations for incident energy and arc fault current magnitude based upon the type of equipment. These equations were derived from results with electrode gaps and test enclosures of different sizes that were deemed to be representative of various equipment. The test setups used to derive these equations used the open tip vertical electrode configuration mentioned earlier. A review of equipment indicated that this may need to be revisited.

The purpose of studying other electrode configurations is to better understand and simulate the variety of conductor orientations present in equipment. Since there is a significant difference in measured incident energy between test set-ups with the same arc duration, it will be necessary to determine if these set-ups are an appropriate representation of actual equipment.

Another reason for studying the various electrode configurations is to determine differences in arc current magnitude. Lower arc current magnitude can more dramatically affect arc energy calculations if the current falls below the short circuit region of the protective device. In this study, 361 out of 869 locations had incident energy calculations determined at the low range of estimated arc current.

The authors faced the problem of assigning an electrode configuration model to each piece of equipment that needed to be raised to a higher HRC level in our modified analysis. There are several difficulties associated with selecting an electrode configuration to represent equipment:

1) *More than one 'electrode configuration' in equipment*. Most equipment contains conductor orientations that could create more than one of the electrode orientation discussed above. Incident energy would depend on where the arc occurs.

2) *Arcs can relocate during an event in real equipment*. Arcs may relocate due to electromagnetic forces and re-striking of the arc upstream from the original location. With this dynamic nature of arcs, the event could begin in one location of the equipment with one electrode configuration and move to another location with another configuration. This can lead to more or less energy depending on configuration and duration of the arc at the various locations.

3) *Equipment may have a different configuration with components installed than when they are removed.* This can be by intention or the component can be ejected during an explosive arcing event. The fuses in Figure 6 served as a barrier for an arc on the horizontal bus connecting the circuit breaker to the switchgear. Convective plasma flow of this event would be expected to be perpendicular to the bus (vertical flows) with the circuit breaker installed. If an arc occurred on the bus with the circuit breaker removed the flows would have likely been outward (horizontal).

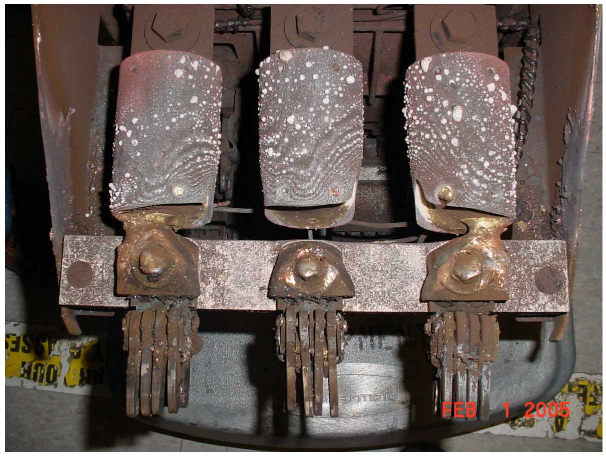

Figure 6. Arc fault damage resembling barrier configuration.

4) *"Broken" equipment may create a configuration not present in "new" equipment*. Since many arc events are initiated when the equipment fails, failure modes must be considered to predict a configuration and resultant plasma flow with respect to worker location. Difficulty in getting a stable arc or outward plasma flows in new equipment is not always a reasonable representation of energy transfers that could occur from 'broken' equipment. Gaps may be different, barriers to arc movement may be removed or horizontal electrodes could be exposed. The arcing event in the bus plug switch shown in Figure 7 may have started as a barrier but became like the horizontal electrodes as evidenced by the burn back of the horizontal bus bars to the left.

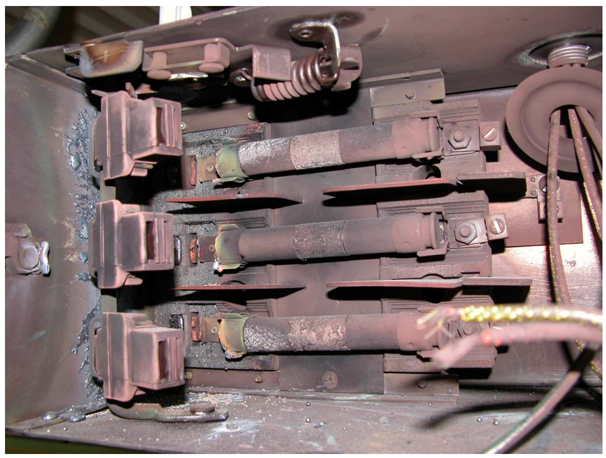

Figure 7. Photo of bus plug switch with burn back of bus bars.

5) *Equipment from different manufacturers or of different vintage may have different conductor arrangements*. This may make it difficult to assign an electrode configuration to a class of equipment.

B. 240V Arc Models

Models for equipment with voltages less than 250V and fault currents less than 10kA need further development. The tests used in the development of IEEE1584 were unsuccessful in sustaining arcs for this range of currents and voltages [1]. Although tests at 208V and 4kA on terminated bus bars with 0.5 inch gaps were successful in sustaining arcs, more research is needed to determine the appropriateness of these tests [6]. In the analysis with standard 1584 calculations, 40 of 158 applications in this range required greater protection than HRC0. With the modified approach this number increased to 75. These predictions would benefit from an improved model.

C. Importance of Current Limitation

All 161 buses shown in the original analysis with a clearing time of 0.004s remained at HRC0 in the modified analysis, while 160 out of 162 buses with a clearing time of 0.008s remained at HRC 0. The two locations that increased were 240V applications with bolted fault currents less than 10kA. This is consistent with published research for fuse performance for arc flash events[11] [5] [6].

D. PPE System Rating Issues

The authors assigned an effective arc rating to PPE systems based on tests of fabric samples. However, additional protection, beyond the stated arc rating, is built into the design and construction of most arc flash suit designs due to arc flash suit overlap areas. One area of additional protection is in the front of the torso area where the hood flap extends over the upper chest area on top of the arc flash coat creating a double layer of the arc suit material system. Similarly the bib overalls extend over the abdomen under the arc flash coat creating another area with a double layer of the arc suit material system. The arc rating in these overlap area is at least twice that of the stated arc rating of the fabric in the arc flash suit. The hood shield window or faceshield has been observed to provide at least the stated ASTM arc rating regardless of the arc test configuration. Consequently, most of the frontal area of the torso provide an arc rating safety factor for the bib overall arc flash suit design. Arc flash protective clothing in a coverall design or arc flash shirts and pants do not provide these overlap areas, and consequently do not provide an arc rating safety factor for the frontal area of torso.

VI. SUMMARY

The modified analysis performed for this paper shows that engineering solutions are available to improve protection of workers from arc flash hazards but are dependent on effective models and standards. The challenge is to advance the research identified in the references and incorporate those findings into improved standards.

Enhanced models for various equipment is essential to moving forward in improving incident energy predictions and effective mitigation actions. The other test configurations discussed may require new equations without the same linear relationships as the IEEE1584 equations. This can allow for more realistic predictions than obtained by increasing the C_f factor for all fault currents.

More testing of PPE in the outward convective flows is needed to better quantify the protection afforded by systems in use today. Developing an arc rating for convective exposures will require an additional ASTM test method. Quantifying the mitigating effects of the fabric overlap described above could alleviate the problems of overdressing or under-protecting workers.

The work of the teams on the IEEE/NFPA Collaboration on Arc Flash Hazard Phenomena Research Project and the ASTM task group, pursuing a new PPE test method, is critical in advancing the level of protection against arc fault hazards.

Considering the uncertainty discussed in this paper and the lack of predictions for the other arc flash hazards, mitigation efforts and well developed practices remain a key element of an electrical safety program. De-energizing equipment (0 cal/cm^2 and 0 volts) prior to work remains the best way to hedge bets on your workers' health.

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VIII. Vita

Mike Lang works with Ferraz Shawmut, in Roswell, GA. In his 14 years with the company he's held various field engineering positions and currently serves as manager of field engineering. A team leader on the IEEE 1584 working group, Lang participated on the IEEE/NFPA RTPC and is on the Technical Advisory Committee as part of Ferraz Shawmut's platinum-level sponsorship of the IEEE/NFPA Arc Flash Collaborative Research and Testing Project. He is a member of ASTM F18.65 Task Group on Arc Resistant Protective Clothing and Equipment.

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