Comparison of IEEE 1584-2018 Predictions with Tests on Real-World Equipment

Paper No. ESW-(do not insert number)

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Abstract – IEEE 1584-2018 contains a significant update to industry models for predicting the incident energy from arc flash. These models include different box sizes, voltages, and electrode geometries. Predictions from these models are compared to tests on medium-voltage equipment. Equipment includes circuit-breaker cabinets, live-front switches, and live-front transformers. Results show what input assumptions are most applicable for each type of equipment (including vertical and horizontal electrodes). For some equipment, particularly with horizontal electrodes, the 1584-2018 predictions underpredicted measurements of incident energy, so multiplier factors may be needed.

Index Terms — Arc flash, medium voltage, power distribution, switchgear, safety, personnel protection.

I. INTRODUCTION

IEEE 1584-2018 [1] improved upon the first version of this Guide. Most notably, this new model accounts for electrode and box geometries by providing predictions for different configurations:

VCB – Vertical Configuration in a Box
VCBB – Vertical Configuration in a Box with a Barrier
HCB – Horizontal Configuration in a Box
VOA – Vertical Configuration in Open Air
HOA – Horizontal Configuration in Open Air

These configurations assume three-phase, parallel electrodes. The horizontal configurations predict the highest incident energies. This follows from results of higher incident energies from horizontal electrodes that were reported by Stokes and Sweeting [2] and Wilkins et al [3].

This paper compares predictions from the IEEE 1584-2018 models to tests of real medium-voltage equipment. These test results were previously reported by Eblen et al. [4] and Short and Eblen [5]. The IEEE 1584-2018 spreadsheet calculator [6] was used for all predictions. The data from the IEEE/NFPA tests that was used to derive the IEEE 1584-2018 models is also used to analyze impacts of variables on prediction results.

II. COMPARISON OF MODELS TO PREDICTIONS

A. Rack-in Circuit-Breaker Cabinets

Rack-in-style circuit breakers are common in industry. Cabinets for these circuit breakers have stabs in the back that point to the front of the cabinet. This is an HCB scenario. Arc-flash test results from Eblen et al. [4] (also EPRI 3002005598 [7]) are compared against predictions from IEEE 1584-2018. Fig. 1 compares predictions for incident energy to maximum incident energies measured during these tests. Each point represents one test. In these tests, the system voltage was a 12-kV, ungrounded laboratory source. Arcing currents ranged from 3 kA to 9 kA. Arc durations were from 0.1 to 1.2 secs. Incident energies were measured at working distances of either 914 mm (36 in), 1219 mm (48 in), or 1476 mm (58 in). For more information on test parameters, see Eblen et al. [4] and EPRI 3002005598 [7].

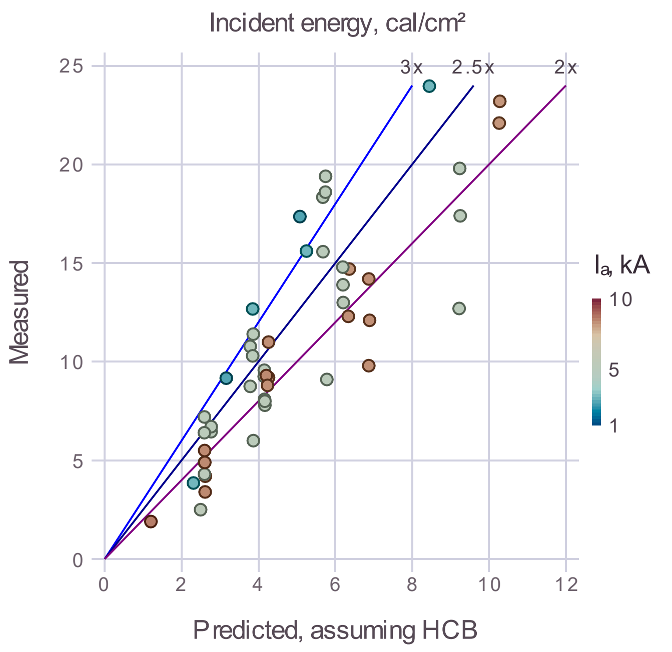

Fig. 1. Comparison of IEEE 1584-2018 predictions to maximum measured incident energy for rack-in circuit-breaker cabinets.

Here are the assumptions used for the IEEE 1584-2018 predictions in Fig. 1:

System voltage = 14.4 kV
Configuration = HCB
Box width = 914 mm (36 in);
Box height = 914 mm (36 in)
Electrode gap = 152 mm (6 in)

These assumptions were chosen to align best with the IEEE/NFPA test data used to derive the IEEE 1584-2018 prediction models. The 152-mm (6-in) gap spacing is the widest gap spacing in the IEEE/NFPA test set. These are expected to be good generic defaults for medium-voltage equipment. The actual cabinet used in these tests was 838-mm (33-in) wide and 1562-mm (61.5-in) tall, and the centerline-to-centerline distance between the stabs was 254 mm (10 in). If actual test parameters are used instead of the default assumptions above, the IEEE 1585-2018 model predictions do not change much: incident energies increase by only 1.3%.

The maximum incident energies measured in these tests were often well above the predictions from IEEE 1584-2018. Under predictions were especially noticeable for lower current, longer duration events. Fig. 2 shows the same results, but the marker coloring shows the working distance. More of the under predictions happened at the 1219 mm (48 in) and 1476 mm (58 in) working distances.

To account for the under predictions for rack-in circuit-breaker cabinets, a multiplier can be used on the IEEE 1584-2018 predictions. To cover all test data, a multiplier of 3x is needed. A multiplier of 2.5x covers the higher-current results.

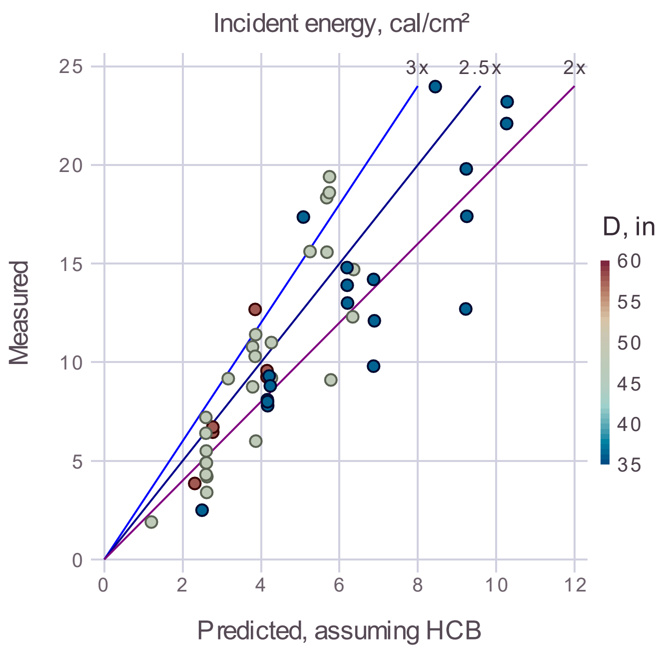

Fig. 2. Comparison of IEEE 1584-2018 predictions to maximum measured incident energy for rack-in circuit-breaker cabinets (working distances highlighted by coloring).

As noted by data from Eblen et al. [4] and EPRI 3002005598 [7], a circuit breaker in the cubicle will block much of the energy release. In tests with a mock circuit breaker in the cubicle, maximum incident energies were 50 to 60% of those without a circuit breaker.

B. Rack-up Circuit-Breaker Cabinets

For circuit-breaker styles where the circuit breaker racks up, the stabs point downward. This is a VCB scenario. Fig. 3 compares predictions using a VCB assumption with test results. For more on the setup and results, see Eblen et al. [4] and EPRI 3002005598 [7].

These predictions used the same assumptions as described in the prior section but with a VCB configuration. The opening on front of this cabinet was 914-mm (36-in) wide and 1422-mm (56-in) tall. There was 241 mm (9.5 in) of separation between phases. If actual test parameters are used instead of the default assumptions above, the predictions for incident energy decrease by 1.7%. Fault currents of 5 and 8 kA were tested, and incident energies were measured at 610 (24 in) and 914 mm (36 in). Durations were between 0.2 and 0.8 secs.

The results from Fig. 3 are all under the maximum measured incident energies. No multipliers or other adjustments are needed for this type of equipment.

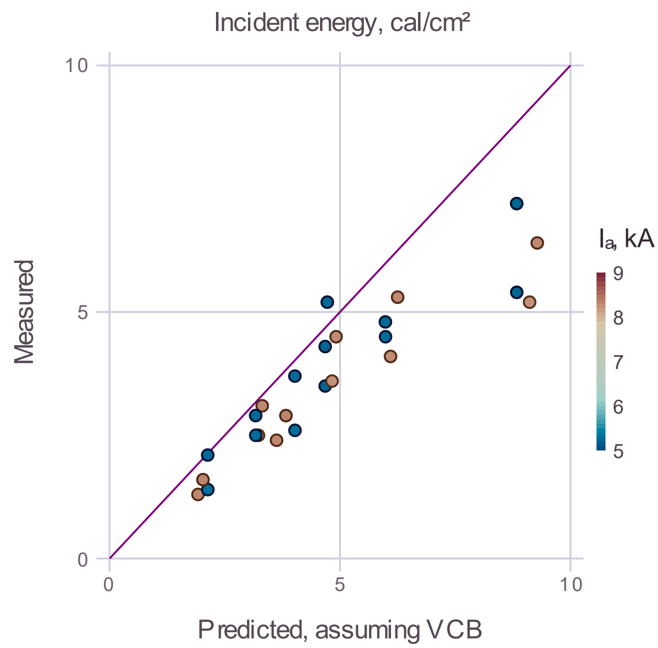

Fig. 3. Comparison of IEEE 1584-2018 predictions to maximum measured incident energy for rack-up circuit-breaker cabinets.

C. Live-Front Transformers

Eblen et al. [4] and EPRI 3002005598 [7] reported results from arc-flash tests in the medium-voltage compartment on five different live-front transformers. Fig. 4 compares predictions to maximum measured incident energies. The assumptions for these predictions are the same as described in section A. In these tests, a 21-kV grounded-wye source was used. Box sizes and phase spacings varied considerably. The smallest unit had a 432-mm (17-in) width and a 686-mm (27-in) height with a minimum gap of 171 mm (6.75 in). The largest unit had a 1041-mm (41-in) width and a 1753-mm (69-in) height with a minimum gap of 216 mm (8.5 in). Fault currents of 2, 5, and 7 kA were tested, and durations ranged from 0.3 to 1.0 secs.

This equipment does not have an obvious HCB configuration. Some of configurations look vertical, and some look horizontal, and the orientation does not correlate with incident energies. The results in Fig. 4 are shown with an HCB assumption used for predictions because the HCB results encompass the test results the best. Note that there was wide variation in the results from these five different units. The HCB assumption matches the configurations with the highest incident energies.

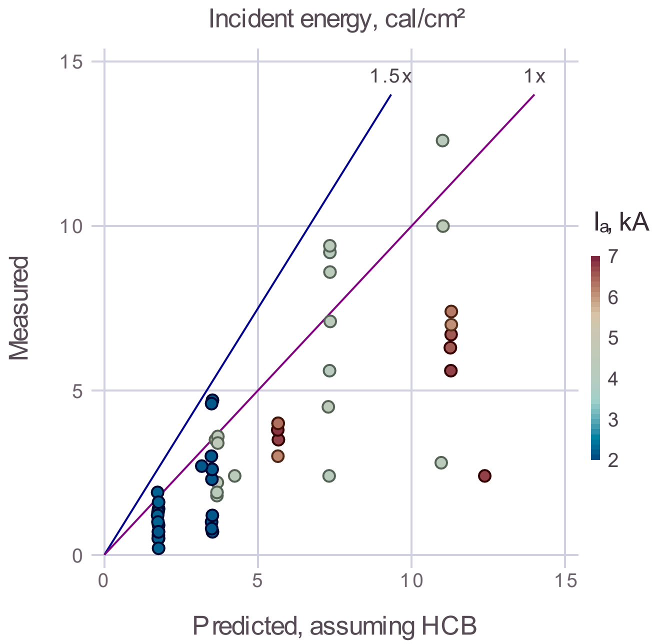

Fig. 4. Comparison of IEEE 1584-2018 predictions to maximum measured incident energy for live-front transformers.

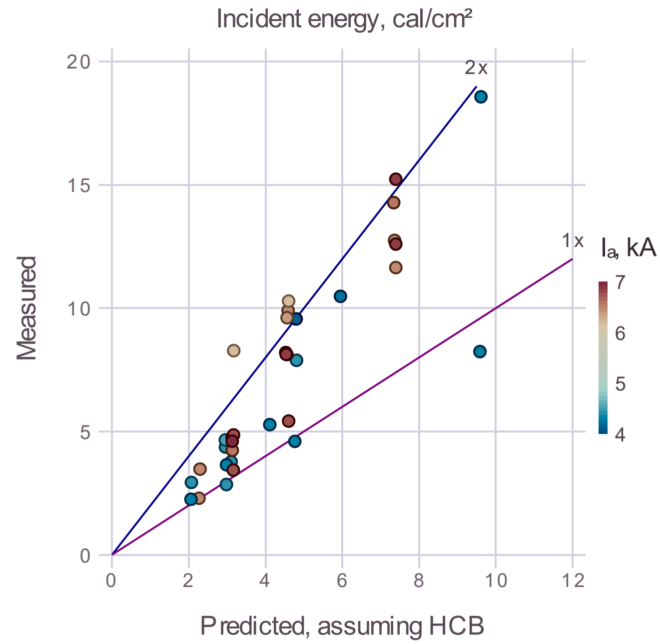

Fig. 5. Comparison of IEEE 1584-2018 predictions to maximum measured incident energy for live-front padmounted switches.

D. Live-Front Padmounted Switches

Short and Eblen [5] and EPRI 1022697 [8] reported results from arc-flash tests in live-front padmounted switches. Fig. 5 compares predictions from IEEE 1584-2018 to the maximum incident energies from these tests. These switches have horizontal bus bars that run from the back of the enclosure to the front. This is an HCB scenario. In these tests, a 21-kV grounded-wye source was used. Fault currents of 4 and 7 kA were tested, and durations ranged from 0.2 to 1.0 secs.

As with the rack-in circuit-breaker cabinets, IEEE 1584-2018 under predicted the measurements. To encompass most tests, a 2x multiplier is needed. Note also that most of these tests were single-phase tests. As reported by Short and Eblen [5] and EPRI 1022697 [8], multiphase faults could increase the energy by 60%. If that factor is included, the multiplier needed is in the same range as that required for the horizontal circuit-breaker cabinets.

III. ANALYSIS OF HCB TEST DATA

Because the IEEE 1584-2018 model under predicted scenarios with horizontal electrodes, more analysis was done to determine what may have contributed to the mismatch between predictions and measurements.

A. Impact of Electrode Spacing

IEEE 1584-2018 identified the electrode gap as an important part of the model for all configurations. The rack-in circuit-breaker enclosures and the live-front padmounted switches both had larger gap spacings than those used in the IEEE/NFPA tests that were used for the development of the IEEE 1584-2018 model.

One way to evaluate the contribution of the gap spacing is to evaluate the impact of gap spacing on arc voltage. Wider gap spacings should increase the length of the arc, and that increased length should increase arc energy. Arc energy is the product of the arc voltage and the arc current. It is expected that wider gaps will produce a longer arc. A longer arc will have a higher arc voltage. Arc voltage is mainly a function of arc length, and current has a minor influence on the arc voltage. For more on the characteristics of arc voltage, see Stokes and Sweeting [2], Strom [9], and Short [10]. An equivalent arc voltage from one phase to ground can be estimated from test results using:

$$V_{arc} = \frac{E}{3 \cdot t \cdot Ia}$$

where

V_{arc} = Arc voltage (L-G), V
E = Total arc energy, J
t = Arc duration, secs
Ia = Average arcing current, A

Fig. 6 shows this calculated arc voltage as a function of the electrode gap. This is shown for test data from EPRI for the rack-in circuit-breaker cabinet and for the IEEE/NFPA tests with a medium-voltage HCB configuration. The arc voltage trends upward as the electrode gap increases.

Note that there is some difference between the EPRI testing and the IEEE/NFPA tests. The EPRI testing had a centerline-to-centerline distance of 25.4 cm (10 in). The electrode terminals were about 3 cm (1.2 in) in diameter, so the direct gap spacing was about 22 cm (9.5 in). The IEEE/NFPA test used an edge-to-edge gap spacing of up to 15 cm (6 in). It is unknown what size or shape electrodes were used in these tests, so it is difficult to directly compare.

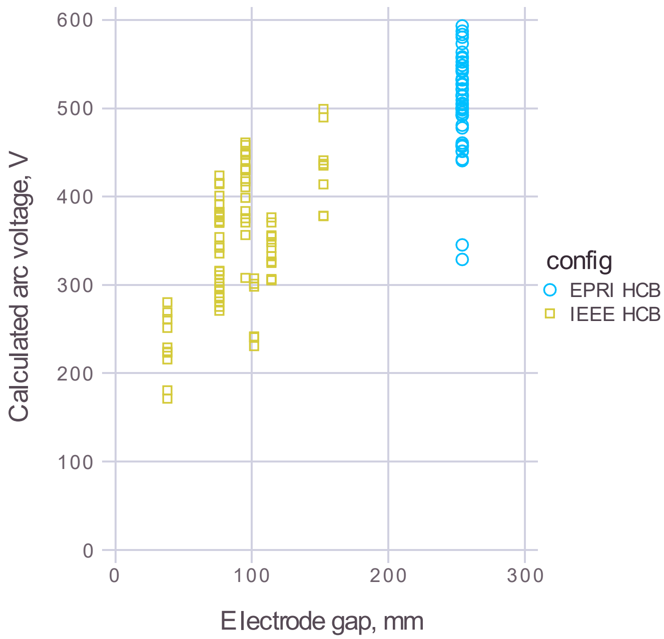

Fig. 6. Calculated arc voltage as a function of electrode gap spacing from test data.

B. *Impact of Duration*

Duration is another important factor. The IEEE/NFPA tests were normally done for a duration of 0.1 or 0.2 secs. The EPRI tests were normally longer than this, ranging from 0.2 to 1.0 secs. Most arc-flash models, including IEEE 1584-2018, assume a constant heat rate. So, if the duration doubles, the incident energy doubles. These test results suggest that the heat rate may not always be constant with duration. Heat rates may increase with duration for some scenarios.

One way to evaluate the impact of duration is to normalize the incident energy to the arc energy. Fig. 7 compares this energy ratio as a function of duration for a working distance of 914 mm (36 in). Fig. 8 shows a similar plot at a working distance of 1219 mm (48 in). Both test datasets show an increasing energy ratio as duration increases. More of the energy of the arc is being transmitted to the measurement location.

The expansion of the hot fireball may explain the time dependence for the horizontal configurations. Fig. 9 shows video frames from one test on the horizontal circuit-breaker cabinet. As a point of reference, the ends of the calorimeters are 1219 mm (48 in) from the electrodes. In three cycles, the fireball expands enough to contact these calorimeters. The fireball continues to expand for most of the event. As it is expanding, it is likely that the higher-temperature regions of the fireball are also expanding.

Stokes and Sweeting [2] and Sweeting [11] showed that the energy transfers (particularly for horizontal scenarios) are largely from conduction from the hot gas cloud pushed out by the arc. At distances greater than 914 mm (36 in), there is more time of contact with the hot gas cloud for longer-duration events.

The data points in Fig. 1 are based on the maximum incident energy measured using an array of nine calorimeters. As shown by Fig. 9, the fireball expands widely, and the average of all calorimeters was typically close to the maximum measurement. For example, the test with the highest incident energy had a peak of 23.2 cal/cm^2, and the average of the calorimeter measurements during that test was 19.4 cal/cm^2.

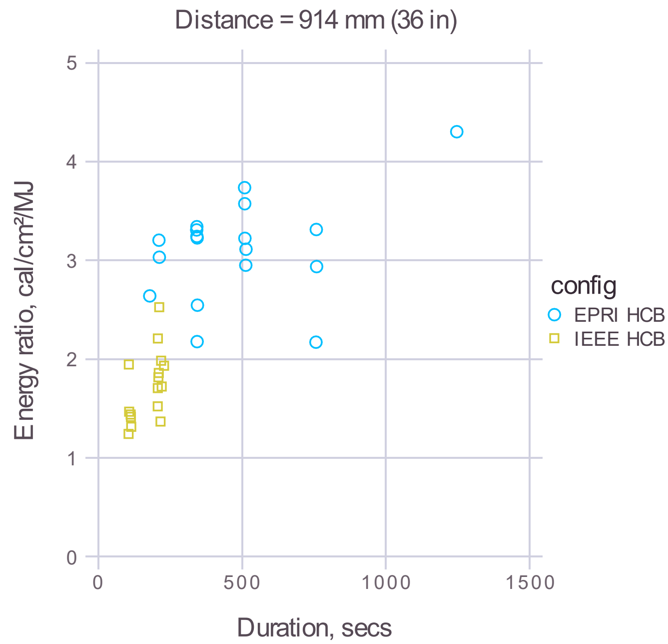

Fig. 7. Ratio of incident energy to arc energy as a function of arc duration.

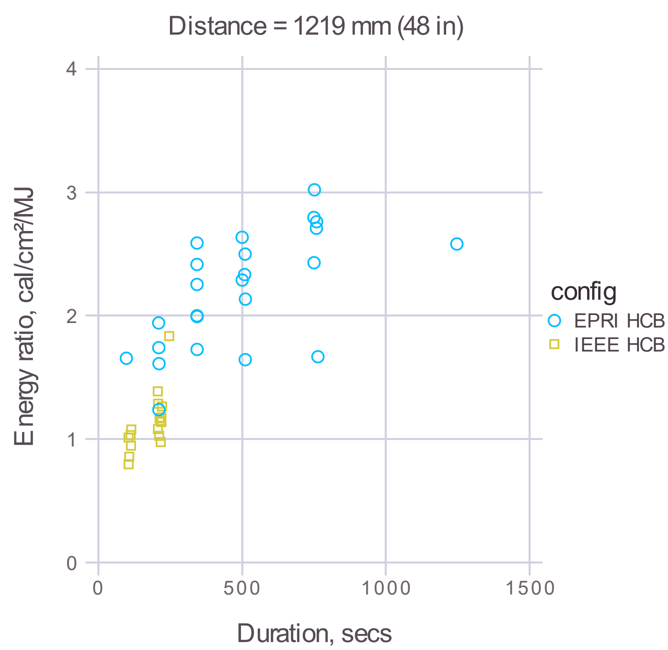

Fig. 8. Ratio of incident energy to arc energy as a function of arc duration.

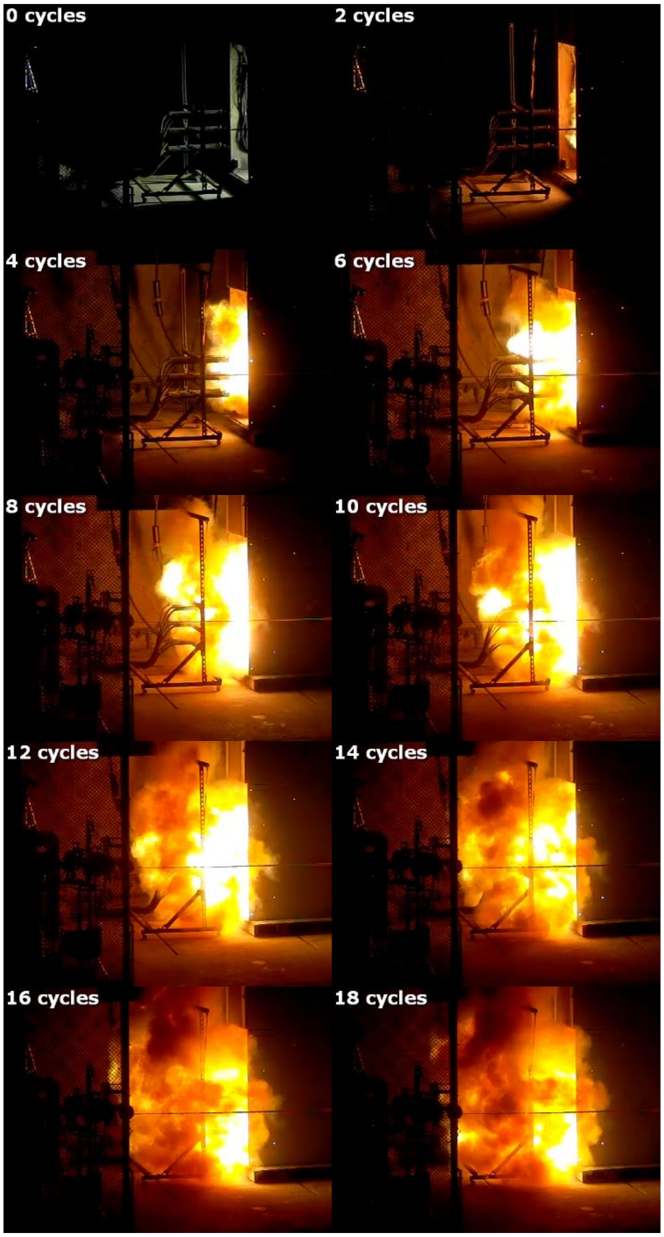

Fig. 9. Video frames from an 8-kA fault in a horizontal rack-in circuit-breaker cabinet.

C. Regression Models

To better explore the impact of duration and gap spacing, several power-law regressions are given. These are meant for exploration, not prediction. The relationship between the gap spacing and the arc voltage can be seen in the following power-law fit to the IEEE/NFPA data for medium-voltage HCB scenarios.

$$V_{arc} \propto Ia^{0.107} G^{0.246}$$

where

V_{arc} = Arc voltage (L-G), normally in V or kV
Ia = Arcing current, normally in kA
G = Electrode gap, normally in mm

TABLE I shows coefficients for this regression model. The coefficients for *Ia* and for *G* are statistically significant. The P values in the last column of this table are well under 0.01. Statistical significance is often given for a P value below 0.05 or 0.01.

TABLE I
Arc-Voltage Regression Model for IEEE/NFPA HCB

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	4.474	0.1971	22.70	1.3e-36
log(*Ia*)	0.107	0.0155	6.90	1.1e-09
log(*G*)	0.246	0.0476	5.17	1.7e-06

The following equation for incident energy was derived using a power-law fit of the IEEE/NFPA data for medium-voltage HCB scenarios.

$$IE \propto D^{-2.013} Ia^{1.145} t^{1.156} G^{0.475}$$

where

IE = Incident energy, normally in cal/cm^2
D = Working distance, normally in mm
Ia = Arcing current, normally in kA
t = Arc duration, normally in secs
G = Electrode gap, normally in mm

The following equation shows a similar model derived from the EPRI data from the horizontal, rack-in circuit-breaker cabinet. The electrode gap is not included in this model because the electrode gap was fixed.

$$IE \propto D^{-1.320} Ia^{1.084} t^{1.269}$$

See TABLE II and TABLE III for regression statistics. All of the coefficients are statistically significant.

TABLE II
Regression Model for IEEE/NFPA HCB Data

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2.292	0.4306	-5.32	9.5e-07
log(*D*)	-2.013	0.0877	-22.95	2.0e-36
log(*Ia*)	1.145	0.0179	64.06	3.3e-69
log(*t*)	1.156	0.0439	26.36	1.4e-40
log(*G*)	0.475	0.0502	9.47	1.3e-14

TABLE III
Regression Model for EPRI HCB Data

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2.416	1.0887	-2.22	3.2e-02
log(D)	-1.320	0.1983	-6.66	3.7e-08
log(Ia)	1.084	0.1492	7.27	4.6e-09
log(t)	1.269	0.0859	14.77	1.1e-18

TABLE IV compared the coefficients from the models above to the IEEE 1584-2018 model. The duration coefficient is statistically significant for both the IEEE/NFPA and the EPRI data. For the IEEE/NFPA with a coefficient of 1.156, the upper and lower 95% intervals for this coefficient are 1.069 and 1.244. For the EPRI model with a coefficient of 1.269, the upper and lower 95% intervals for this coefficient are 1.096 and 1.442.

TABLE IV
Comparison of Regression Exponent Terms

	1584-2018 official model (14 kV)	Model from IEEE/NFPA data	Model from EPRI data
D	-1.655	-2.013	-1.320
Ia	Complicated	1.145	1.084
T	1.000	1.156	1.269
G	0.125	0.475	NA

A model developed for the live-front padmounted switches (a HCB case) also showed a time dependence. Short and Eblen [5] and EPRI 1022697 [8] reported on a similar power-log model for these padmounted switches where $IE \propto t^{1.35}$.

TABLE IV shows interesting differences in the working-distance (*D*) coefficient between the different models. Fig. 10 shows the ratio of incident energy to arc energy as a function of this distance. The EPRI tests are over a smaller range of working distances, so that may explain some of the difference in the working-distance coefficient.

These regression models help to quantify some of the differences between the IEEE/NFPA test data and the EPRI test data. These explain some—but maybe not all—of the difference in the predictions between IEEE 1584-2018 and the test results in real equipment. The IEEE/NFPA tests were generic tests with uniform electrodes in a uniform box. In addition to gap spacing and duration, other equipment-specific factors may affect results. Fig. 11 shows the stabs on the test sample used. The stabs might affect arcing and energy-transfer patterns.

IV. Impact of Voltage and Box Size

The IEEE 1584-2018 guide states that the predictions are only valid to 15 kV, and the calculation spreadsheet enforces this limit. This section provides data to support use of the IEEE 1584-2018 model and other models up to 35 kV.

System voltage does not play a role in medium-voltage arc flash. In the tests of real-world equipment, the switchgear cabinets were tested with a system voltage of 12 kV, and the live-front padmounted transformers and switches were tested with a 21-kV source. There were no noticeable differences between the results of these tests that could be related to system voltage.

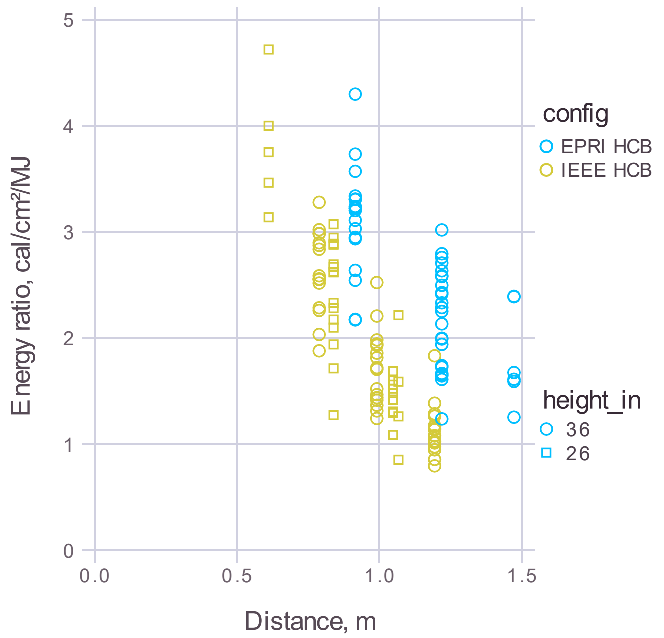

Fig. 10. Ratio of incident energy to arc energy as a function of working distance.

Fig. 11. Horizontal, rack-in-style stabs with the shutter removed.

The arc voltages (line to ground) for most of these tests in medium-voltage equipment are under 600 V (see Fig. 6). Whether the system voltage is 7200 V or 14400 V from line to ground, that is large relative to a 600-V arc voltage. It's a nearly bolted fault. With the same spacings, moving to a voltage above 15 kV may slightly increase the arcing current, but arcing currents are already 95% of the bolted fault in many cases for medium-voltage equipment. The arc voltage is determined by the arc length and to a small extent by the arc current. The system voltage does not play a role. 25-kV and 35-kV equipment normally has spacings similar to 15-kV equipment. Box and electrode configurations are important, but system voltage is not.

Most of the IEEE/NFPA tests used different box sizes at different voltages. The 2.7-kV tests used a box size of 660 mm (26 in), and the 14.4-kV tests used a box size of 914 mm (36 in). There were some tests in a 914-mm (36-in) box at both 2.7 kV and 14.4 kV. Fig. 12 compares heat rates from these tests for a bolted fault current of 20 kA for the VCB scenario. Fig. 13 shows a similar graph for the HCB scenario. In both cases, the heat rates were higher at the higher voltage, but that's mainly because the tests at the higher voltage had a larger gap distance.

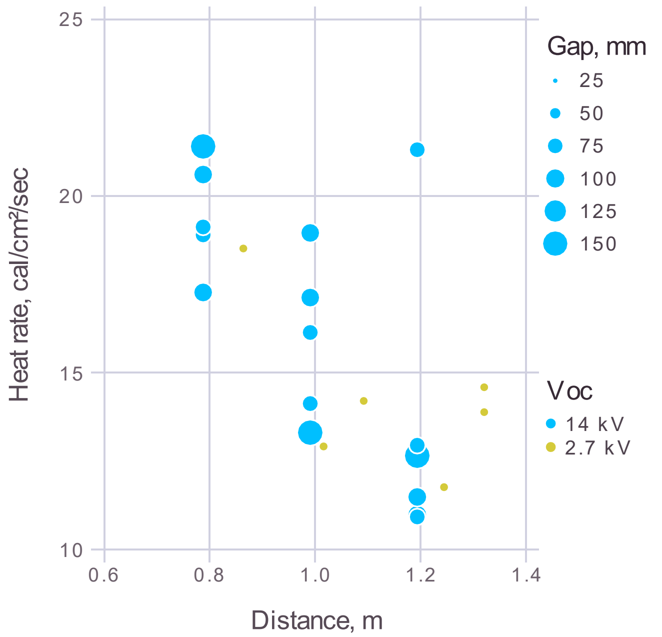

Fig. 12. Comparison of the impact of system voltage for VCB with a 914-mm (36-in) box size for I_b=20 kA.

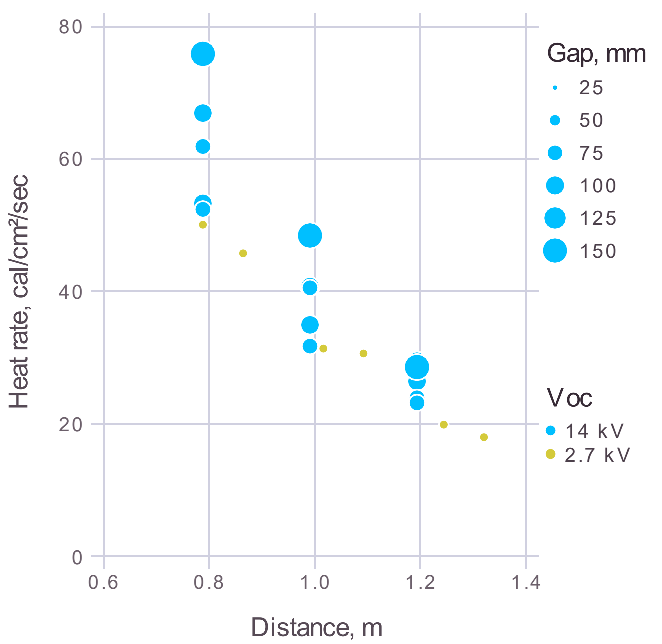

Fig. 13. Comparison of the impact of system voltage for HCB with a 914-mm (36-in) box size for I_b=20 kA.

TABLE V and TABLE VI show regression model results for incident energy for VCB and HCB for this data. The system voltage coefficient is highlighted in the last row of both tables. Both coefficients on voltage are negative; a higher system voltage means the incident energy is lower. For the VCB case, the voltage coefficient is not statistically significant. For the HCB case, the voltage coefficient is statistically significant (the P-value in the last column is low).

For the VCB model in TABLE V, the coefficient for the electrode gap (*G*) is not statistically significant. It is for the HCB model. For VCB scenarios, the length of the arc leaving each electrode is mainly determined by the distance from the bottom of the electrode to the bottom of the box (when power is fed from the top). The arcs normally shoot out the bottom of the electrodes and land on the floor of the enclosure. The distance between the electrodes does not affect the arc length much. This is shown by tests in two different size boxes and different electrode arrangements in EPRI 1022697 [8].

TABLE V

Regression for IEEE/NFPA VCB Data for a 914-mm (36-in) Box

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.016	0.929	-0.02	9.9e-01
log(D)	-1.006	0.115	-8.72	1.4e-12
log(Ib)	0.818	0.019	42.35	1.4e-49
log(t)	1.004	0.072	13.88	3.0e-21
log(G)	0.080	0.099	0.81	4.2e-01
log(Voc)	**-0.039**	**0.067**	**-0.58**	**5.6e-01**

TABLE VI

Regression for IEEE/NFPA HCB Data for a 914-mm (36-in) Box

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	5.560	0.514	10.82	1.5e-15
log(D)	-2.096	0.065	-32.35	8.3e-39
log(Ib)	1.090	0.013	81.60	1.5e-61
log(t)	1.150	0.042	27.29	8.8e-35
log(G)	0.428	0.054	7.91	8.8e-11
log(Voc)	**-0.143**	**0.038**	**-3.80**	**3.4e-04**

These results support the idea that system voltage does not make a significant difference in incident energies for medium-voltage equipment. The IEEE 1584-2018 model and other models of arc flash can be applied from 5 kV to 35 kV as long as the spacings are comparable to 15-kV equipment. To evaluate 25- and 35-kV scenarios, the IEEE 1584-2018 spreadsheet can be applied by entering a system voltage of 14.4 kV.

V. CONCLUSIONS

IEEE 1584-2018 can underpredict incident energies for some medium-voltage equipment. Multipliers or other analysis approaches would be needed to match the data from real equipment testing. Horizontal-electrode scenarios were the worst scenarios, particularly for a rack-in circuit-breaker cabinet. Multipliers of at least two times IEEE 1584-2018 predictions are needed to reproduce the measured data from real equipment with horizontal electrodes. No multipliers would be needed for live-front transformers (HCB) or vertically racked switchgear (VCB).

Two reasons were found to explain some of the differences in the IEEE 1584-2018 predictions for horizontal electrodes. One is that electrode gap spacing continues to be important for spacings wider than the largest spacings used in the IEEE/NFPA tests (152 mm [6 in]). Another factor is the impact of duration. Most of the IEEE/NFPA tests were 0.1 or 0.2 secs. The EPRI tests found that heat-flux rates increased with duration, and the duration parameter is statistically significant for incident energy.

There is value in additional industry tests on medium-voltage equipment. The equipment tests reported here and in [4] have a limited range of currents and durations. The tests used for IEEE 1584-2018 had limited tests for longer durations and wider gap spacings. More data is needed on scenarios with a wider range of parameters, include short and long fault durations and scenarios with wider electrode gaps. This test data could be used to improve industry models of incident energies. More tests on real equipment would also improve confidence in models and reveal equipment-specific factors that are important.

The IEEE 1584-2018 model is specified to cover system voltages up to 15 kV. Results from the IEEE/NFPA and the EPRI testing showed that the system voltage is not a statistically significant factor for medium-voltage scenarios. The most important factors are electrode and box geometries. Because of that, the IEEE 1584-2018 model or other industry models can be used up to 35 kV if the electrode and box geometries are similar to 15-kV class equipment.

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VII. VITA

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