ARC FLASH EXPOSURE OUTSIDE OF ENCLOSED EQUIPMENT

Paper No. PCIC-(do not insert number)

Clinton Carne
Senior Member, IEEE
Schneider Electric
3700 6th St. SW
Cedar Rapids, IA 52404
USA
clint.carne@se.com

Henry (Hank) Clark
Member, IEEE
Chevron Pipe Line and Power Company
P.O. Box 338
Sour Lake, TX 77659
USA
heclark@chevron.com

Michael McConnell, P.E.
Member, IEEE
Schneider Electric
1650 W Crosby Rd
Carrolton, TX 75006
USA
michael.mcconnell@se.com

Abstract – Current standards have made good progress in helping engineers calculate the incident energy a worker would be exposed to when bare energized conductors are present. However, there are no alternate calculation methods or adjustment factors available to quantify the effects of equipment enclosures, or other conditions where a user maybe indirectly exposed to an internal arcing fault. IEEE C37.20.7, which sets criteria for Arc Resistant Switchgear, does not directly establish potential incident energy exposure levels outside the equipment under test. UL RP 2986 does begin to lay groundwork to quantify incident energy levels outside of enclosed equipment including instrumentation and testing parameters. However, it does not clearly define how to apply said procedures. This paper will address selection of appropriate parameters based on experience with testing low-voltage distribution equipment to the UL RP 2986 practice. Selected test results will be compared with the results of IEEE 1584-2018 calculations. The paper will also discuss the benefits of tested equipment that has been examined to measure the actual incident energy levels outside of enclosed equipment, including identifying situations where a worker may be shielded from incident energy levels greater than 1.2 cal/cm^2.

Index Terms — UL RP 2986, IEEE 1584, energy-reducing line side isolation, arc flash, energized electrical equipment, incident energy, internal arcing test.

I. INTRODUCTION

Standards exist for the testing, evaluation, and calculation of arc flash hazards which workers could be exposed to while working on energized electrical equipment. These standards include various UL, NFPA, ASTM, IEEE and others detailing the methods for testing and calculations. Each standard addresses specific equipment and circumstances but does not evaluate all aspects of hazards presented to workers while working on or near energized electrical equipment. Specifically, these typical industry practices do not allow for incident energy (IE) to be evaluated when a worker is not in direct exposure to an internal arcing fault. For example, arc flash evaluations methods like IEEE 1584 assume workers are directly exposed to energized parts and provides no methodology or modification to assess how the hazard is affected by an indirect arcing fault, ie arcing faults blocked by doors, panels or other physical objects. Even arc resistant switchgear tested to IEEE C37.20.7 does not measure the true IE level when the arc is contained within the shell of the switchgear.

The methods presented herein will detail testing of incident energies outside energized electrical equipment and other conditions where workers may be indirectly exposed to internal arcing faults. These methods include the use of existing standards that have been adapted and/or expanded to allow performance evaluations of incident energies meeting the prior descriptions.

The current standards do not consider the effects of indirect arcing fault exposure of workers and employees to incident energies generated from internal arcing faults within energized electrical equipment. Two case studies will be reviewed that will show indirect arcing faults have reduced incident energies outside said electrical equipment. These case studies which have been tested to UL RP 2986 will be compared against the latest IEEE 1584 calculations to show the benefit of indirect arc fault exposure.

Numerous benefits can be realized by employers and employees when incorporating designs that prevent direct internal arc fault exposure to workers. The industry has begun to explore other IE reduction methods and design specific solutions reducing the exposure to workers and employees. The requirements of NFPA 70E can be accomplished through task specific design modifications and adaptation and/or expansion of existing standards to account for all energy reducing factors inherent in electrical equipment including other new industry concepts.

II. REVIEW OF EXISTING TESTING, CALCUATIONS, AND METHODOLOGIES

The industry utilizes standards that prescribe performance testing, calculations, and methodologies for evaluating electrical equipment and potential hazards to personnel. Modern electrical switchgear and equipment offer protective features that may afford protection to workers and personnel. The IEEE Guide for Performing Arc-Flash Hazard Calculations (IEEE 1584-2018) has been updated to account for internal characteristics of the electrical equipment such as conductor orientation and spacing and accounts for those effects on the calculation of incident energies [1]. However, IEEE 1584-2018 does not account for indirect arc fault exposures though these conditions provide some level of protection to personnel under deleterious conditions. As mentioned earlier, IEEE C37.20.7 is a test guide for arc resistant equipment but does not provide a way to measure the IE during the test. Additionally, there have been several predecessors to the IEEE 1584, Ralph Lee [2] and Richard Doughty [3], to calculate arc flash incident energy levels.

However, they have the same assumption in that the worker is directly exposed to the arc with no mechanism to account for indirect arc fault exposures.

III. REVIEW OF UL RP 2986 – RECOMMENDED PRACTICE FOR MEASURING INCIDENT ENERGY EXPOSURE

UL RP 2986 [4] defines core details of how-to setup test devices to measure IE during an arcing event. It outlines basic consideration for sample preparation, such as specifying the product construction to be as it is intended to be used, specific cabling length and type, and location of over-current protective devices. It defines the range of voltage to be 100 – 105 percent of the voltage rating for the device under test. Regarding current levels, the device must be tested at its maximum short circuit current rating, and additionally at “currents just below the instantaneous or current limiting region of the overcurrent protective device in order to determine the worst case condition for available incident energy” [4]. The instrumentation to measure the IE is the same copper slug type used for IEEE 1584 [1] and arc rating of materials for clothing, per ASTM F1959 [5]. Additionally, the sample rate of the calorimeters is defined at 20 samples/second. The placement of the calorimeters is defined as a pattern of 7 as shown in Fig. 1, and the center row of the calorimeters should be placed at the same elevation of the arc. The arc is to be initiated using a single 20 AWG solid copper wire, with the clause to allow larger wire if a sustainable arc is not achieved. The location of the arc ignition wire should be placed such that the highest arc voltage is generated, which occurs at the highest test circuit voltage. The location should “simulate realistic service conditions” and at the non-insulated location closest to the source and the non-insulated location closest to the operator. Finally, the closing angles of the tests are defined, and the worst-case IE of any calorimeter is recorded as the maximum available IE. As described, this recommended procedure alone is insufficient to meet the requirements of a product standard. In the next section we will review some of the gaps that require additional thought and oversite to ensure that a device is thoroughly tested.

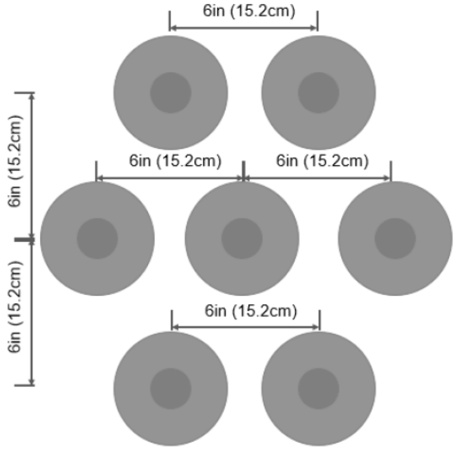


Fig. 1 Arrangement of slug calorimeters, per UL RP 2986 [4]

IV. APPLICATION OF UL RP 2986 – RECOMMENDED PRACTICE FOR MEASURING INCIDENT ENERGY EXPOSURE

Although UL RP 2986 is not a complete product standard, it does not mean that a sufficiently robust test program cannot be developed to evaluate the product’s performance. In fact, it is quite easy to take a single device to the lab and execute the test. The interesting steps are determining how to test a subset of samples for a product range and to ensure the subset is representative of the entire product range. A key action that can be taken to develop a robust test program is using other test standards as a guide. The next sections will help outline the creation of a complete test program.

A. *Sample Selection:*

When a product range is developed, there is typically a common product architecture for the entire range. However, there may be variation in the architecture that could impact the incident energy measured during an internal arc fault. These variations need to be tested unless justification can be defined to reduce testing. One avenue for justification is to look at existing product standards as a guide in sample selection.

B. Test Voltage and Current:

Typically, products are rated at different short circuit currents at different voltage levels. The result is the same product will likely need to be tested at several different test circuits. The highest short circuit rating will generate the largest electromagnetic force on the conductors inside the device during the interruption. Alternatively, the largest kVA circuit will result in the largest power during interruption. The maximum pressure generated during the interruption occurs on the maximum power circuits. Pressure is a relevant consideration for devices that keep the arc enclosed during the interruption. Like arc resistant gear, the integrity of the enclosure should be verified at the worst-case pressure conditions.

C. IE Measurement Instrumentation and Locations:

The UL RP 2986 procedure defines one location for placement of calorimeters during testing. However, this view is too simplistic. During an interruption, features in the product design, like enclosure walls, can prevent the plasma cloud and by-products from expanding. The product may even have purposeful pressure relief venting. Where intentional or unintentional plasma could vent, additional calorimeters should be placed to measure the arc flash exposure. If the worker is prevented from accessing these areas during the internal arcing fault event, then additional calorimeters are not warranted. Understanding the incident energy level around the equipment is helpful for the worker to wear the proper PPE for the activity they are doing.

V. CASE REVIEW: APPLICATION OF UL RP 2986 FOR ENERGY-REDUCING LINE SIDE ISOLATION

A. Energy-Reducing Line Side Isolation Background:

Energy-reducing line side isolation (ERLSI) “is equipment that encloses the line side conductors and circuit parts and has been listed to provide both shock and arc flash protection from (internal arcing) events on the line side of a circuit breaker or switch” per NFPA 70E [7]. Since this solution encloses the line side conductors, the enclosure does not allow a direct arc exposure to the worker outside the ERLSI system. Therefore, it is not possible to apply IEEE 1584 calculations to determine the IE exposure to a worker. Using UL RP 2986, physical testing of the device can be performed to measure the IE risk.

B. Sample Selection of ERLSI:

ERLSI is a device that must mate up to a specific circuit breaker or switch. Therefore, the ERLSI will have a unique design for each product device. This solution can be installed into a variety of equipment types and or configurations. Typically, the device is installed into a piece of equipment that has the following variants: top-fed or bottom-fed wiring; 3 phase 3 wire vs. 3 phase 4 wire. This results in 4 different cases that may need to be considered for one section of equipment. Is testing of every possible variant required, or can a worst-case configuration be identified? A core feature of the ERLSI design is the resemblance to an arc resistant enclosure, therefore we can look to IEEE C37.20.7 [8] the “IEEE Guide for Testing Switchgear Rated Up to 52 kV for Internal Arcing Faults” section 5.2 Test Sample Configuration for guidance in identifying the worst-case configuration. This section defines key parameters that define the worst-case samples: “minimum volume”, “maximum unbraced wall surface”, “maximum amount of openings (total area) designed for equipment ventilation”, and “minimum amount of openings (total area) designed for arc fault pressure relief”. Using these parameters as a reference, identification of which samples to be tested is revealed.

C. ERLSI Test Voltage and Current:

ERLSI does not rely upon an upstream device to clear an internal arcing fault between conductors. Instead, the completely passive system is such that only a long-stretched arc can briefly exist for less than 1 cycle and then self-extinguishes due to the resultant arc voltage. Fig. 2 shows an example of how the long arc ignition wire is installed to create the phase-to-phase fault during testing. To determine the proper test circuit voltage and current we must look outside of the recommend practice for guidance. Each ERLSI assembly is tailored to a specific circuit breaker, the circuit breaker interrupting ratings define the maximum circuit where the ERLSI assembly can be applied. As the ERLSI device is much like a circuit breaker with stationary contacts, we can look to UL 489 [6] 7.1.11 High Available Fault Current Test Sequence for guidance on testing the worst-case circuits. Per Table 7.1.11.1 the relevant circuits listed are: maximum interrupting current rating, interrupting current rating at maximum voltage rating, and interrupting current at maximum kVA ratings.

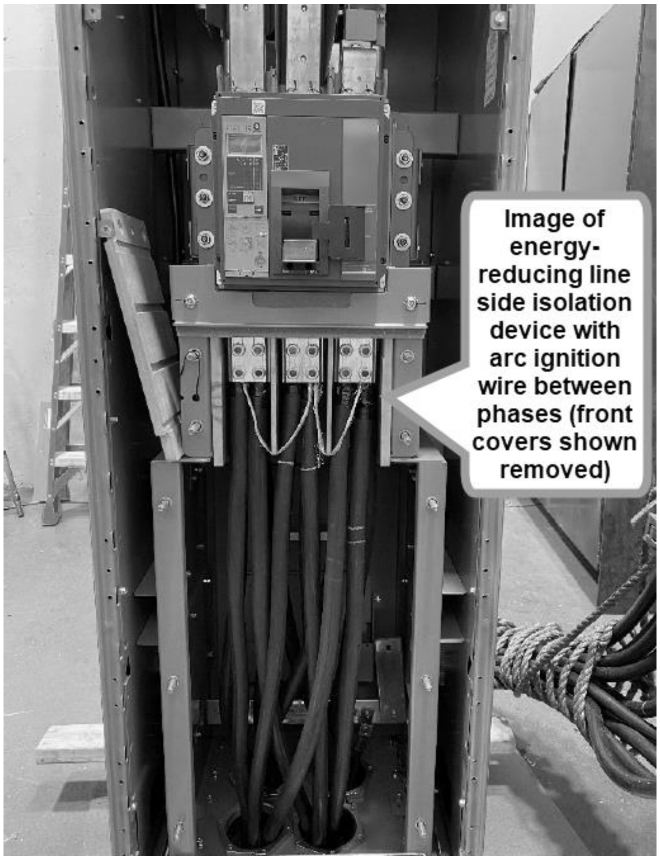


Fig. 2 Energy-reducing line side isolation UL RP 2986 test photo showing arc ignition wire before interruption test

D. ERLSI Incident Energy Measurement Instrumentation and Locations:

The ERLSI device was tested with the 7-slug calorimeter configuration at the elevation of the arc, but also at other critical regions. The design of the ERLSI incorporates venting to help ensure the quick clearing of the arc. The vents are low to the floor for a bottom fed solution, and high towards the ceiling for a top fed solution. Therefore, it was prudent to place additional calorimeters at these vented locations. A diagram of calorimeter positions is marked by circles and numbers shown in Fig. 3. Fig. 4 shows a photo of calorimeters positioned in front of the ERLSI unit under test.

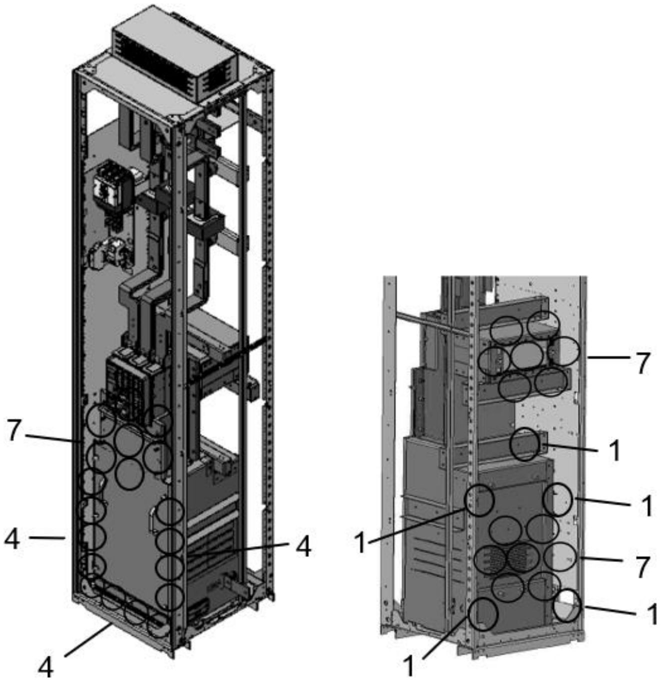


Fig. 3 Arrangement of slug calorimeters

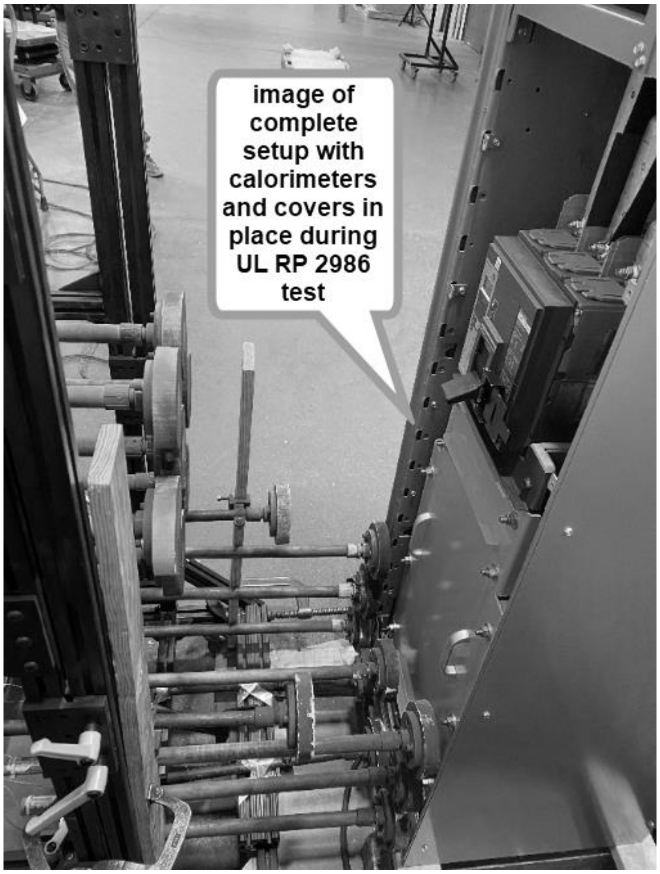


Fig. 4 Energy-reducing line side isolation UL RP 2986 test photo showing calorimeters

E. ERLSI IE Comparison to IEEE 1584 Calculations:

The goal of the UL RP 2986 test program was to demonstrate that all IE levels measured were to be less than 1.2 cal/cm^2. The input variables for the IEEE 1584 calculations would be the test circuit the device was tested at: 480 V - 100 kA, and 600 V - 50 kA. The clearing time was calculated at 1 second clearing time. The working distance at 457.2 mm. The equipment configuration class would be the "vertical electrodes terminated in an insulating "barrier," inside a metal "box" VCBB enclosure" [1]. One variable that cannot be properly accounted for is the electrode gap; the internal phase barriers force the arc length to be significantly longer than the formula maximum of 76.2 mm. As shown in Fig. 6 below, the IEEE 1584 calculations calculate the IE to be at least 2.5 cal/cm^2. The final measurements at each calorimeter were measured to be less than the 1.2 cal/cm^2 per equipment design.

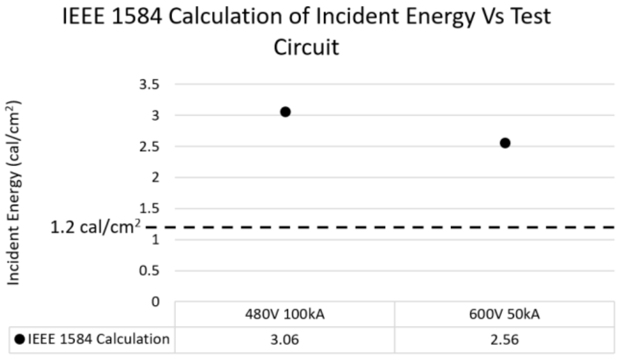


Fig. 6 IE Vs Test Circuit

VI. CASE REVIEW: APPLICATION OF UL RP 2986 FOR UPS SYSTEM

A. UPS Verified for Reduced Arc Flash Energy Exposure Background:

Manufacturers are always working on improving the safety of their products. For one UPS product there was a goal to reduce the arc flash exposure risk to a worker in front of the UPS [9]. It has become common design practice to guard, isolate, or insulate energized parts to ensure that a worker is not exposed to a shock hazard. But how does one design a piece of equipment to address an arc flash risk? The arc flash hazard only exists if a worker is in a zone where the IE level exceeds 1.2 cal/cm^2 per NPFA 70E. Through the coordination of over current protection devices, it can be demonstrated using UL RP 2986 testing that a worker in specific locations would not cross the 1.2 cal/cm^2 arc flash boundary.

B. Sample Selection of UPS:

For this UPS design, there was a common architecture from 200 – 500 kW. Therefore, a single variant was selected to represent the product performance for the entire range. Within this architecture, there was a critical zone identified where the worker was not in direct exposure to the arc. This zone was the upper line side compartment where a front cover was in place for all UL RP 2986 testing, ensuring indirect exposure of the arc to the workers. See Fig. 7 for an image of the UPS.

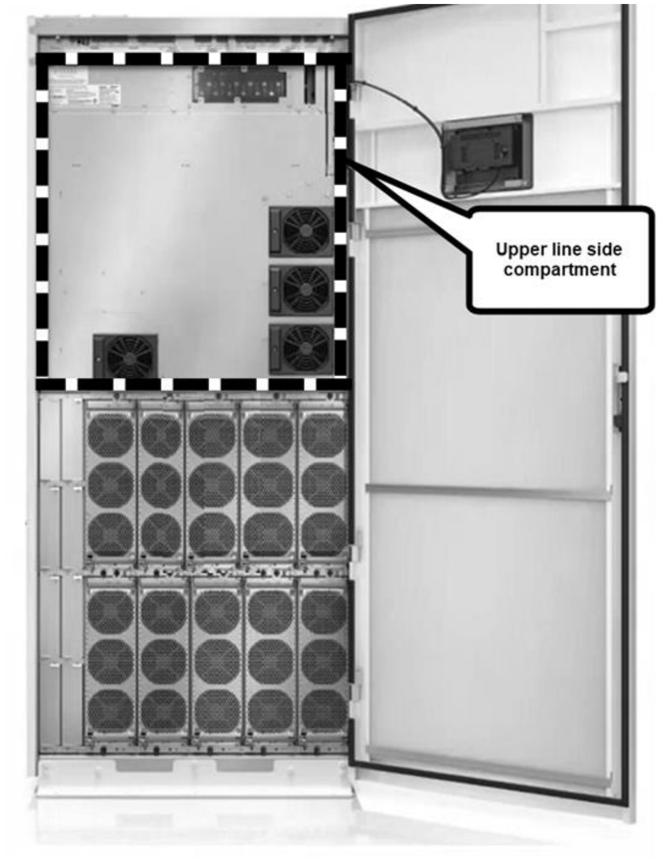


Fig. 7 Upper line side compartment in UPS [9]

C. UPS Test Voltage and Current:

This type of UPS used a combination of circuit breakers, fuses and bolted front covers to meet the claim that the IE exposure risk to a worker in front of the UPS was less than 1.2 cal/cm^2. Because of the multiple protection layer scheme employed, the IE risk was not a consistent risk across all test circuits. As described in UL RP 2986, the device needed to be tested at maximum current and at "currents just below the instantaneous or current limiting region of the overcurrent protective device" to demonstrate that the 1.2 cal/cm^2 limit was not exceeded at any test circuit [4]. An illustration of how the IE varies is shown in Fig. 8; where it can be seen there are two intermediate points of interest (saw tooth peaks), one at the maximum arcing current of the react & escape slope, and second at the maximum circuit breaker operating current. For the analysis in this paper we will focus on the critical test case, the third peak, which was the 65kA maximum short circuit current rating of the gear where the fuse operated at the maximum arcing current.

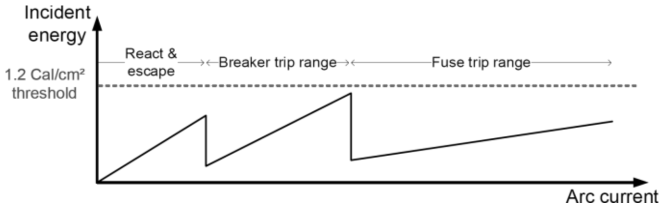


Fig. 8 Examples of protective devices with different clearing times [9]

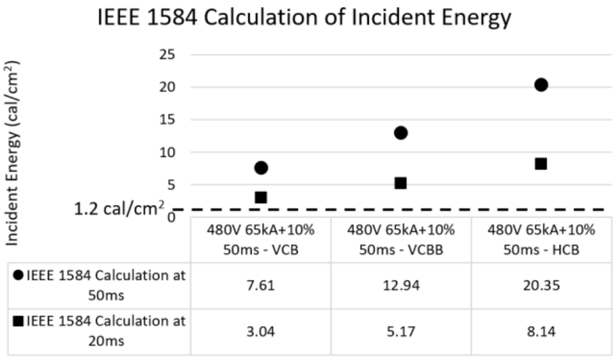
D. UPS Incident Energy Measurement Instrumentation and Locations:

For the upper line side compartment, the calorimeters were placed in front of the upper line side cover in the 7-slug arrangement per UL RP 2986. Fig. 9 shows an example image of calorimeters used during one of the UL RP 2986 tests.

Fig. 9 Placement of slug calorimeters

E. UPS IE comparison to IEEE 1584 calculations:

The input variables for the IEEE 1584 calculations were 480 V - 65 kA+10%. Two duration levels were defined based on the published tolerance band of the circuit breaker clearing time at 20 ms minimum and 50 ms maximum. Unlike the prior case review that had only one arc position throughout testing, in this case the arc moved around within the unit during the test. Therefore, all configurations of conductors in a box were calculated to cover all possibilities. Due to the movement of the arc, the best approximated working distance was calculated at 300 mm. An electrode gap of 27.5 mm was defined by conductor spacing. An additional parameter that the calculations could not be adjusted for was the fact that the rear of the UPS did have some venting which would allow some IE to exit the rear of the cabinet and reducing the IE measured at the front cover. Shown in Fig. 10 below are the calculated results at the front of the UPS and the 1.2 cal/cm^2 design limit of the product. A number of assumptions were made during the IEEE 1584 calculations, but the best calculation still determined that the incident energy should have been higher than the measured IE values. This is likely partially due to the fact there is no input parameter that the front cover is in place during the testing.



	480V 65kA+10% 50ms - VCB	480V 65kA+10% 50ms - VCBB	480V 65kA+10% 50ms - HCB
● IEEE 1584 Calculation at 50ms	7.61	12.94	20.35
■ IEEE 1584 Calculation at 20ms	3.04	5.17	8.14

Fig. 10 IE Vs Test Circuit

VII. BENEFITS OF TESTED DEVICES TO QUANTIFY IE LEVELS

The modeling and prediction of arc flash behaviors is an on-going endeavor. The more we investigate and test assumptions, the more we learn. As our knowledge grows, so does the complexity of the calculated model. A purely computational approach could easily suffer from a few issues:

1. As manufacturers continue to improve product designs to limit the incident energy exposure to workers, it may become more difficult to apply simplified models of real-world equipment with accurate results.
2. When the model is incorporated into a software package, there could be many dependent variables that the user may not understand or be able to accurately obtain from physical measurements. This could promote the use of standardized values to arrive at a calculated result. But the applicable calculated numbers may not be realistic to the risk.
3. As the volume of input data increases, so does the opportunity to input erroneous data.
4. Since Personal Protective Equipment (PPE) choices depend on accurate modeling and calculation, seemingly small errors can have huge impacts on personnel safety. It is prudent to note that in the case studies reviewed the calculation overestimates the measured IE, which means a worker could potentially suit up for a higher category of arc flash PPE if relying on calculation alone. Further analysis across a broader range of system designs should be considered to see if this trend remains consistent or if there are exceptions.
5. If calculated models were ever sophisticated enough to calculate the IE of an indirect arc. It would still be prudent to test the device to ensure the features blocking the arc remain operational during the full clearing time.

To augment the computational prediction of arc flash behaviors, actual testing of equipment in simulated field situations provides many benefits. In addition to occasionally providing unexpected results that foster our understanding, it can validate design calculations. However, in some instances to those similar to the results depicted in Fig. 6 and Fig. 10, field testing can show that the calculations provide a result that are excessive with respect to the documented test results.

Providing the calculated IE on the equipment labeling gives one a sense of the exposed hazard relative to the PPE being worn. If the IE is on the low end of the PPE rating, one can be confident in the adequacy of the protective measures. But when the IE is on the high end of the PPE hazard category rating, one may question the adequacy of the selected PPE. While performing the job hazard analysis, one may be dubious of what minimum hazard category PPE is required. Uncertainties regarding any calculation assumptions that may have been made, or the possibility of erroneous data being used in the IEEE 1584 calculations may cloud the confidence of the worker. This could easily cause the worker to want additional validation of what minimum hazard category PPE is required. A way to quell these concerns would be to provide functional testing data where the equipment is subjected to maximum withstand ratings. Full functional testing can provide:

1. Validation that the design and construction is sound.
2. Detailed scrutiny of the results can advance our understanding of the complex nature of an arc flash.
3. Unforeseen opportunities for equipment enhancements may become evident.
4. The possibility of updating industry standards may become a prudent result.
5. Confidence where a supervisor must assign work tasks or a worker that is to perform these tasks that the equipment will perform in a safe and predictable manner.
6. Substantiation of safe operations for DC, single-phase systems, and or short circuit faults over 106 kA for low voltage circuits since IEEE 1584 doesn't currently apply to these circuits.

VIII. CONCLUSIONS

One nice thing about electricity is that it follows physical laws. Assuming a facility's electrical system does not appreciably change, and the equipment is properly maintained, the actual IE will not markedly change over time. But the evolving calculations tend to make one question their accuracy for the specific instances such as the indirectly exposed internal arcing faults reviewed in this paper. Further, even for the instances where one is exceptionally diligent in validating the data used in an IEEE 1584 calculation, this process does not cover the growing DC, single-phase applications, and or short circuit faults over 106 kA for low voltage circuits. Additionally, for instances where there are multiple possible fault locations within a particular piece of equipment, the arc flash will follow where physics dictates. This segment of physical reality will occur irrespective of how accurately one may have computed the IE. Given the above conditions, one can be confident that the measured IE will stand the test of time, whereas it is expected that calculations will continue to evolve over time.

Another evolving consideration in the endeavor to protect workers is to analyze the actual body position of a worker when a fault occurs. The tables in NFPA 70E and calculations of IEEE 1584 assume the worst-case conditions. That is, with doors open and an unobstructed exposure to the arc event. In most cases this is the prudent situation to plan for. But as discussed in this paper, there are instances where a worker cannot physically have a direct exposure to the arc fault event. Under these circumstances, it would be desirable to have a method which more accurately evaluates the arc flash hazards a worker would be exposed to.

Testing can be an exceptional tool when properly used. But it may not be the best solution in all circumstances. Where the equipment to be tested is very complex, or possibly exceeds the capabilities of the testing lab, the best analysis may be achieved via calculations. As arc flash modeling skills improve with time, perhaps there will become a transition when some of these tested products can be modeled accurately enough through calculation. Until then, some short-term industry changes may include updating IEEE C37.20.7 to replace cloth indicators with calorimeters. However, this change would need to be balanced between the logistical challenges of getting enough calorimeters in the proper location, the financial burden of purchasing the necessary equipment, and the current use of cloth indicators. As we move forward, we must be cognizant of the need to promote confidence in the worker standing next to the equipment as well as determining the correct IE.

IX. ACKNOWLEDGEMENTS

Thank you to Claus Andersen from Schneider Electric for his major contributions to the UPS case study.

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XI. VITAE

Clinton Carne received the BSE degree from the University of Iowa in 2007, and then received the ME from the Iowa State University in 2013. He has worked for Schneider Electric for 14 years and is presently a product architect in low-voltage strategy team. He is an IEEE Power & Energy Society Senior member and has been participating in standards development since 2011.

Henry (Hank) Clark received his BSEE in Electrical Engineering in 1989 at Lamar University in Beaumont, Texas. He has more than 33 years of electrical engineering experience in the fabrication and testing of low voltage and medium voltage switchgear, refining and petrochemical, Midstream pipeline, rail car, and marine operations. He is proficient in conceptual engineering and design, project development, construction, and commissioning, and assisted in the development of the CPP electrical safety training system. Mr. Clark has 20 years of experience in overhead power system design, maintenance, and operation. He has been employed by Chevron Pipeline and Power, in Houston, Texas since 2005, and currently works as a Sr. Electrical Consulting Engineer. He is presently a member of IEEE and IAS. He is the lead author for an ESW paper presented in 2018 at Fort Worth, which has been accepted for printing by IAS. He is also the lead author of one paper and a co-author of a second paper presented at PCIC in 2019 at Vancouver, Canada.

Michael McConnell, PE received a BSEE degree from Texas A&M University – Kingsville, is 2004. Michael joined Schneider Electric in 2016 and is currently a Staff Power System Engineer. He has extensive experience in power system design including low, medium, and high voltage power systems. He has experience in turn-key projects, construction, power system analysis including steady-state and electro-magnetic transient studies. He also has experience in power system maintenance, testing, troubleshooting and support. Michael is a Master Electrician, a member of the IEEE Power & Energy Society and is a licensed Professional Engineer in several states to include Texas with more than 17+ years of experience.

APPENDIX A

IEEE 1584 INPUTS FOR IEEE 1584 CALCULAITONS

IEEE 1584 DATA INPUTS AND OUTPUTS:

Below is a list of all IEEE 1584 input variables and the IE calculations for each of the calculations documented in the papers.

TABLE A-I
IEEE 1584 CALCULATIONS

Type size	Input Variables & IE Calculation								
CASE TYPE	Configuration Class[a]	Open Circuit Voltage (kV)	Bolted Fault Current (kA)	Electrode Gap (mm)	Working Distance (mm)	Arcing Duration (ms)	Box Width (mm)	Box Height (mm)	IE (Cal/cm^2)
ERLSI	VCBB	0.48	100	76.4	457.2	16.6	302	761	3.06
ERLSI	VCBB	0.6	50	76.4	457.2	16.6	302	761	2.56
UPS	VCB	0.48	71.5	27.5	300.0	20	850	1000	3.04
UPS	VCB	0.48	71.5	27.5	300.0	50	850	1000	7.61
UPS	VCBB	0.48	71.5	27.5	300.0	20	850	1000	15.17
UPS	VCBB	0.48	71.5	27.5	300.0	50	850	1000	12.94
UPS	HCB	0.48	71.5	27.5	300.0	20	850	1000	8.14
UPS	HCB	0.48	71.5	27.5	300.0	50	850	1000	20.35

[a] VCBB - vertical electrodes terminated in an insulating “barrier,” inside a metal “box” enclosure
VCB - vertical electrodes inside a metal “box” enclosure
HCB - horizontal electrodes inside a metal “box” enclosure