Medium-Voltage Arc Flash in Switchgear and Live-Front Transformers

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***Abstract*—Arc flash on distribution circuits is a safety issue that can impact work practices for line and substation workers. This paper shows test results for arc flash events in medium-voltage switchgear cubicles and live-front transformer enclosures. Both scenarios can result in more incident energy than the prediction of IEEE 1584-2002. Much higher than expected energies were measured from rack-in style switchgear breaker cubicles due to the orientation of the electrodes. Live-front transformer cubicles showed wide variability that was not directly related to the enclosure size or arc directionality. Unexpectedly high energies were measured in multiple configurations. For selection of the appropriate clothing systems, incident energy multipliers are suggested based on IEEE 1584-2002.**

***Index Terms*—Arc flash, power distribution, safety, personnel protection.**

I. Introduction

Arc flash analysis and protection on distribution circuits is still evolving. More test data, better understanding of arc physics, and more industry experience with arc flash will help utilities protect workers. In this paper, we discuss results of arc flash testing of, switchgear enclosures, both rack-in (horizontal electrodes) and rack-up (vertical electrodes) styles. Five different styles of live-front transformers were tested, including single-phase and three-phase units. The severity of an arc flash event is normally quantified as the incident energy that would reach a worker, normally given in terms of cal/cm^2. Flame-resistant (FR) clothing systems have an arc thermal performance value (ATPV) rating or an energy break-open threshold (Ebt), based on ASTM test standards [1]. The ATPV rating is the incident energy in cal/cm^2 on the clothing surface that has a 50% probability of causing a second-degree skin burn, and Ebt is the 50% probability of break-open. The goal of an arc flash analysis is to ensure that workers have an arc rating sufficient to handle the incident energy that might be expected in a given work scenario.

To estimate incident energies on enclosed distribution equipment, most utilities follow the assumptions and approach used in IEEE 1584-2002 for arc flash in equipment [2].

II. ARC FLASH IN MEDIUM VOLTAGE SWITCHGEAR

Metal-clad switchgear is manufactured so that the circuit breakers are rolled into the cubicles until they engage with the racking mechanism. Metal-clad switchgear can be separated into two main categories. For breakers that "rack in," the racking mechanism picks up the breaker and as the racking gear turns, the breaker moves farther into the cubicle horizontally until the movable primary contacts on the breaker engage fully with the stationary primary contacts inside the cubicle. For breakers that "rack up," the racking mechanism picks up the breaker and moves the breaker farther up vertically inside the cubicle until the movable primary contacts on the breaker engage fully with the stationary primary contacts inside the cubicle.

A. Test Setup

Testing was performed at the PG&E high-current testing facility in San Ramon, California. The fault source was created from a 12-kV ungrounded delta circuit fed by a direct utility connection with a maximum available fault current of 9.1 kA.

For measuring incident energies and heat rates, copper slug calorimeters were installed. These are thin copper plates with a thermocouple attached. The temperature change measured by the thermocouples before and after the arc flash event is used to estimate the incident energy to the copper plate. Calorimeters were built and calibrated according to ASTM specifications [1, 6]. Incident energy measurements were made at 36, 48, or 58 in (91, 122, or 147 cm) away from the arc initiation plane.

B. Horizontal, Rack-in Style

Three older-style rack-in switchgear cubicles were obtained. These units were single breaker full size cubicles with the breaker going in the bottom half of the switchgear cubicle. The stationary primary contacts (electrodes) inside the cubicle were surrounded by a ceramic insulating bottle. The bottle assemblies are normally covered by a phenolic bottle barrier and shutter assembly that shields the normally energized parts from direct contact when the breaker is removed from the cubicle. The shutter assembly was removed for testing, but the bottle barriers were left in place for the first test shot in each cubicle section. See Figure 1. The interior dimensions of the cubicle were 33×69.5×39 in (83×142×149 cm) with the line side stationary contacts pointing out of the back wall of the cubicle towards the front with 10 in (25 cm) of separation between phases and approximately 30 in (76 cm) up from the bottom of the cubicle. The "rack-in" style was also tested with a simulated breaker inserted into the cubicle.

C. Vertical, Rack-up Style

Three full-size cubicles with the breaker going in the bottom of the switchgear and racking up after insertion were tested. The shutter assembly was removed for testing. See Figure 2. The interior dimensions of the cubicle were 36×56×58.5 in (91×142×149 cm) with the line side stationary contacts

pointing down from the top of the cubicle at approximately 24 in (61 cm) from the front edge. There was 9.5 in (24 cm) of separation between phases.

Fig. 1. Horizontal, rack-in style switchgear cubicle tested

Fig. 2. Vertical, rack-up style switchgear cubicle tested

The stationary primary contacts were potted into a single metal flange for each of the three phases for both the line side and the load side. The majority of the ceramic bottles surrounding the stationary contacts were on the bus side of the cubicle instead of the breaker side of the cubicle. This is distinctly different from the rack-in style. See Figure 3 and 4. Incident energy measurements were made in front of the cubicle

Fig. 3. Horizontal, rack-in style; stationary contacts shutter removed

Fig. 4. Vertical, rack-up style; stationary contacts shutter removed

E. Test Results: Horizontal, Rack-in Style

To initiate the test, a solid #10 AWG copper wire was wrapped from A to B to C phase on the line-side stationary contacts. Current and durations were varied. In addition, a calorimeter sensor head was used simultaneously with the calorimeter array to evaluate arc flash boundary questions. The sensor head was placed in the back of the test chamber, making the face sensors approximately 10 ft. (3 m) away from the arc and approximately 6 ft. (1.8 m) off the ground, which is a good approximation of where another worker might be.

When the calorimeter array was spaced 36 in (0.9 m) from the back wall of the enclosure, it was about 3 in (7.6 cm) inside the front plane of the opening. During the longer events—30 cycles or longer—a large arc plasma (fireball) projected out of the enclosure and enveloped the calorimeters. See Figure 5.

Arcing for all events was very similar. As shown in Figure 6, the arc starts between phases with the fuse wire but quickly moves to the case and arcs around the bottom of the CTs and to the side wall.

Fig. 5. Test ID 6: 5.7 kA, 30 cycles, 13 cal/cm^2 max, 10.4 cal/cm^2 avg., 25.6 cal/cm^2/sec heat rate

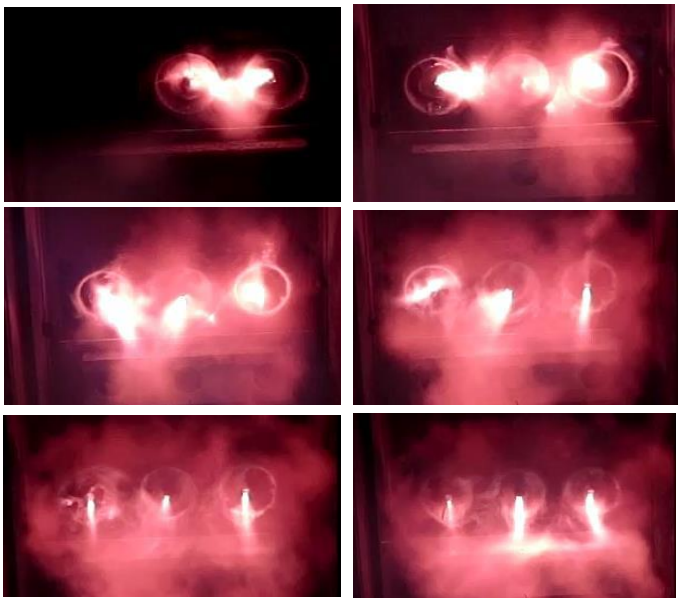


Fig.6. Video frames from test ID 40 for the first six frames (300 fps) viewed through an infrared-passing filter

When the ceramic bottles were in place, the arcing pattern was similar, but the arc lengths were extended. Even with extended arcs, the measured incident energies were reduced. This is due to the absorption of the energy by the ceramic bottles. The ceramic always broke, and in the process, some of the energy was used to heat and break the ceramic, leaving less to be ejected out of the cubicle onto the calorimeters. Due to the limitations of available hardware and destructiveness of the testing, the three samples were used to their maximum limitations i.e. much of the testing was conducted with broken bottles. See Figure 7.

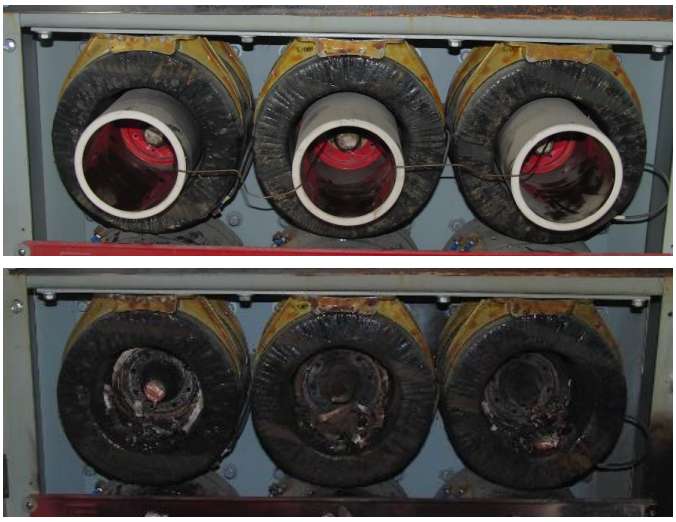
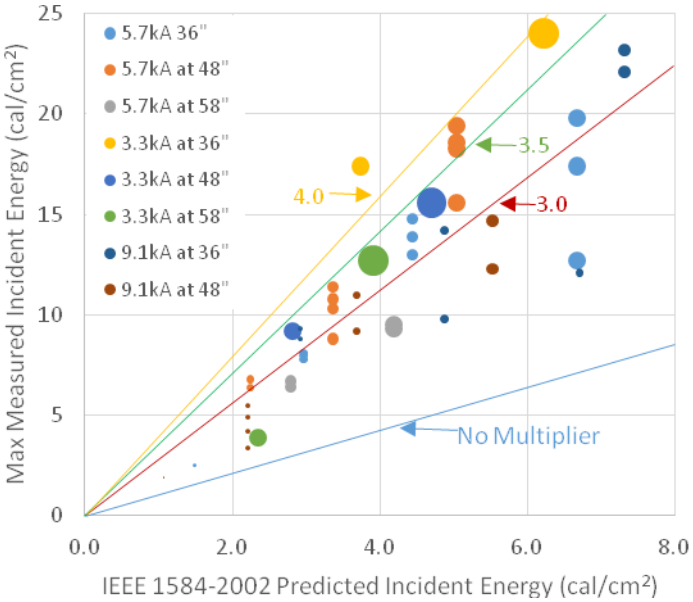


Fig 7. Bottles intact TOP vs bottles broken BOTTOM

Measured heat rates were fairly linear with time and with magnitude of arcing current. However, the Figure 8 shows that measured incident energies significantly exceeded the IEEE 1584-2002 switchgear formula. Multipliers of 3.0 to 4.0 would be needed to accurately predict resultant incident energies. See Figure 8. Longer events would be more likely to be at the higher end multiplier (a 3.0 multiplier encompasses all the events that were 20 cycles or less in duration). See Table 1 for the overall probability that each multiplier encompasses all the test data points.



Note 1: Bubble size reflects arc durations of 5.8, 10, 12, 20, 30, 45, 75 cycles respectively. Lines represent multipliers to IEEE 1584-2002.

Fig 8. Horizontal switchgear: measured vs. predicted energy

TABLE 1
PROBABILITIES OF ENCOMPASSING TEST DATA

Multiplier to IEEE 1584-2002	Probability
3.0	65%
3.5	89%
4.0	98%

Figure 9 shows that the heat rises significantly above the sensor head (located 10 ft. [3 m] away from the arc). This is true for all cases. The measured energy at the sensor head was a fraction of what IEEE 1584-2002 predicts. This will significantly reduce the arc flash boundary predictions from those previously done. Actual measurements at 10 ft. (3 m) varied from 40% to 90% of what IEEE 1584 would predict, with the bulk at 50% to 60%. This is an indicator that the "distance factor" relationship is finite at some boundary point. Beyond 5 ft. (1.5 m) away from the arc, a different formula would need to be developed to determine the real arc flash boundary (the point at which incident energy would fall below 2 cal/cm^2, the OSHA limit for FR clothing protection) [Paragraph (l)(8) of §1910.269, 2014 and Paragraph (g) of §1926.960].

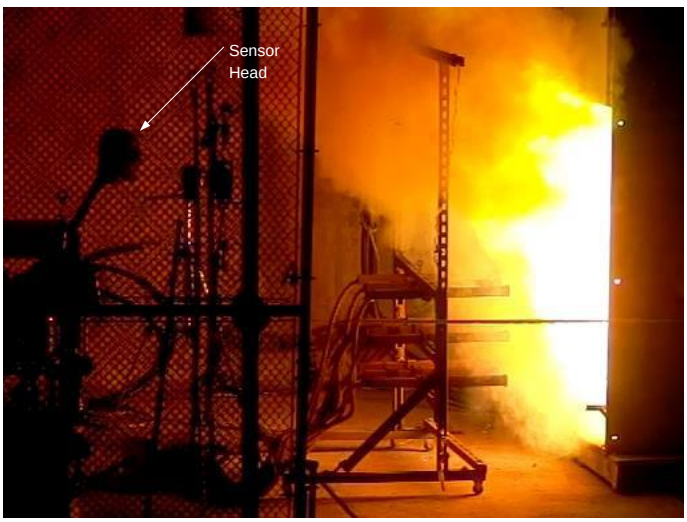


Fig. 9. Test ID #134- 3.3 kA, 45 cycles, calorimeter array at 58 in (147 cm) from arc, image at or very near end of the event

Current research by the IEEE/NFPA collaboration project has confirmed the effect of electrode configuration and enclosure geometry on increasing incident energy beyond the values predicted by IEEE 1584-2002. IEEE Std. 1584 is currently in the revision process to develop new more representative formulas for these conditions. Higher incident energies with horizontal electrodes matches other test results [4, 7].

Previous testing [4] concluded that if an obstacle (circuit breaker) was inside the switchgear, much of the incident energy would be diverted or absorbed by the obstacle. To verify this conclusion, a simulated breaker was constructed. As shown in Figure 10, the presence of the object forced most of the incident energy out the sides and bottom of the cubicle.

Fig 10: More energy from sides and bottom, test ID #48

The presence of an object in the cubicle reduced the amount of energy ejected. However, the values generally exceeded the IEEE 1584-2002 predictions but with smaller multipliers. As shown in Table 2, the multipliers varied from 1.0 to 1.8. This appears to be a function of how far the simulated breaker was inserted into the cubicle. More energy is ejected with the breaker farther out of the cubicle. This confirms the conclusions with the laboratory arc-in-a-box mock up done during previous testing [4].

TABLE 2
MULTIPLIERS REQUIRED
(SWITCHGEAR WITH SIMULATED BREAKER)

Multiplier to IEEE 1584-2002	Test ID
1.8	41
1.8	42
1.6	43
1.5	46
0.8	47
1.2	48
1.0	49

F. Test Results: Vertical, Rack-up Style

To initiate the test, #16 AWG solid copper wire was wrapped from A to B to C on the line side of the stationary contact. The bottle assemblies were only able to withstand one test shot each, so test data was limited to the 12 available bottle assemblies.

As expected, with a vertical electrode configuration, the emission of arc plasma (fireball) out of the cubicle took longer than for the horizontal electrode configuration. For 5.7 kA, it took six cycles for the fireball to reach 36 in (91 cm), as compared to about three cycles for the horizontal electrodes.

Higher currents also eject energy faster than lower currents. For 5.7 kA, it took three cycles to reach 24 in (61 cm) and six cycles to reach 36 in (91 cm). However, for 9.1 kA, it took only one cycle to reach 24 in (61 cm) and only three cycles to reach 36 in (91 cm). See Figure 11 for a side-by-side comparison of Test ID #52 and Test ID #55. Figure 11 also

demonstrates higher overall energy. The end of the 9.1-kA event appears "brighter" than the end of the 5.7-kA event.

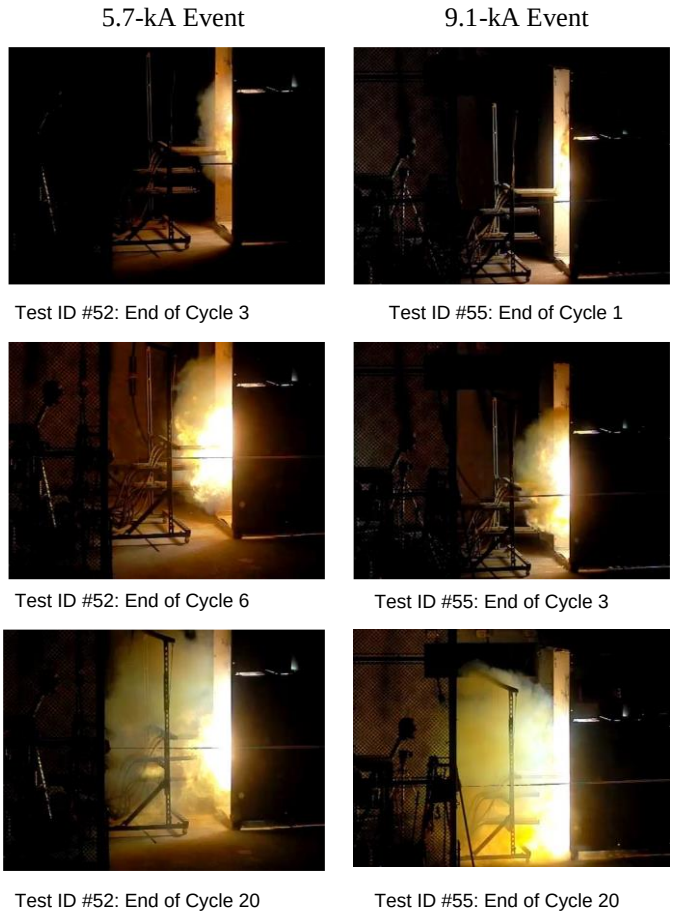


Fig. 11. Side-by-side comparison, 5.7 kA on left, 9.1 kA on right

Figure 12 shows that measured incident energies were below the predicted values of the IEEE 1584-2002 switchgear formula. The trend line is showing more conservatism as fault currents increase. However, additional testing would be needed to confirm this trend.

IEEE 1584-2002 has a 20% difference between grounded and ungrounded switchgear predictions. This is done from the original laboratory testing that suggested 20% of the energy returned via the ground connection and was not available for heat production. Figure 12 was overlaid with the IEEE 1584-2002 grounded switchgear predicted energy to show the relative difference between the ungrounded and grounded predictions. Even though this switchgear was tested with an ungrounded source, the IEEE 1584-2002 grounded prediction envelopes all but one measured value.

While the existing IEEE formulas were reasonably accurate for 24 and 36 in (61 and 91 cm), measurements at the sensor head (92 and 100 in [2.3 and 2.5 m]) were less than 20% of what IEEE 1584-2002 predicts for that distance. Beyond 5 ft. (1.5 m), using a distance factor of 2 might be more predictive of the arc flash boundary.

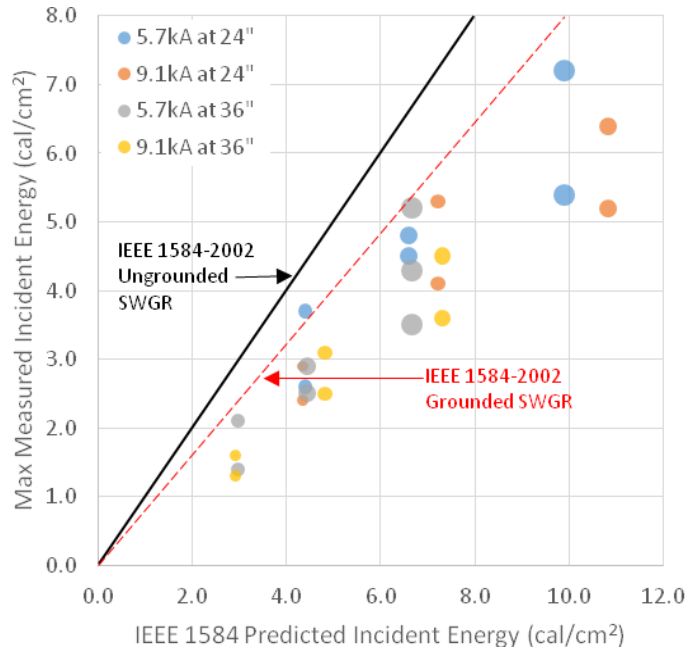


Fig. 12. Rack-up style switchgear: IEEE 1584-2002 predicted versus measured incident energy

III. ARC FLASH IN MEDIUM VOLTAGE LIVE FRONT TRANSFORMERS

Live-front transformers vary greatly in size and configuration. Five different types of enclosures and transformer sizes were chosen that span from the smallest to the largest that are likely to be encountered in the field. The selected transformers were drained of oil and the windings were disconnected from the bushing compartment. Fault initiation was single-line-to grounding the primary bushing compartment to replicate the most likely scenario of an actual field initiated arc. Multi-phases were energized to determine if the arc would propagate on its own beyond the single phase started. Not all transformers were rated for 21 kV line to line, but the bushing sizes and spacing allowed the primary bushings to be energized with a 21-kV grounded-wye source. Results are expected to apply for similar equipment for voltages from 4 kV to 35 kV.

A. Test Setup

The transformers tested are shown in Fig; 13 through 17 by the order they were tested.

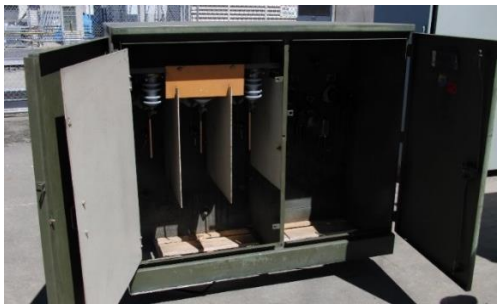


Fig. 13. Specimen #1: 3Φ 12kV-120/208V 75 kVA (small one) style IIA

Fig. 14: Specimen #2: 1Φ 4160/7200 X 12000V-120/240V 50-kVA clamshell with 3Φ cabinet

Fig. 15. Specimen #3: 1Φ 4160 X 12000V-120/240V 37.5kVA OLD style with 3Φ cabinet

Fig. 16: Specimen #4: 1 Φ 12kV x 21kV-120/240V 50-kVA box style with 1Φ cabinet

Fig. 17: Specimen #5: 3 Φ 12kV x 21kV-277/480V 750kVA (large one) radial style

Specimens #1 and #5 had pin terminals that pointed vertically while the others had pin terminals facing horizontally. The pins were bent at a right angle to left to fit into the horizontal terminal. See Figure 18.

Fig. 18: Horizontal (left) specimen #3 vs vertical (right) specimen #5 pin terminals

Specimen #1 had a set of standoff bushings installed from the top down in front of the primary bushings coming out of the transformer on the back wall. These were left in place to see if they had a deflecting influence on the heat. See Figure 19.

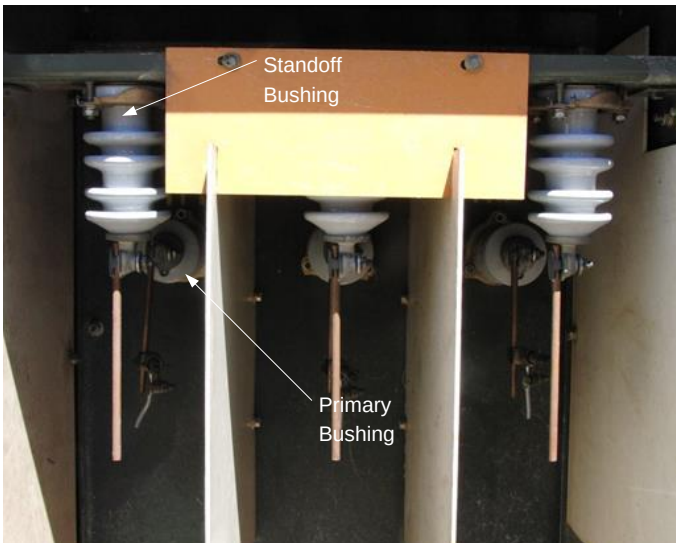


Fig. 19: Specimen #1 primary bushing compartment: showing standoff bushing in front of primary bushing

The dimensions and phase spacing for each specimen is shown in Table 3.

TABLE 3
TEST SPECIMEN DIMENSIONS

Spc #	Box Dim (inches) WxHxD	PH Space top/back/ph (inches)	Pin Config
1	30x41x24	14/8/10	Vert
2	28x29x18	9.5/8/10	Horiz
3	26x26x17	8.5/9/9	Horiz
4	17x27x18	8.5/6.75/9	Horiz
5	41x69x32	24/8.5/11.5	Vert

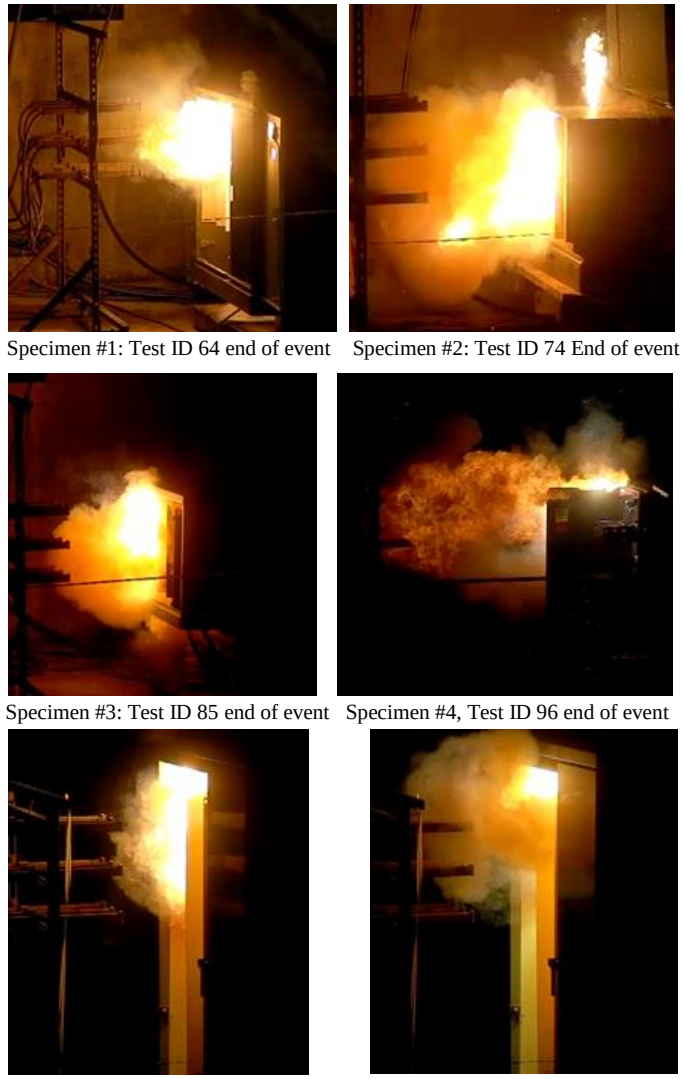
A #20 AWG copper wire was used to start a single phase arc for all bushing compartments. The wire was wrapped around the pin terminal and attached to the nearest grounded metal, preferably near the front of the enclosure. If no readily available spot was near the front of the cubicle, the wire was connected to a bolt head on the back wall.

Fault current levels of 2.3 kA and 6.7 kA were chosen at the beginning with durations of 20 and 40 cycles. After the second specimen was tested, we discovered that the test values were exceeding laboratory limits. The test plan was altered to have 4.5 kA as the highest available fault current with a goal of gathering some data at 60 cycle durations. All incident energy measurements were made at 33 in (84 cm) from the tip of the bushing.

B. Test Results

All transformers behaved very differently. The transformers that had pin terminals pointing straight up tended to start with arcing to the back wall of the enclosure, but some went to the top. Both 3Φ transformers had this style of terminal, but both exhibited extremely different incident energy behavior. The largest cubicle had much higher incident energy expelled than the smaller cubicle (opposite of expectations). The transformers that had pin terminals pointed to the left tended to start with the arc bouncing off the left side wall and attaching to either the roof or to a back wall protrusion. For these, the smallest did expel the most energy, but the values were higher than expected.

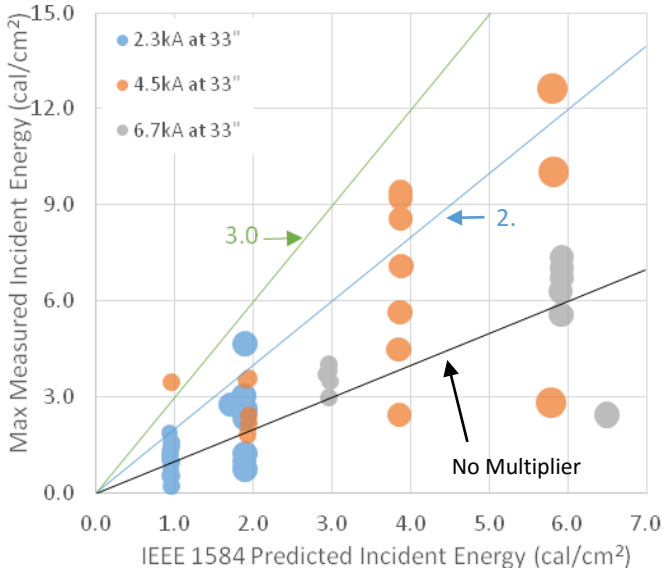
Most specimens propagated to multiphase arcs on their own very early in the test, except for the smallest and the largest enclosures, specimen #4 and specimen #5. These did not propagate to multi-phase until the bushings were very contaminated and beginning to erode. However, even with single-phase arcing, these two expelled more incident energy than any of the other specimens even when they went three phase. The fireball ejected from the cubicle was not only different in magnitude but also direction. Every specimen had a first test of 2.3 kA for 20 cycles. Figure 20 shows the comparison of incident energy patterns (fireball) for each specimen.



Specimen #1: Test ID 64 end of event
Specimen #2: Test ID 74 End of event
Specimen #3: Test ID 85 end of event
Specimen #4, Test ID 96 end of event
Specimen #5: Test ID 106 mid-event
Specimen #5: Test ID 106 end of event

Fig 20: Comparison of energy pattern from each specimen

Recommendations in previous EPRI reports [4, 5] were to use IEEE 1584 for all arc-in-a-box scenarios for voltages from 1 to 35 kV. For 25- and 35-kV class equipment, enter a voltage of 10 kV in the IEEE 1584 spreadsheet, so the Lee Method is not triggered (the Lee Method gives incident energies that are unrealistically high). The measured values exceed predicted values using the IEEE 1584-2002 formula, as shown in Figure 21. See Table 4 for the overall probability that each multiplier to IEEE 1584-2002 encompasses all the test data points.



Note 1: Bubble size reflects arc durations 20, 40, 60 cycles respectively. Lines represent multipliers to IEEE 1584-2002.

Fig 21: Live-front transformers: IEEE 1584-2002 prediction vs measured incident energy

TABLE 4
PROBABILITIES OF ENCOMPASSING TEST DATA

Multiplier to IEEE 1584-2002	Probability
1.0	34%
2.0	87%
3.0	98%

Additionally, when separated by specimen, the multipliers vary widely, as shown in Table 5.

TABLE 5
MULTIPLIER RANGE FOR EACH SPECIMEN

Multiplier Range to IEEE 1584-2002	Specimen
0.2 – 1.6	#1
0.4 – 1.3	#2
0.4 – 1.5	#3
1.4 – 3.6	#4
1.1 – 2.5	#5

The measured energy at the sensor head was a fraction of what IEEE 1584-2002 predicts. This will significantly reduce the arc flash boundary predictions from those previously done. Actual measurements at the sensor head (91 to 101 in or 2.3 m to 2.5 m from the arc initiation point) varied from 10% to 50% of what IEEE 1584-2002 would predict, with the bulk under 25%. Only specimen #4 had values that exceeded 25%. As with the switchgear, this is an indicator that the IEEE 'distance factor' relationship is finite at some boundary point.

IV. CONCLUSIONS

The test results discussed here show that it is important to evaluate the specific equipment or arc flash scenario to better refine arc flash analysis approaches.

With horizontal bus configurations (rack-in style), incident energies ranged from 1.5 times that predicted by IEEE 1584-2002 up to 4.7 times the predicted value. 89% of the measurements had energies less than 3.5 times the IEEE 1584 formula. Only 2% exceeded 4.0 times IEEE 1584 predictions. With vertical bus configurations, incident energies were between 0.5 and 1.0 times what IEEE 1584 predicts.

Rack-in switchgear with horizontal electrodes had much higher incident energies than the switchgear with vertical electrodes. With horizontal electrodes, the magnetic forces push the arc and the fireball out the front of the enclosure. With horizontal electrodes, the fireball goes downward, and more energy stays in the enclosure. Figure 22 and Figure 23 compare similar events on the two types of switchgear tested. Both events were done with I_{arc} = 8.4 kA and duration = 31 cycles. IEEE 1584-2002 predicts 6.9 cal/cm^2 for these conditions.

Fig 22: Horizontal racking configuration: 22.1 cal/cm^2

Fig 23: Vertical racking configuration: 6.4 cal/cm^2

There was wide variability between incident energies for different types and sizes of live-front transformers. To predict the incident energy using the existing IEEE 1584-2002 switchgear formula, a multiplier should be used. Measured multipliers ranged from 0.2 to 3.6. However, only 13% of the measurements exceed 2.0, and only 4% exceeded 2.5. Additionally, the largest enclosure and the smallest enclosure had incident energies that were typically more than the medium-sized enclosures; and with single-phase initiation, it is very likely that the arc will propagate to the other phases in all but the largest enclosure.

Future work could include:

- Tests on other types of horizontal switchgear especially switchgear with non-ceramic electrode barriers.
- More testing on livefront transformers to determine if there is any commonality to predict which ones would need the higher multipliers
- Testing to determine arc flash boundary prediction methods

If anyone would like copies of the test data reported here, please request it from one of the authors.

ACKNOWLEDGEMENTS

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