REVIEW OF IEEE 1584-2018 AND ITS IMPACT ON ARC-FLASH SAFETY

Paper No. PCIC Middle-East SA22_70

Abdullah Al-Nujaimi
Consulting Services Department
Saudi Aramco
Dhahran, Saudi Arabia
Email: abdullah.alnujaimi@aramco.com

Cory A. Helfrich
Consulting Services Department
Saudi Aramco
Dhahran, Saudi Arabia
Email: cory.helfrich@aramco.com

Rakan El-Mahayni
Consulting Services Department
Saudi Aramco
Dhahran, Saudi Arabia
Email: rakan.mahayni@aramco.com

Rashid O. Al-Rashidi
Consulting Services Department
Saudi Aramco
Dhahran, Saudi Arabia
Email: rashid.rashidi@aramco.com

Abstract — This paper highlights the major changes that the recently published IEEE 1584-2018 makes to the calculations of the arc flash incident energy and boundary. The new standard was published in December, 2018, and considers new factors, including electrode configurations and the enclosure dimensions of the electrical equipment. These factors were not considered in the 2002 version of the same standard. The paper also highlights the impact of new changes on electrical equipment installed in the facilities of a large oil company. The new arc-flash model might increase the arc flash energy on electrical equipment beyond the safety limits specified in the company's engineering requirements. Therefore, the report recommends a way forward to minimize the impact of the new changes for existing and new facilities.

Index Terms — arc blast, arc fault currents, arc flash, arc-flash hazard, arc-flash hazard analysis, arc in enclosures, electrical hazard, IEEE 1584

I. INTRODUCTION

Until 1982, electrical engineers generally considered only one electrical hazard related to electrical shocks: current passing through the human body. In 1982, a technical paper highlighted the danger of a current passing through plasma from the arc terminal conductive metal or carbon material, which is called the arc flash (AF) hazard [1].

Since then, several papers and best practices tried to quantify the incident energy associated with this arc in order to specify the proper personal protective equipment (PPE) to protect the personnel working on electrical equipment. In 2002, IEEE working group P1584 conducted hundreds of tests to develop an empirical model that predicts the incident energy (IE) and the associated arc flash boundary (AFB). As a result, IEEE 1584- 2002 [2] was published and utilized throughout the industry for the next 16 years.

Late in 2018, a new version of IEEE 1584 [3] was published with major changes to the arc-flash predictive model. Compared to the 2002 revision, the 2018 calculations generally yield increased IEs for the same type of equipment. This is due to new factors being included in this model, such as the enclosure dimensions and the equipment configuration. The new changes will be discussed in detail in the following sections.

II. SUMMARY OF THE MAJOR CHANGES

The new arc-flash model is an empirical model that was developed based on thousands of experiments on different enclosure and bus configurations. The 2018 model depends on much more complex equations that consider several factors that were not considered in the 2002 model. Minor changes to individual equipment will be discussed in the respective subsection of the equipment. The summary of the general changes is discussed in the following sections.

A. Inclusion of Electrode Configuration in AF Model

The 2002 arc-flash model considers only whether the arc flash occurs in a metal box or in an open air. The 2018 arc-flash model considers the orientation and arrangement of the electrodes within the electrical equipment. The 2018 configurations are:

- VCB: Vertical conductors/electrodes inside a metal box/enclosure.
- VCBB: Vertical conductors/electrodes terminated in an insulating barrier inside a metal box/enclosure.
- HCB: Horizontal conductors/electrodes inside a metal box/enclosure.
- VOA: Vertical conductors/electrodes in open air.
- HOA: Horizontal conductors/electrodes in open air.

VCB, VCBB, and HCB configurations exist in metal enclosed electrical equipment such as metal-clad switchgear, metal-enclosed switchgear, and motor controlgear. Fig. 1 shows examples where these configurations exist. Multiple configurations can exist in one electrical equipment during different operation and maintenance scenarios. Since a variety of tasks can be performed on the equipment, the configuration of interest can change.

The VOA and HOA electrode configurations exist in electrical equipment that either do not have a metal enclosure or that have their cover removed to perform a certain task while energized. Fig. 2 shows examples of these two configurations. The possible configuration of each equipment will be discussed in later sections of the paper.

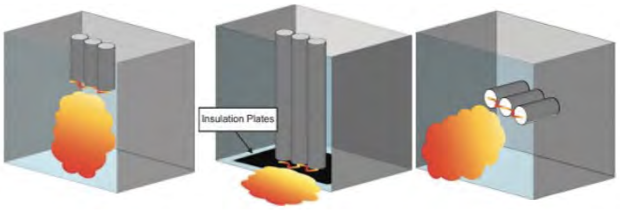

Fig. 1. Electrode configuration inside a metal enclosed box: VCB, VCBB and HCB

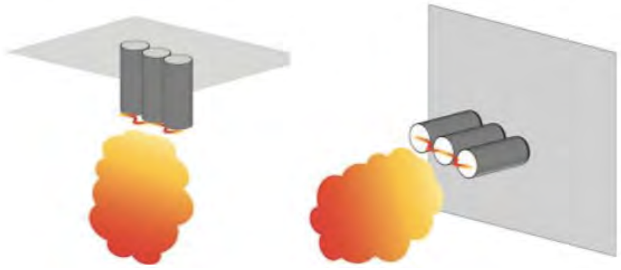

Fig. 2. Electrode configuration inside a metal enclosed box: VCB, VCBB and HCB

B. *Inclusion of Enclosure Dimensions*

The 2002 AF model does not consider enclosure geometries in the incident energy and arc flash boundary calculations at all. However, the incident energy in the 2018 model depends on the enclosure dimensions where the arc is initiated. The impact of enclosure dimensions is considered in a new factor called the enclosure-size correction factor (CF). Empirical tests showed that, for a typical enclosure with a depth higher than 8 inches, as the enclosure dimensions decrease, the arc-flash incident energy (IE) will increase. However, for shallow enclosures (depth of 8 inches or less) in low-voltage (LV) equipment, the opposite impact for enclosure dimensions is expected. Therefore, this impact will be more pronounced in LV motor controlgear where several enclosures with different dimensions exist in one line-up. Moreover, in a switchgear line-up, any compartment where the arc can be initiated shall be considered, including the compartments containing circuit breakers, cable terminations, and instrument transformers.

C. *Arcing Current Variation Calculations*

In arc flash calculations, it is important to determine the impact of the arcing-current variation on the operating time of protective device and, consequently, incident energy. If the arc-clearing device exhibits an inverse time over-current characteristic, a lower arcing current can result in a longer clearing time that would result in a higher IE than the IE associated with higher arcing current.

In the 2002 arc flash model, the variation of the arcing current was fixed and was considered to be 85% of the average arcing current. In the 2018 model, the arcing current variation is variable and depends on both the system voltage and equipment configuration. Table I shows the arcing-current variation correction factor for different voltages with all possible configurations.

Since all high-voltage (HV) and most LV equipment in Saudi Aramco have protection devices with definite-time over-current characteristics (i.e., relays with energy-reducing maintenance switches (ERMS) and differential relays), this change in the 2018 model will have a minor impact on panelboards where faults are typically cleared by a molded-case circuit breaker (MCCB) with inverse-time over-current characteristics. This change will be a maximum of 2% in terms of the minimum arcing current as per Table I and its impact on the final IE will be discussed in III-F.

TABLE I
ARCING CURRENT VARIATION FACTOR FOR DIFFERENT VOLTAGES AND CONFIGURATIONS

Voltage	VCB	VCBB	HCB	VOA	HOA
208 V	86.2%	85.6%	84.3%	85.4%	84.3%
240 V	86.3%	85.9%	84.5%	85.8%	84.5%
277 V	86.6%	86.3%	84.8%	86.2%	84.8%
400 V	87.2%	87.5%	85.7%	87.3%	85.6%
480 V	87.7%	88.2%	86.2%	88.0%	86.1%
4.16 kV	97.7%	97.8%	97.4%	98.2%	96.6%
13.8 kV	98.8%	98.1%	98.8%	98.3%	96.8%

III. IMPACT ON ARC-FLASH SAFETY

With the publication of IEEE 1584-2002 and based on the standard personal-protective equipment available at the time, a large oil company introduced a safety limit of $8\,\mathrm{cal/cm^2}$ on the IE permissible in new installation This section discusses the impact of implementing the new model on the incident energy for different electrical equipment.

A. *13.8-kV Metal-Clad Switchgear Incident Energy*

According to Annex C of IEEE 1584-2018, several configurations can exist in the switchgear while performing different tasks. When the circuit breaker (CB) is in the enclosure and racked in, the electrode configuration is considered to be HCB. When the CB is in the enclosure but racked out, both HCB and VCBB should be considered. However, if the CB has an internal fault, VCB is the best representation of the electrode configuration.

In this analysis, a typical enclosure dimension (height H = 45 in, width W = 30 in, and depth D = 30 in) and a typical working distance (36 in) is used. A clearing time with a standard 5-cycle HV circuit breaker, a transformer differential relay with a 50 ms operating time, and a lockout relay with a 10 ms operating time (total clearing time = 143 ms) is utilized in the comparison against the 2002 AF model. The results can be seen in Fig. 3, along with the blue and red dashed lines representing the 8 and $12\,\mathrm{cal/cm^2}$ incident energy limits, respectively.

Table II presents the same results in $(\mathrm{cal/cm^2})$ for different short circuit currents using 2002 calculations against the electrode configuration in 2018 version for a clearing time of 143 ms. Energy calculations for the HCB case is higher than VCB and VCBB configurations since the incident energy will be directed to the worker torso, unlike the other two configurations.

Many vendors also provide three-cycle HV circuit breakers. The total clearing time of the relay, HV circuit breaker, and lockout relay will be around 110 ms. IE results for 13.8-kV metal-clad switchgear are seen in Fig. 4 and Table 3.

Even with a 110-ms clearing time, IE resulting from the worst-case electrode configuration for both the 2018 AF

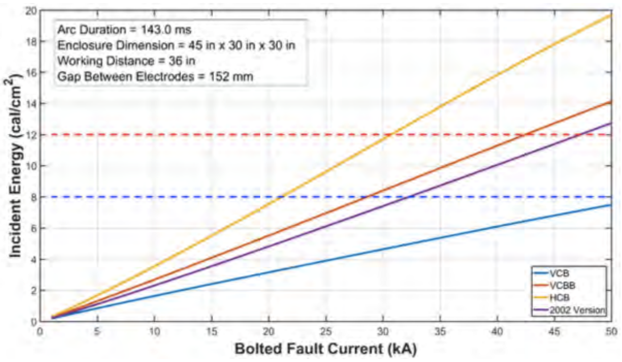

Fig. 3. Incident energy trends for 13.8-kV Switchgear using 2002 and 2018 AF model (143 ms)

TABLE II
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 13.8-KV SWITCHGEAR USING 2002 AND 2018 AF MODEL (143 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	1.10	0.84	1.30	1.67
10	2.30	1.63	2.68	3.54
15	3.54	2.40	4.08	5.50
20	4.81	3.15	5.51	7.53
25	6.10	3.90	6.95	9.61
30	7.40	4.63	8.40	11.70
35	8.72	5.37	9.85	13.79
40	10.05	6.09	11.29	15.83
45	11.39	6.80	12.72	17.81
50	12.74	7.49	14.13	19.69

model (i.e., HCB) s well as from the 2002 AF model are not within the 8 cal/cm^2 limit set by the company. The clearing time for bus-side and line-side faults can be further reduced to 90 ms by using faster relays with an operating time of 30 ms along with the three-cycle HV circuit breaker. The incident energies for 13.8-kV metal-clad switchgear with a 90-ms clearing time are shown in Fig. 5 and Table IV.

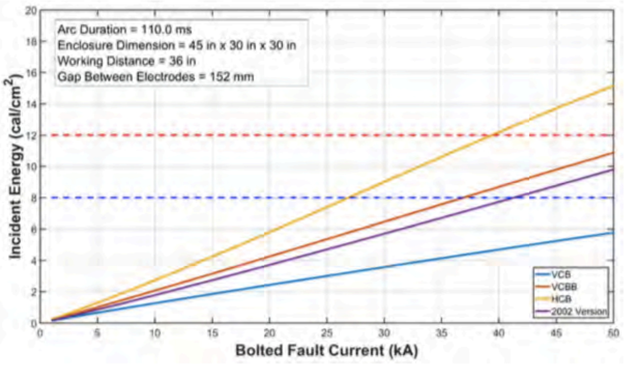

Fig. 4. Incident energy trends for 13.8 kV Switchgear using 2002 and 2018 AF model (110 ms)

TABLE III
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 13.8-KV SWITCHGEAR USING 2002 AND 2018 AF MODEL (110 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.85	0.65	1.00	1.28
10	1.77	1.26	2.06	2.72
15	2.73	1.84	3.14	4.23
20	3.70	2.42	4.24	5.79
25	4.69	3.00	5.35	7.39
30	5.69	3.56	6.46	9.00
35	6.71	4.13	7.58	10.60
40	7.73	4.68	8.69	12.18
45	8.76	5.23	9.79	13.70
50	9.80	5.76	10.87	15.14

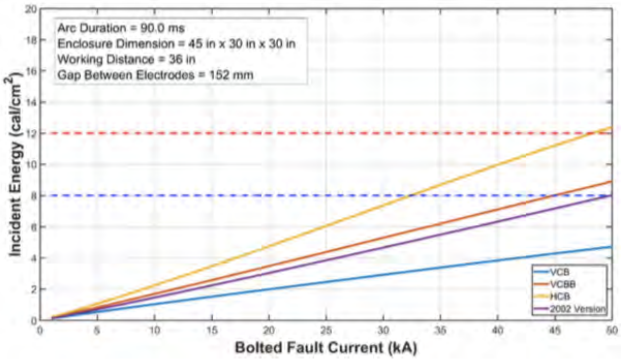

Fig. 5. Incident energy trends for 13.8-kV Switchgear using 2002 and 2018 AF model (90 ms)

By using three-cycle circuit breakers and relays with a 90-ms operating time, the IE can be reduced to be close to 8 cal/cm^2 with the 2002 AF model and 12 cal/cm^2 with the worst-case configuration of the 2018 AF model.

B. 4.16-kV Metal-Clad Switchgear Incident Energy

The 2018 model for 4.16-kV switchgear is similar to the model for 13.8-kV switchgear. Changes include the reduced typical gap between electrodes (104 mm from 152 mm) and smaller enclosure dimensions (36 in × 36 in × 36 in or 45 in × 30 in × 30 in).Calculations show that the IE is slightly higher with the enclosure dimensions of 36 in × 36 in × 36 in than with the enclosure dimensions of 45 in × 30 in × 30 in, so this paper considered the dimensions as 36 in × 36 in × 36 in

The results in cal/cm^2 are shown for a clearing time of 143 ms in Fig. 6 and Table V. Similar to the 13.8-kV results, the clearing time can be further reduced using three-cycle circuit breakers and relays with operating times of 30 ms. This will result in clearing times of 110 ms (results in Fig. 7 and Table VI) and 90 ms (results in Fig. 8 and Table VII).

Overall, the IE is lower in the 4.16-kV switchgear than in the 13.8-kV switchgear. However, in both cases, the incident energy will exceed the 8 cal/cm^2 limit set by the company engineering standards at 32 kA for the 13.8-kV switchgear

TABLE IV
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 13.8-KV SWITCHGEAR USING 2002 AND 2018 AF MODEL (90 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.69	0.53	0.82	1.05
10	1.45	1.03	1.69	2.23
15	2.23	1.51	2.57	3.46
20	3.03	1.98	3.47	4.74
25	3.84	2.45	4.37	6.05
30	4.66	2.92	5.29	7.36
35	5.49	3.38	6.20	8.68
40	6.33	3.83	7.11	9.96
45	7.17	4.28	8.01	11.21
50	8.02	4.72	8.89	12.39

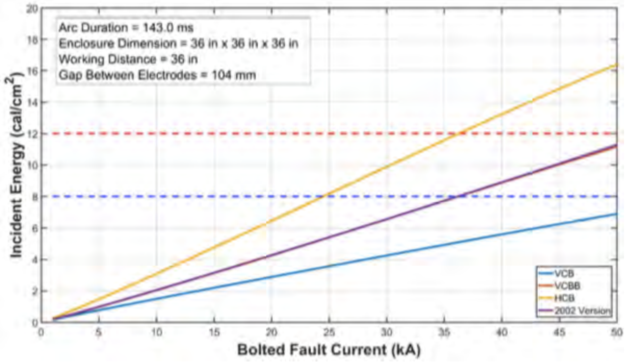

Fig. 6. Incident energy trends for 4.16-kV Switchgear using 2002 and 2018 AF model (143 ms)

and at 38 kA for the 4.16-kV switchgear, even with a 90-ms clearing time.

C. 4.16-kV Motor Controlgear Incident Energy

Faults on the line side and bus side of HV controlgear will be cleared by HV vacuum circuit breakers. Therefore, the IE results for HV controlgear is very similar to the HV switchgear. There will be a slight increase in the IE due to the controlgear having smaller enclosure dimensions than the 4.16-kV switchgear. The HV controlgear IE results are shown for a clearing time of 143 ms in Fig. 9 and Table VIII.

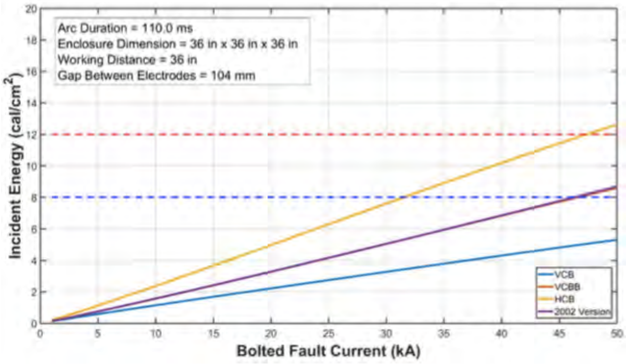

Fig. 7. Incident energy trends for 4.16-kV Switchgear using 2002 and 2018 AF model (110 ms)

TABLE V
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 4.16-KV SWITCHGEAR USING 2002 AND 2018 AF MODEL (143 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.98	0.76	0.97	1.46
10	2.04	1.48	2.03	3.07
15	3.14	2.18	3.12	4.75
20	4.26	2.87	4.25	6.45
25	5.40	3.56	5.39	8.17
30	6.56	4.24	6.55	9.88
35	7.72	4.92	7.71	11.57
40	8.90	5.59	8.87	13.23
45	10.09	6.24	10.03	14.85
50	11.28	6.89	11.18	16.40

TABLE VI
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 4.16-KV SWITCHGEAR USING 2002 AND 2018 AF MODEL (110 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.75	0.59	0.74	1.12
10	1.57	1.14	1.56	2.36
15	2.41	1.68	2.40	3.65
20	3.28	2.21	3.27	4.96
25	4.15	2.74	4.15	6.28
30	5.04	3.26	5.04	7.60
35	5.94	3.78	5.93	8.90
40	6.85	4.30	6.83	10.18
45	7.76	4.80	7.72	11.42
50	8.68	5.30	8.60	12.61

The HV controlgear IE results are shown for a clearing time of 110 ms in Fig. 10 and Table IX.

The HV controlgear IE results are shown for a clearing time of 90 ms in Fig. 11 and Table X.

It is important to note that the above IE calculations for the 4.16-kV Controlgear assumed a working distance of 36 in. This working distance is acceptable if the fault occurs at the disconnect switch (electrode configuration of HCB). However, the motor T leads terminal bus is closer to the torso of the worker than this typical value (electrode configuration of VCB). The 2002 version of IEEE 1584 did not recommend any working distance value for HV controlgear while power system software generally assumed a typical value of 18 in

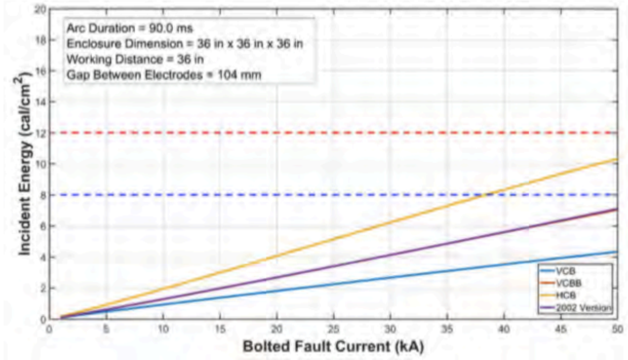

Fig. 8. Incident energy trends for 4.16-kV Switchgear using 2002 and 2018 AF model (90 ms)

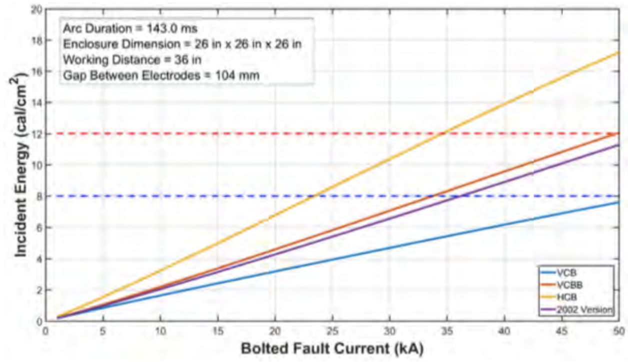

Fig. 9. Incident energy trends for 4.16-kV Controlgear using 2002 and 2018 AF model (143 ms)

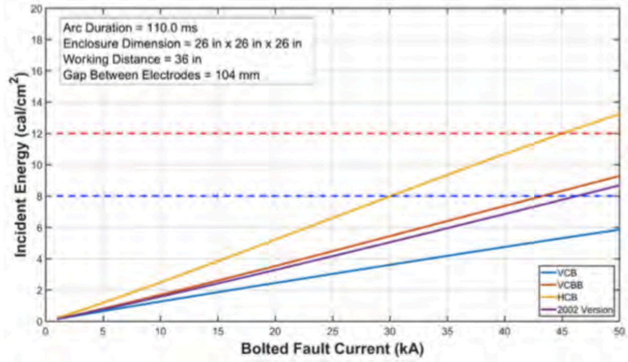

Fig. 10. Incident energy trends for 4.16-kV Controlgear using 2002 and 2018 AF model (110 ms)

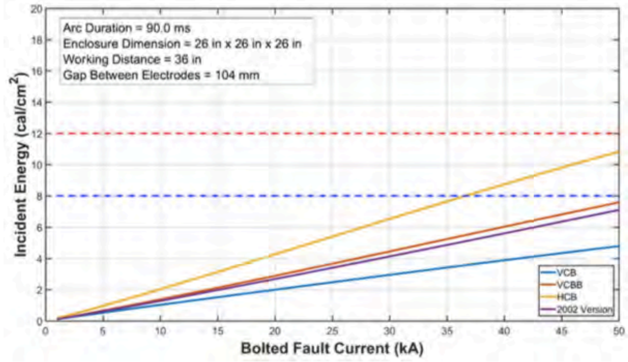

Fig. 11. Incident energy trends for 4.16-kV Controlgear using 2002 and 2018 AF model (90 ms)

TABLE VII
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 4.16-KV SWITCHGEAR USING 2002 AND 2018 AF MODEL (90 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.61	0.48	0.61	0.92
10	1.28	0.93	1.28	1.93
15	1.98	1.37	1.97	2.99
20	2.68	1.81	2.67	4.06
25	3.40	2.24	3.39	5.14
30	4.13	2.67	4.12	6.22
35	4.86	3.09	4.85	7.28
40	5.60	3.52	5.59	8.33
45	6.35	3.93	6.31	9.34
50	7.10	4.33	7.03	10.32

TABLE VIII
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 4.16-KV CONTROLGEAR USING 2002 AND 2018 AF MODEL (143 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.98	0.84	1.04	1.53
10	2.04	1.64	2.19	3.22
15	3.14	2.41	3.37	4.98
20	4.26	3.17	4.58	6.77
25	5.40	3.93	5.81	8.57
30	6.56	4.68	7.06	10.37
35	7.72	5.43	8.32	12.14
40	8.90	6.17	9.57	13.88
45	10.09	6.89	10.82	15.58
50	11.28	7.60	12.05	17.20

for HV controlgear. Therefore, careful engineering must take place to determine these values for each equipment along with possible equipment configuration. Table XI specifies the electrode configuration and working distances for these two fault locations. Two different working distances are associated with these conditions as illustrated in the table. Results are shown in Fig. 12 and Table XII for a clearing time of 90 ms.

D. 480-V Switchgear Incident Energy

In 480-V switchgear, there are two types of faults that will be cleared by different types of protection devices. Line-side faults will be cleared by the upstream HV circuit breaker on the primary of the upstream transformer, which, again, has a standard minimum clearing time of 143 ms, 110 ms with three-cycle breakers, or 90 ms with three-cycle breakers and a relay with an operating time of 30 ms. However, bus

TABLE IX
INCIDENT ENERGY LEVELS $(\mathrm{CAL/CM^2})$ FOR 4.16-KV CONTROLGEAR USING 2002 AND 2018 AF MODEL $(110\,\mathrm{MS})$

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.75	0.65	0.80	1.17
10	1.57	1.26	1.68	2.48
15	2.41	1.85	2.59	3.83
20	3.28	2.44	3.52	5.21
25	4.15	3.02	4.47	6.59
30	5.04	3.60	5.43	7.97
35	5.94	4.18	6.40	9.34
40	6.85	4.74	7.36	10.68
45	7.76	5.30	8.32	11.98
50	8.68	5.85	9.27	13.23

TABLE X
INCIDENT ENERGY LEVELS $(\mathrm{CAL/CM^2})$ FOR 4.16-KV CONTROLGEAR USING 2002 AND 2018 AF MODEL $(90\,\mathrm{MS})$

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.61	0.53	0.66	0.96
10	1.28	1.03	1.38	2.03
15	1.98	1.52	2.12	3.13
20	2.68	2.00	2.88	4.26
25	3.40	2.47	3.66	5.39
30	4.13	2.95	4.44	6.52
35	4.86	3.42	5.23	7.64
40	5.60	3.88	6.02	8.74
45	6.35	4.34	6.81	9.80
50	7.10	4.79	7.59	10.83

faults will be cleared by the incomer breakers of the LV switchgear, which has a standard minimum clearing time of $50\,\mathrm{ms}$ (i.e., ERMS). This means the worst-case scenarios are associated with line-side faults. Fig. 13 shows the different between 2002 AF model and 2018 AF model IE results for a typical enclosure of $20\,\mathrm{in} \times 20\,\mathrm{in} \times 20\,\mathrm{in}$.

Unlike the 2002 model, the trends in the 2018 model do not have a linear relationship with the short-circuit current for low-voltage switchgear. Therefore, the incident energy curve flattens with very high short-circuit currents. Table 13 lists the results for some bolted fault currents.

Fig. 14 and Table XIV provide the incident energy results for faults in LV switchgear with a clearing time of $110\,\mathrm{ms}$.

Fig. 15 and Table XV provide the incident energy results for faults in LV switchgear with a clearing time of $90\,\mathrm{ms}$.

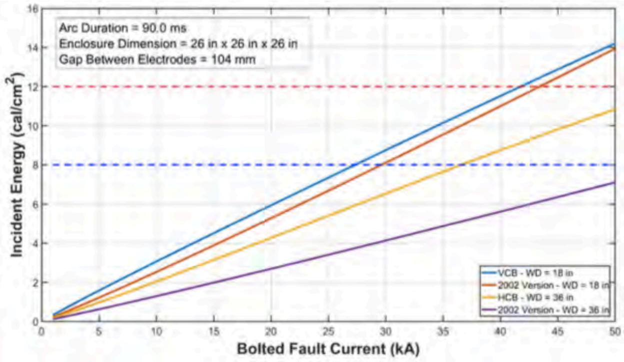

Fig. 12. Incident energy trends for 4.16-kV Controlgear for more practical cases $(90\,\mathrm{ms})$

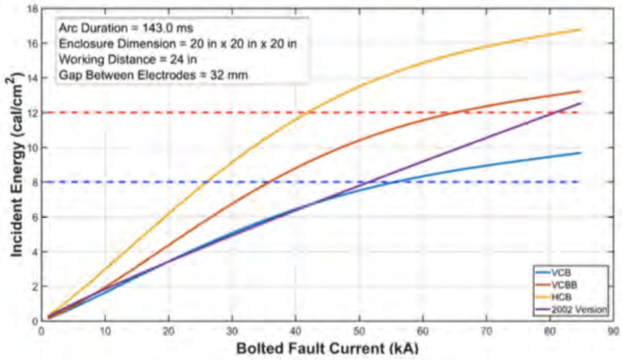

Fig. 13. Incident energy trends for 480-V Switchgear using 2002 and 2018 AF model $(143\,\mathrm{ms})$

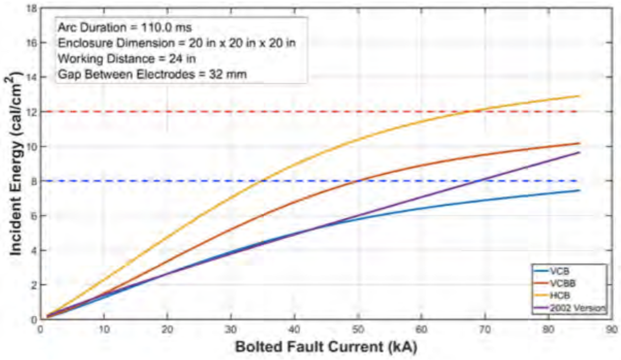

Fig. 14. Incident energy trends for 480-V Switchgear using 2002 and 2018 AF model $(110\,\mathrm{ms})$

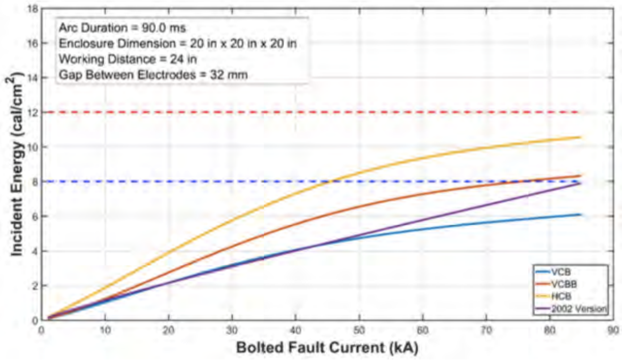

Fig. 15. Incident energy trends for 480-V Switchgear using 2002 and 2018 AF model $(90\,\mathrm{ms})$

TABLE XI
POSSIBLE ELECTRODE CONFIGURATION AND WORKING DISTANCES FOR 4.16-KV CONTROLGEAR

Fault Location	Electrode Configuration	Working Distance
Motor T Leads	VCB	18 in
Disconnect Switch	HCB	36 in

TABLE XII
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 4.16-KV CONTROLGEAR FOR MORE PRACTICAL CASES
(90 MS)

I_{bf} (kA)	2002 WD= 18 in	VCB WD= 18 in	2002 WD= 36 in	HCB WD= 36 in
5	1.21	1.57	0.61	0.96
10	2.52	3.05	1.28	2.03
15	3.88	4.50	1.98	3.13
20	5.26	5.93	2.68	4.26
25	6.67	7.34	3.40	5.39
30	8.10	8.74	4.13	6.52
35	9.54	10.14	4.86	7.64
40	10.99	11.51	5.60	8.74
45	12.46	12.87	6.35	9.80
50	13.94	14.20	7.10	10.83

E. 480-V Motor Controlgear Incident Energy

The analysis of LV controlgear is similar to LV switchgear with the following differences:

- Line and bus faults will be cleared by LV circuit breaker located in the upstream switchgear (50 ms with ERMS clearing time).
- Enclosure dimensions are smaller than the LV switchgear compartments.
- Working distance is reduced from 24 in to 18 in.

The results of the incident energy are shown in Fig. 16 and Table XVI for all metal-box configurations.

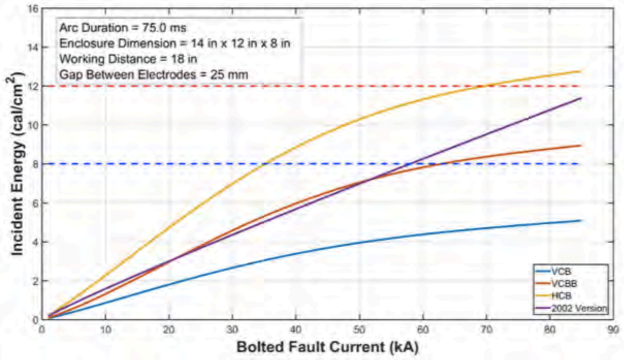

Fig. 16. Incident energy trends for 480-V Controlgear using 2002 and 2018 AF model (75 ms)

TABLE XIII
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 480-V SWITCHGEAR USING 2002 AND 2018 AF MODEL
(143 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.98	0.76	0.86	1.41
15	2.63	2.53	3.13	4.58
25	4.17	4.27	5.58	7.70
35	5.65	5.78	7.82	10.43
45	7.08	7.01	9.65	12.61
55	8.48	7.95	11.02	14.23
65	9.86	8.65	11.99	15.36
75	11.22	9.20	12.68	16.16
85	12.55	9.68	13.23	16.79

TABLE XIV
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 480-V SWITCHGEAR USING 2002 AND 2018 AF MODEL
(110 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.75	0.58	0.66	1.08
15	2.03	1.95	2.41	3.52
25	3.21	3.28	4.29	5.92
35	4.34	4.45	6.02	8.03
45	5.45	5.39	7.42	9.70
55	6.52	6.11	8.48	10.94
65	7.58	6.66	9.22	11.82
75	8.63	7.08	9.75	12.43
85	9.66	7.45	10.17	12.91

Similar to HV controlgear, careful consideration must be given to defining the practical cases and the associated working distances. HCB configuration could be removed since this configuration is not possible in the LV MCC (Refer to Annex C of IEEE 1584-2018). It is worth noting that both shallow (≤ 8 in) and deep (> 8 in) LV controlgear can exist, which results in a different enclosure correction factor (CF). Moreover, a LV controlgear contains several compartments with different dimensions in one assembly. The enclosure with the worst-case incident energy must be considered for the entire electrical equipment. Table XVII lists typical dimensions for enclosures of different NEMA starter sizes that can exist in one LV controlgear assembly. The analysis will be conducted for these enclosures assuming both deep and shallow enclosures.

Fig. 17 and Fig. 18 show the incident energies for different enclosures for the configuration of VCBB against the incident energy from the IEEE 1584-2018 recommended typical enclosure dimensions for LV controlgear for the shallow and deep enclosures respectively. All these trends are compared

TABLE XV
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 480-V SWITCHGEAR USING 2002 AND 2018 AF MODEL (90 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.62	0.48	0.54	0.89
15	1.66	1.59	1.97	2.88
25	2.62	2.69	3.51	4.85
35	3.55	3.64	4.92	6.57
45	4.46	4.41	6.07	7.94
55	5.34	5.00	6.94	8.95
65	6.21	5.45	7.55	9.67
75	7.06	5.79	7.98	10.17
85	7.90	6.10	8.32	10.57

TABLE XVI
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 480-V CONTROLGEAR USING 2002 AND 2018 AF MODEL (75 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
5	0.83	0.40	0.58	1.08
15	2.29	1.33	2.12	3.50
25	3.68	2.24	3.78	5.88
35	5.02	3.04	5.30	7.97
45	6.33	3.68	6.54	9.62
55	7.62	4.17	7.46	10.84
65	8.89	4.54	8.12	11.70
75	10.14	4.83	8.58	12.29
85	11.38	5.08	8.94	12.76

to the IEEE 1584-2002 AF model.

It is worth noting that the results for NEMA size 0 to NEMA size 4 on deep LV controlgear are the same since they all have the same enclosure correction factor. Overall, the results of the 2018 model with different sizes are still are comparable to the values calculated in the 2002 model. In general, the worst-case IE associated with the 2018 model for LV controlgear is with VCBB configuration with typical enclosure size recommended by IEEE 1584-2018 ($H = 14\,\text{in} \times W = 12\,\text{in} \times D > 8\,\text{in}$) which is between the sizes of NEMA starter 4 and NEMA starter 5, which are very common in LV controlgear assemblies.

F. LV Panelboards Incident Energy

For a 400-A LV panelboard, there are two areas of interest: clearing faults with high arcing current and clearing faults with low arcing currents. Since the clearing protective device of the panelboard does not have a definite time overcurrent characteristic, the arcing current variation factor becomes important for faults with low arcing current. However, for high arcing currents (higher than $20\times$ the MCCB trip rating), a worst-case clearing time of 50 ms can be considered. This leads to a low incident energy for all possible configuration (VCB, VCBB and HCB). Fig. 19 and Table XVIII compare the 2002 AF model calculations for system voltage of 480 V (worst-case scenario). Similar to the LV controlgear case, HCB will not appear in the panelboard and analysis can be restricted to VCB and VCBB electrode configurations.

For the practical LV panelboards with 42 branch circuits ($72\,\text{in} \times 20\,\text{in}$), the VCB and VCBB configuration are within acceptable limits. However, for faults with arcing currents less than 7 kA ($17.5\times$ the MCCB trip rating), the analysis is carried out differently. The VCBB electrode configuration will result in a higher arcing current than the VCB electrode

TABLE XVII
TYPICAL DIMENSIONS FOR DIFFERENT NEMA STARTERS

NEMA Size	Dimensions $H \times W \times D$ (in)
0	$6 \times 12 \times 8$
1 and 2	$12 \times 12 \times 8$
3 and 4	$18 \times 12 \times 8$
5	$36 \times 12 \times 8$
6	$42 \times 12 \times 8$
7	$72 \times 12 \times 8$

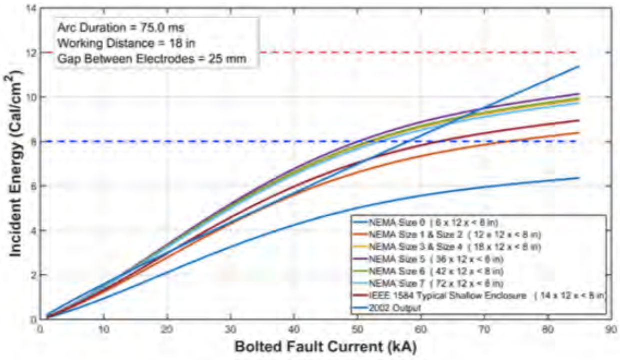

Fig. 17. Incident energy trends for 480-V Controlgear for different NEMA starter sizes (shallow)

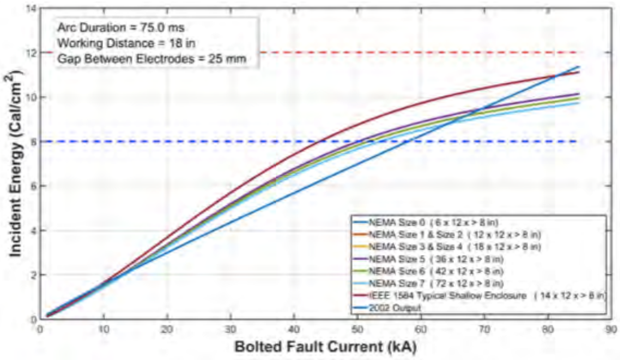

Fig. 18. Incident energy trends for 480-V Controlgear for different NEMA starter sizes (deep)

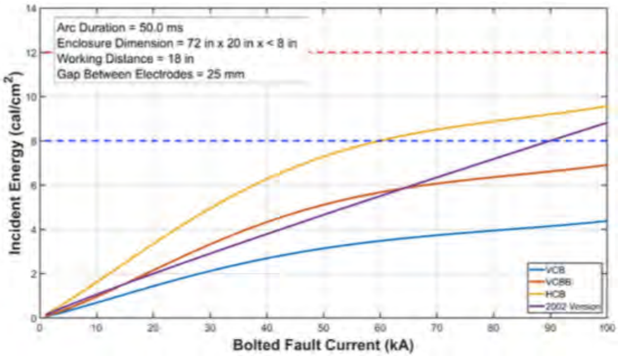

Fig. 19. Incident energy trends for 480-V panelboards with different configurations

TABLE XVIII
INCIDENT ENERGY LEVELS (CAL/CM^2) FOR 480-V PANELBOARDS USING 2002 AND 2018 AF MODEL (50 MS)

I_{bf} (kA)	2002	VCB	VCBB	HCB
10	1.05	0.68	0.95	1.60
20	1.99	1.43	2.14	3.34
30	2.90	2.11	3.32	4.94
40	3.78	2.69	4.32	6.27
50	4.65	3.14	5.10	7.28
60	5.50	3.48	5.67	8.01
70	6.34	3.73	6.07	8.51
80	7.18	3.94	6.36	8.88
90	8.00	4.14	6.61	9.20
100	8.82	4.38	6.91	9.57

configuration because of the arcing current variation factor, which is 0.882 for VCBB at the 480-V level. Therefore, this case is compared to the 2002 AF model for currents less than 7 kA. Table XIX and Table XX present the results for average arcing current (AAC) and reduced arcing current (RAC) for the 2002 AF model and the VCBB configuration of 2018 AF model, respectively, for a panelboard protected by an MCCB with a trip rating of 400 A. The final results are shown in Fig. 20 for the low arcing-current region.

G. Arc Flash Boundary Impact

The arc flash boundary (AFB) calculations were updated also in IEEE 1584-2018. The IEEE 1584-2018 equations yield smaller AFB than the IEEE 1584-2002 calculations for all electrical equipment. It is worth noting that the IEEE1584-2018 AFB equations are less dependent on the resultant incident energy than the IEEE 1584-2002 equations, which were linearly dependent on the incident energy. Therefore, no impact is expected on the arc flash boundary results.

IV. WAY FORWARD

The following conclusions can be drawn from the comparison of the IEEE1584-2018 with IEEE 1584-2002:

TABLE XIX
INCIDENT ENERGY LEVELS (CAL/CM^2) WITH AAC AND RAC IN 2002 AF MODEL

I_{bf} (kA)	AAC (kA)	RAC (kA)	RAC CT (ms)	RAC IE
0.5	0.475	0.431	2000	2.220
1.0	0.917	0.780	2000	4.210
1.5	1.297	1.102	2000	6.122
2.0	1.658	1.410	2000	7.984
2.5	2.007	1.706	2000	9.811
3.0	2.345	1.993	2000	11.610
3.5	2.675	2.273	2000	13.387
4.0	2.998	2.548	2000	15.143
4.5	3.315	2.818	2000	16.883
5.0	3.627	3.083	2000	18.608
5.5	3.935	3.345	2000	20.320
6.0	4.239	3.603	2000	22.020
6.5	4.539	3.858	2000	23.710
7.0	4.835	4.110	50	0.635

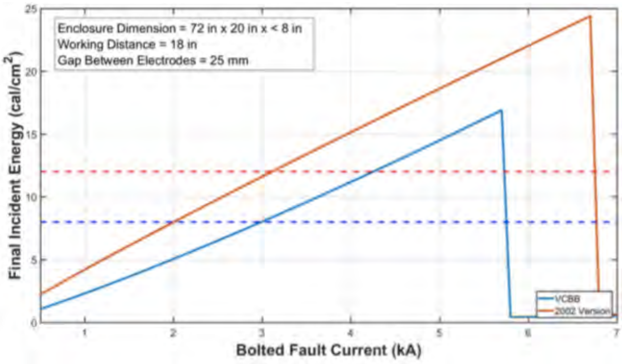

Fig. 20. Incident energies for low-arcing current in VCBB configuration with 2002 model

1) The IEEE1584-2018 calculations are more complex than the IEEE 1584-2002 calculations. To ensure consistent application of IEEE 1584-2018, the company needs to develop a detailed best practice to guide both company engineers and design offices.
2) For the most part, the IEEE 1584-2018 IE clearly will increase compared to the IEEE 1584-2002 IE. To comply with the arc-flash safety requirement of 8 cal/cm^2, the short-circuit rating must be restricted in most electrical equipment. However, if the maximum allowed incident energy level increased from 8 cal/cm^2 to 12 cal/cm^2, as requested by company engineering standards, the impact of the standards will be greatly reduced if not eliminated. It is worth noting that PPE associated with both incident energy levels are the same and considered to be level B as per company safety instructions.

TABLE XX
INCIDENT ENERGY LEVELS ($\mathrm{CAL/CM^2}$) WITH AAC AND RAC IN 2018 AF MODEL

I_{bf} (kA)	AAC (kA)	RAC (kA)	RAC CT (ms)	RAC IE
0.5	0.392	0.346	2000	1.069
1.0	0.775	0.684	2000	2.315
1.5	1.159	1.022	2000	3.650
2.0	1.544	1.362	2000	5.052
2.5	1.931	1.704	2000	6.512
3.0	2.321	2.047	2000	8.022
3.5	2.714	2.394	2000	9.578
4.0	3.109	2.742	2000	11.176
4.5	3.507	3.093	2000	12.812
5.0	3.907	3.446	2000	14.484
5.5	4.310	3.802	2000	16.191
6.0	4.715	4.159	50	0.448
6.5	5.122	4.518	50	0.492
7.0	5.532	4.879	50	0.537

V. CONCLUSION

In summary, the IE resulting from the IEEE 1584-2018 model is much different that the IE resulting from the IEEE 1584-2002 model. In many cases, the IE will increase beyond the current values on most electrical equipment. Several solutions can be implemented to minimize the investment needed to comply with IEEE 1584-2018 and to avoid restricting the short-circuit rating of electrical equipment, including relaxing the maximum allowed IE from $8\,\mathrm{cal/cm^2}$ to $12\,\mathrm{cal/cm^2}$. Moreover, shorter clearing time can be implemented to reduce IE by specifying 3-cycle circuit breaker and faster high-speed relays (i.e., less than $50\,\mathrm{ms}$ operating time) which is currently allowed but not required by company standards.

VI. VITAE

Abdullah Al-Nujaimi (M'12) received Bachelor's (First Hons.) and Master's degrees in electrical engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in 2013 and 2018 respectively. In July 2013, he joined Saudi Aramco working for the Consulting Services Department as a Power System Analysis and Design Engineer. He also worked with Ras Tanura Refinery as a Technical Support Engineer for two years. His primary interests are power systems studies, power system quality, and electrical equipment troubleshooting and commissioning.

Cory A. Helfrich (S88, M'99, SM'14) received a B.S.E.E. degree from the University of Saskatchewan in 1989. Following ten years with The Dow Chemical Company in Fort Saskatchewan, Alberta, he joined the Saudi Arabian Oil Company in Dhahran, Saudi Arabia, in 1999. He is currently working as an Engineering Specialist in the corporate Consulting Services Department. Mr. Helfrich is a Professional Engineer in the province of Alberta.

Rakan El-Mahayni (IEEE S'04, M'07, SM'09) is an Electrical Engineer with Saudi Aramco. In 1998, he graduated from University of Damascus, Syria, and joined Siemens AG as a Testing and Commissioning Engineer for the 400-kV interconnection projects between Middle East and Europe. In 2002, he joined Eaton corporation as a Field Service Engineer. In 2005, he joined the Power System Engineering Department as a Power System Engineer. In 2012, he joined Saudi Aramco's Consulting Services as an Electrical Engineer providing technical consultancy to various Saudi Aramco operations. He is a licensed Professional Engineer in CA, and received a MSEE from California State University, Sacramento, in 2006.

Rashid Al-Rashidi received his B.S. in Electrical Engineering from King Fahd University in Dhahran, Saudi Arabia in 2008 and MS degree from Michigan Technological University in USA in 2014. In 2008, he Joined the Saudi Aramco's Consulting Services Department as an Electrical Engineer. Mr. Rashidi is a licensed professional engineer in Saudi Arabia since 2012 and he specializes in power system analysis and design.

VII. REFERENCES

[1] R. H. Lee, "The Other Electrical Hazard: Electric Arc Blast Burns," in IEEE Transactions on Industry Applications, vol. IA-18, no. 3, pp. 246-251, May 1982, doi: 10.1109/TIA.1982.4504068.

[2] *IEEE Guide for Performing Arc Flash Hazard Calculations*, IEEE Std 1584-2002.

[3] *IEEE Guide for Performing Arc-Flash Hazard Calculations*, IEEE Std 1584-2018.