Development of Improved High Energy Arcing Fault (HEAF) Target Damage Thresholds and Zone of Influence (ZOI) Models

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ABSTRACT

In order to improve the realism of High Energy Arcing Fault (HEAF) hazard modelling, the U.S. Nuclear Regulatory Commission (NRC), in cooperation with the Electric Power Research Institute (EPRI), has developed improved HEAF target fragility estimates and a zone of influence (ZOI) model. In the context of this project, the target damage threshold (i.e., target fragility) is determined by assessing the damage threshold at which the target of interest can no longer perform its function. The ZOI defines the region in which the hazard exceeds this damage threshold. This work, being performed under the NRC's HEAF research project plan, advances the understanding of the early HEAF models contained in NUREG/CR-6850 / EPRI 1011989, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, to better reflect arc characteristics (such as duration, power, and location); enclosure configuration; and electrical cable target fragilities. Updated fragility data was obtained from physical testing that assessed the performance of common targets to very short duration, high energy exposures expected during a HEAF. This testing information, along with relevant operating experience and the current state-of-knowledge, was evaluated by a joint NRC-EPRI working group to reach consensus positions on the fragility of various electrical cable configurations exposed to a HEAF. To develop the improved ZOI model, the joint NRC-EPRI working group relied on computational fluid dynamics simulations using the National Institute of Standards and Technology (NIST) Fire Dynamics Simulator (FDS) to calculate the thermal exposure levels in the vicinity of a HEAF. The ZOI was determined based on where thermal exposure exceeds the fragility limits for targets exposed to the HEAF. This method was applied to a large matrix of simulations that varied the fault duration, power, location, electrode composition, and type of equipment. This approach allowed the NRC-EPRI working group to construct a detailed tabulation of ZOIs for each simulation in the matrix and improves the realism of the ZOIs. To provide independent corroborating evidence for the model, the NRC performed additional confirmatory analysis using a modified IEEE 1584 Arc Flash model. The confirmatory NRC calculations showed good agreement with the results of the FDS simulations and provided further confidence in the new ZOI results developed by the joint NRC-EPRI working group.

INTRODUCTION

Electrical system failure HEAF events are energetic electrical arcing faults that can lead to the rapid release of energy. This energy release can result in high heat fluxes in the vicinity of the HEAF failure, vaporization of metal, release of ionized gas and smoke, and mechanical shocks to nearby equipment. These effects can result in the loss of functionality of safety critical components in the vicinity of the HEAF, which in combination with the associated electrical system perturbations, can initiate a plant shutdown (e.g., a reactor or turbine trip) and degrade accident mitigation capability. Operating experience has shown that HEAF can be a significant contributor to plant risk [1], [2], [3].

In the United States, the fire protection regulations contained 10 CFR 50.48, “Fire Protection,” require a nuclear power plant to implement a fire protection plan that meets the requirements of 10 CFR 50, Appendix A, General Design Criterion (GDC) 3, “Fire protection”. GDC 3 specifies, in part, that nuclear power plant systems, structures, and components important to safety be designed and located to minimize the probability and effect of fires and explosions. The NRC’s regulations provide two options for meeting this requirement: (1) a deterministic option described under 10 CFR 50.48(b) that references the requirements contained in 10 CF R 50, Appendix R, “Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979”, or (2) a risk-informed, performance-based, option described under 10 CFR 50.48(c) that allows use of National Fire Protection Association Standard NFPA 805, “Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition” [4], with some exceptions. As described in the Statements of Consideration for the final rulemaking approving use of NFPA 805 [5], the NFPA 805 methodology incorporates a number of performance-based attributes, including identification of objective performance criteria and flexibility in the means by which a licensee determines how these criteria are met. The NRC provides guidance for implementing the NFPA 805 option in Regulatory Guide (RG) 1.205, “Risk-Informed, Performance-Based Fire Protection for Existing Light-Water Nuclear Power Plants [6]”. Further, the NRC endorsed NUREG/CR-6850/EPRI 1011989, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Final Report” [7] and its Supplement 1 [8], as one acceptable method for conducting a Fire PRA (*P*robabilistic *R*isk *A*ssessment). Guidance for HEAF events is provided in both NUREG/CR-6850 and its supplement. For example, the following guidelines are provided in establishing a zone of influence (ZOI), within which equipment is assumed to be damaged for the purposes of the probabilistic risk assessment (PRA) during a HEAF event:

- For HEAF events within an electrical cabinet, any unprotected cables in the first overhead cable tray within 1.5 m (5 ft) vertical distance of the top of the cabinet and 0.3 m (1 ft) horizontally from the cabinet face will be within the ZOI and assumed to be damaged. Additionally, any equipment within 0.9 m (3 ft) horizontal distance from the cabinet front or rear panel and at or below the top of the cabinet will be within the ZOI (NUREG/CR-6850, Volume 2, Appendix M [7]).
- For HEAF events within an iso-phase bus duct, the ZOI is assumed to be a sphere centered on the fault point and measuring 1.5 m (5 ft) feet in radius (NUREG/CR-6850, Supplement 1 [8]).
- For HEAF events within non-iso phase bus ducts, the ZOI includes: (1) a downward expanding cone from the point of arcing enclosing a total solid angle of 30° to a maximum diameter of 6.0 m (20 ft); (2) a sphere with a radius of 0.45 m (1.5 ft) from the point of arcing (assumed to be the center of the bus duct) (NUREG/CR-6850, Supplement 1 [8].

A limitation of the NUREG/CR-6850 ZOI approach is that it is insensitive to a number of factors which influence the potential of hazard of a HEAF, including target equipment fragility, voltage level, amperage, and duration of the arcing event (which is related to the time needed for clear an electrical fault). In addition, recent operating experience [9], has suggested that materials used to construct conductors (e.g., copper or aluminum) and electrical enclosures (e.g., steel or aluminum) may also influence the magnitude of the HEAF hazard. These factors may either increase or decrease the ZOI size, depending on the specific HEAF conditions. To address this issue, the U.S. NRC, in collaboration with the NIST and the EPRI, implemented a research plan to improve the realism of HEAF modelling. This research plan leveraged physical testing, computational tools, and improved fragility data to update the HEAF methods described in NUREG/CR-6850 and its supplement. Three specific activities are described in this paper:

- **Updated fragility modelling**: A joint NRC and EPRI working group used updated fragility data, obtained from physical testing, and operating experience insights to reach consensus positions on the fragility of various electrical cable configurations exposed to a HEAF.
- **Computational fluid dynamics simulation to update ZOIs**: The joint NRC-EPRI working group relied on computational fluid dynamics simulations using the NIST Fire Dynamics Simulator (FDS) to calculate the thermal exposure levels in the vicinity of a HEAF. The ZOI was determined based on where thermal exposure exceeds the fragility limits for targets exposed to the HEAF. This method was applied to a large matrix of simulations that varied the fault duration, power, location, electrode composition, and type of equipment. This approach allowed the NRC-EPRI working group to construct a detailed tabulation of ZOIs for each simulation in the matrix and to improve the realism of the ZOIs.
- **Confirmatory ZOI analysis**: To provide independent corroborating evidence for the model, the NRC performed additional confirmatory analysis using a modified IEEE 1584 arc flash model. The confirmatory NRC calculations showed good agreement with the results of the FDS simulations and provided further confidence in the new ZOI results developed by the joint NRC-EPRI working group.

These research activities are described in more detail in the following sections.

UPDATED FRAGILITY MODELLING

The objective of this portion of the research project plan was to establish the target fragilities for equipment that might be present within the HEAF ZOI. HEAF events, which generate short duration high heat fluxes, have different characteristics than traditional combustion fires which have longer duration but lower heat fluxes. Therefore, the fragility for equipment, particularly cables, was examined under the higher heat fluxes from HEAF exposures.

Cable Fragility Experiments

In support of this work, fragility testing was conducted at the Solar Furnace at Sandia National Laboratories (SNL) [10]. The Solar Furnace facility consists of a heliostat containing a total reflective surface of 55 m^2 which directs sunlight to a parabolic reflector. This facility is capable of concentrating sunlight to generate a heat flux of up to 6 MW/m^2 within a circle that is approximately 5 cm in diameter.

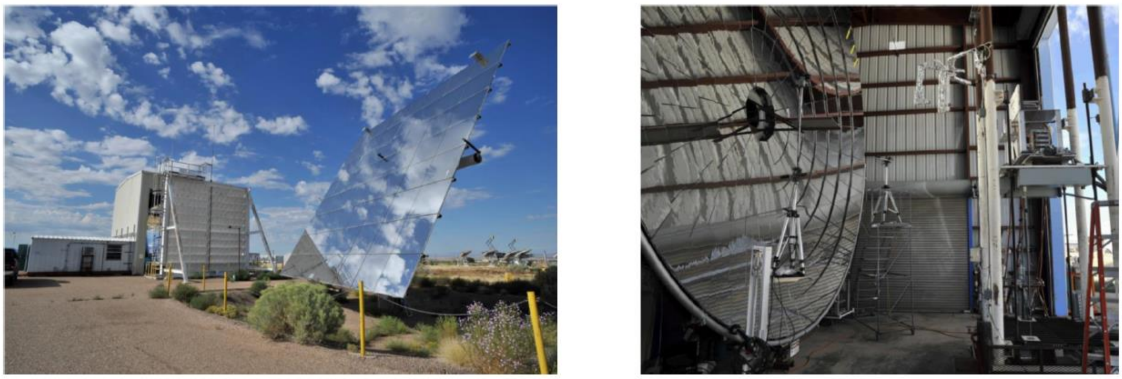

Figure 1 Solar Furnace at Sandia National Laboratories

Both thermoplastic and thermoset cables were evaluated. The distinction between these cable types is that thermoplastic materials soften, flow, or distort when subjected to sufficient heat and pressure while thermoset cables do not. The failure threshold for thermoplastic cables is generally lower than thermoset cables; for example, Appendix H of NUREG/CR-6850 [7], provides generic screening non-HEAF fire scenario fragilities for TP cables of > 6 kW/m^2 and > 205 °C and fragilities of > 11 kW/m^2 and 330 °C for TS cables. However, the underlying physics of failure used to determine cable fragilities for non-HEAF events, may not accurately capture the HEAF phenomena such as high heat fluxes for a short duration. The Solar Furnace testing varied the heat flux, cable material (thermoplastic and thermoset), and exposure duration. In addition, the heat flux profile was dynamically adjusted during some of the tests to better represent secondary heat fluxes to the target representing combustion of surrounding materials and thermal radiation from heated surfaces following the initial HEAF event.

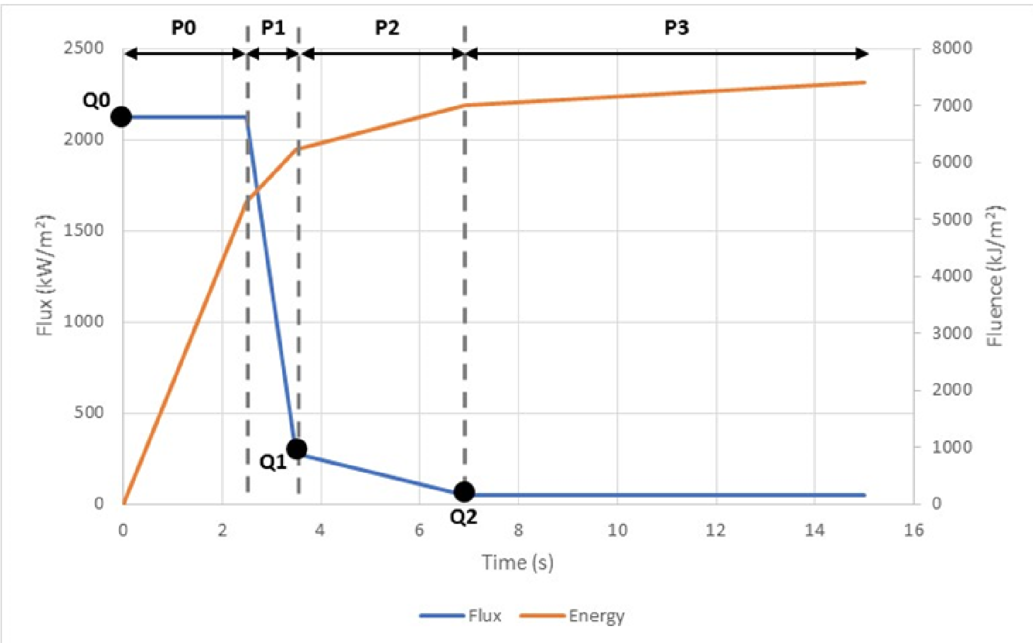

Figure 2 Typical Solar Furnace testing heat flux profile

Several different cable failure criteria were evaluated during the testing such as cable ignition, damage as a function of total energy, electrical failure of cables, and temperature. However, some criteria did not provide repeatable results at small scale (e.g., sustained ignition) and others were not reliable indicators of failure during the time scale of a HEAF event (e.g., electrical failure and sub-jacket temperature). Based on the testing results, it was determined that cable jacket damage resulting in exposure of the insulated cable wiring was a reliable metric for cable failure and provided repeatable data for tests conducted with different levels of heat flux. Because the cable jacket material tends to be black and the conductor insulation is multi-coloured, it is relatively easy to visually determine that the jacket is breached. Example test results for a thermoplastic cable exposed to an incident energy level of approximately 7 MJ/m^2 (Test 1-22, showing jacket damage), 24 MJ/m^2 (test 1-32, showing wiring insulation exposure), and 206 MJ/m^2 (test 1-09, showing wire conductor exposure) are shown in Figure 3.

Figure 3 Post-test thermoplastic cable following incident energy exposure to 7 MJ/m^2 (test 1-22), 24 MJ/m^2 (1-32), and 206 MJ/m^2 (test 1-09)

A total of 38 solar furnace cable tests were conducted, and the data was analysed to categorize the results into jacket damage, insulation exposure, and conducting wire exposure. Figure 4 provides plots of the thermoplastic (TP) and thermoset (TS) cable test results for initial heat fluxes greater than 1 MW/m^2, which were considered to be more representative of an actual HEAF event. These plots show the incident energy at which jacket damage, insulation exposure, and wire exposure were found.

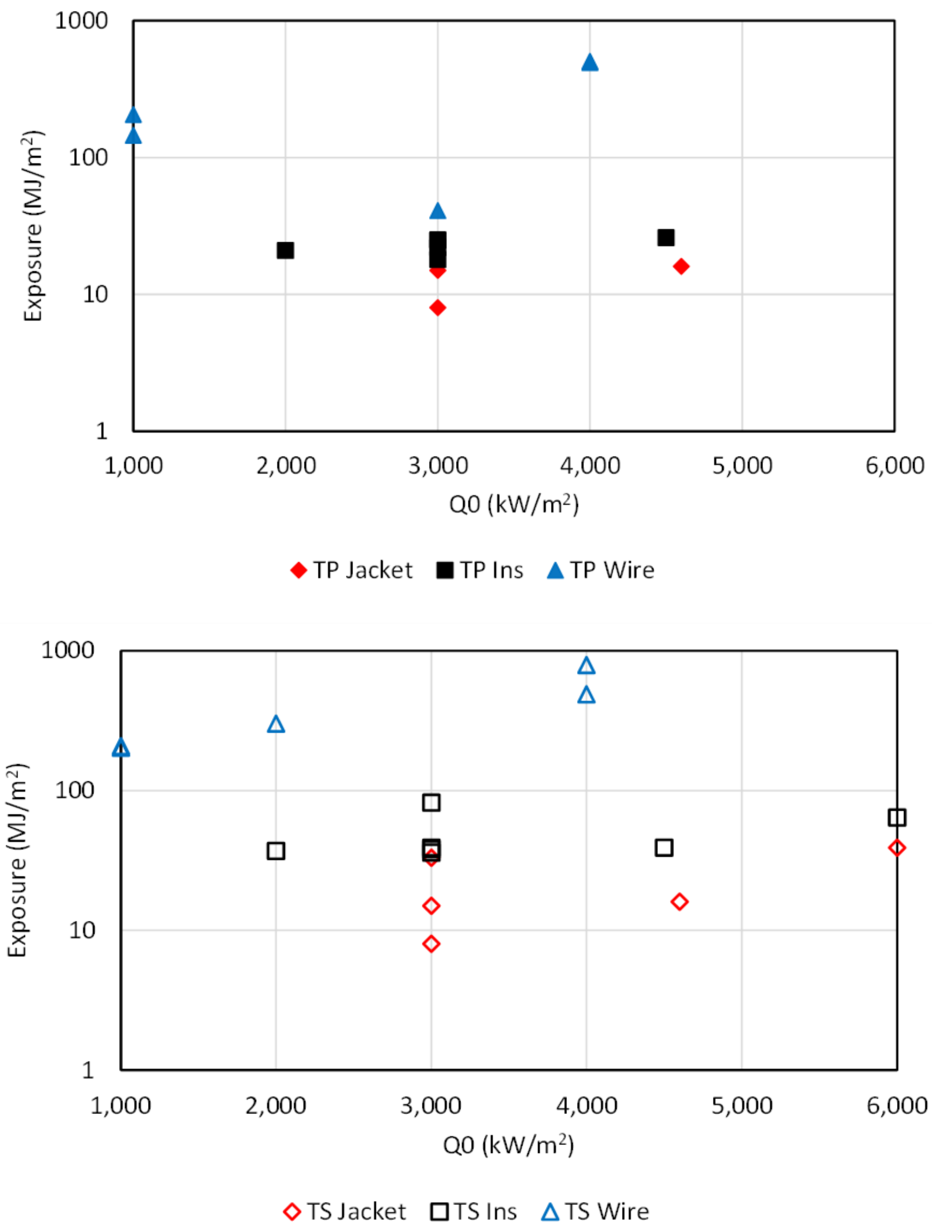

Figure 4 Results for thermoplastic (TP, top) and thermoset (TS, bottom) cables plotting incident energy for jack damage, insulation exposure, and wire exposure

Fragility Working Group

A joint NRC and EPRI working group evaluated the results of the solar furnace testing, in addition to operating experience (e.g., [1], [2], [3], and [9], HEAF related testing (e.g., [11], [12], and [13]), and the current state of knowledge to develop a consensus model for HEAF target fragilities. Results from this testing, along with the full- and medium-scale data were then used to develop a fragility model by the joint NRC/EPRI working group [14]. The working group evaluated damage by considering both the cable electrical functionality and potential for fire ignition. Further, the working group focused on electrical cable (control, power, and instrumentation) fragilities since these were considered to be the most common target assessed for Fire PRA. In addition, the working group developed fragilities for electrical bus ducts and provided guidance for crediting electric raceway fire barrier systems.

The working group team members were assigned specific roles supporting the expert elicitation process, but some flexibility in the process was retained to expedite determinations when consensus could be reached quickly. The working group roles included the following specific activities:

- Proponents: technical experts who developed, presented, and defended a proposal to the working group members. The proponents were organized into two different teams, each tasked with developing a proposal for each area requiring consensus
- Technical evaluators and integrators: technical experts without a vested interest in the development of any proposal and therefore were able to objectively evaluate the proposals, views, and available data to inform their decision. The technical evaluators and integrators were also responsible for developing a working group consensus.
- Resource experts: Subject matter experts with detailed knowledge of the data sets, experimentation, instrumentation, physics, modelling, or other discipline related to target fragility of specific devices, HEAF testing, or phenomena.

The working group approach consisted of the following key steps:

- Proposal development: Each of the proponent teams developed a proposal to address a specific technical issue
- Weekly meetings: The proposals were presented to the full working group during weekly meetings, which allowed working group members to ask questions and provide feedback on the proposals
- Consensus: The technical evaluators and integrators caucused to reach agreement on the path forward on each issue. The path forward involved selection of one of the proposals, combining the proposals to use key attributes of each, or requesting specific revisions to a proposal. There were no cases where the working group was unable to eventually reach a consensus position.

It is important to note that the working group focused on fragilities associated with the initial HEAF event. However, a full assessment of HEAF risk requires a two-step process which considers the immediate failures caused by the HEAF followed by an assessment of subsequent impacts from induced thermal fires. The HEAF fragility work considered the potential for a HEAF event to lead to sustained ignition of electrical cable fire and any ensuing thermal fires are addressed by the HEAF PRA method.

Fragility Results

Based on application of the consensus process, the NRC-EPRI working group reached the following conclusions on cable fragility [14]:

- The threshold for electrical failure/damage of thermoplastic jacketed cables is 15 MJ/m² and the threshold for thermoset jacketed cables is 30 MJ/m².
- Sustained ignition is assumed for cables within the enclosure of origin (e.g., internal cables and components within switchgear and load centers).
- For cables outside of the enclosure of origin, but within the postulated HEAF ZOI, no sustained ignition is assumed.

The working group also evaluated protective feature capabilities including electrical raceway fire barrier systems (ERFBS, also referred to as “fire wraps”), electrical raceway protection (e.g., conduit and cable tray covers) and bus duct damage limits.

In evaluating ERFBS, the working group considered the thermal protective properties of the barrier system (i.e., its ability to limit temperature rise on the protected side of the barrier during a fire) and the mechanical response during a HEAF event. The working group concluded that a 1 hour rated ERFBS is capable of protecting enclosed cables located within the HEAF zone of influence (but outside the enclosure where the HEAF originated) such that the protected cables are not damaged, ignited, or contribute to the fire load. Cables within a rated ERFBS inside an electrical enclosure are assumed to be damaged, but not ignited.

The working group evaluated the thermal and mechanical protection afforded by various types of conduits and cable tray covers. With regard to thermal protection, the working group believed that while some conduit configurations may provide some increase in thermal protection, several factors offset this benefit. For example, the increased surface area associated with the conduit (which can increase thermal load on the protected cables) and the ability of the conduit to retain heat following the HEAF event can lead to additional heat flux exposure for the protected cables. Therefore, the working group concluded that there was insufficient information to credit conduit with providing any additional protection during a HEAF. The working group used a similar process to evaluate cable tray top and bottom covers and for similar reasons concluded that no additional credit for these covers was warranted during a HEAF event. As such, cables in conduits and cables in trays with a cover should use the thermoplastic (15 MJ/m^2) and thermoset (30 MJ/m^2) fragility criteria.

Evaluation for bus ducts was more complicated because there is not an existing consensus on the fragility limits for electrical bus bars. The working group considered the capability of bus bar insulation (e.g., Noryl, a polymer-based material developed by General Electric used as an insulating bus bar sleeving) and the impact of hot gases and aerosols on bus bars following duct breach and concluded that bus duct failure would lead to immediate bus bar failure. The working group then used several methods to evaluate the thermal capability of bus ducts, including simplified energy balance calculations and use of a computational fluid dynamics (CFD) thermal hydraulic computer code. The analysis methods were in general agreement and the working group concluded that the fragility limit for steel bus ducts was 30 MJ/m^2 and 15 MJ/m^2 for aluminum ducts.

UPDATED ZONE OF INFLUENCE MODEL USING FDS SIMULATIONS

The objective of this work was the development of a tool that could leverage experimental data and provide ZOI information for configurations that were not subject to full-scale testing. This provided a more cost-effective and flexible approach considering the high costs associated with conducting full-scale HEAF experiments. Therefore, this activity focused on the development of a CFD model of HEAF events capable of calculating the total incident energy in the vicinity of a HEAF for a variety of equipment configurations and materials. The predicted incident energy levels were then used to determine the ZOIs for specific equipment. The Fire Dynamics Simulator (FDS) [15] was used to support this effort. The FDS computer code includes a hydrodynamic model capable of solving the low-Mach number, thermally driven flow equations using a large eddy simulation turbulence model [16]. FDS includes a combustion model and a radiative heat transport model, in addition to capabilities for accommodating a wide variety of geometric configurations. Key modelling considerations for HEAF events are discussed in [16], and include the following:

- FDS is a well-recognized and validated fire model that has been used for evaluating smoke and heat transport from fires since 2000. FDS has been subjected to extensive validation activities including comparisons to full-scale experiments, standard tests, documented fire experience, and engineering correlations. These activities have served to validate FDS models in several areas of importance to this HEAF work, including fire plumes, fire growth, flame spread, and combustion modelling [17].

- The FDS numerical solver is generally appropriate for low speed (i.e., less than ~ 30 % of the speed of sound) thermally driven flow. Although FDS is not capable of resolving the shock waves that may accompany a HEAF event, this impact is considered to be relatively minor given that the major damage to targets is via thermal radiation and convection.
- FDS does not include physical models for electric and magnetic fields; the disassociation of molecules at high temperature; or the formation of plasma. These factors limit the ability of FDS to accurately predict temperature or account for movement of the electrical arc within the cabinet. However, the FDS model does account for total arc energy (as determined by arc voltage, amperage, and duration) and can appropriately account for the arc energy associated with the HEAF event. The other modelling limitations are believed to have a minor impact on the FDS results.
- The arc itself was modelled as a volumetric heat source. Three generic arc power profiles were used: (1) a constant current source of 30 kA used for medium voltage switchgear and non-segregated bus ducts; (2) a constant current followed by a decay curve to represent generator fed faults; and (3) a two-stage profile using a high initial current followed by a reduced second stage current. The radiative emission from the arc was based on experimental data for aluminum and copper electrodes. Combustion was modelled for metal vapor oxidation and contributed to the total energy associated with the HEAF. Electrode mass loss rate was modelled using a correlation for aluminum and copper determined based on open box testing [13] and previous medium voltage switchgear tests [12].
- In order to reduce the potential for input errors given the large number of simulations, an algorithmic approach was used to automatically generate input files.

The FDS model was validated against four medium voltage switchgear experiments [12]. Data collected from the experiments was compared to FDS simulations of the same experimental configurations. Figure 5provides the results of this comparison for temperature rise associated with two of the instrument racks used for the medium voltage switchgear testing and shows that FDS underpredicted temperature rise values (which is directly related to incident energy). Based on consideration of factors that impact the FDS results (e.g., unmodeled enclosure leakage), a bias factor and standard deviation were determined to adjust the FDS results to better align with the experimental results. This resulted in identification of a relative standard deviation of 0.71 and a bias factor of 0.59. This information allows calculation of a 95% confidence interval for the FDS results using the following formula (where M is the FDS prediction, δ is the bias factor and σ is the relative standard deviation):

- Lower bound: $\left(\frac{M}{\delta}\right) / \, (1 + 2\sigma)$
- Upper bound: $\left(\frac{M}{\delta}\right) \; (1 + 2\sigma)$

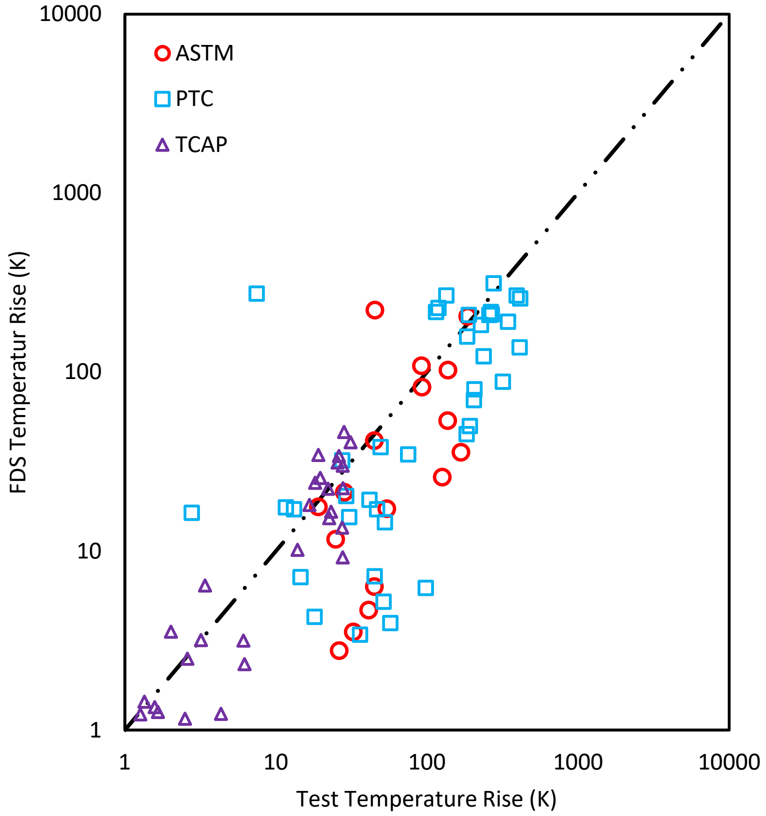

Figure 5 Comparison between unbiased FDS predictions and experimental results for medium voltage Switchgear testing (instrument racks 1 and 4

FDS predictions for enclosure breach were also compared to experimental results to assess the ability of FDS to predict location and extent of HEAF induced cabinet openings (see Figure 6).

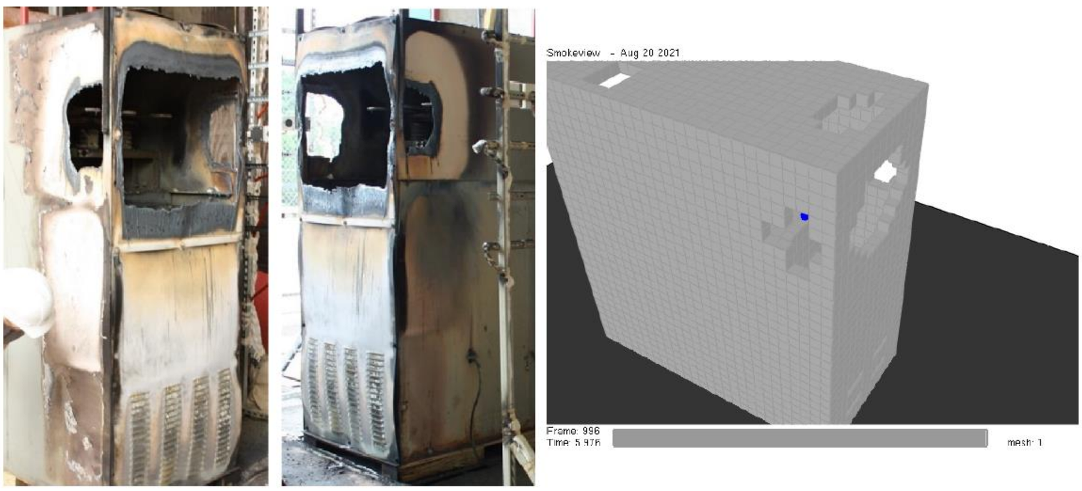

Figure 6 Results from MV switchgear experiment 2-21 and associated FDS results

In addition to the medium voltage experiments, the FDS model was also used to evaluate several HEAF events from operating experience, in order to assess enclosure breach time and damage extent.

Following validation of the FDS model, a calculation matrix for FDS simulations was built on in-formation gathered from surveying the U.S. nuclear fleet (e.g., switchgear manufacturer, bus bar materials, potential fault locations), operating experience, and previous testing. Over 130 simulation runs were identified, covering the following characteristics:

- Low voltage switchgear with steel enclosure – bus bar material (aluminum, copper), arc duration, arc location (mid compartment bus, circuit breaker), arc energy (34 FDS simulations);
- Medium voltage switchgear with steel enclosure - bus bar material (aluminum, copper), switchgear type (GE Magneblast, ABB/ITE HK), arc duration, arc location (main bus bars, compartment bus bars, circuit breaker), and arc energy (42 FDS simulations);
- Non-segregated bus ducts – duct material (steel, aluminum) and bus bar material (aluminum, copper), arc duration, arc location, and arc energy (57 FDS simulations).

The FDS HEAF simulations provided a significant amount of data related to particle distributions, thermal plume behaviour, heat release rates, incident energy, and temperature profiles. Figure 7 is an example of the results obtained from these simulations.

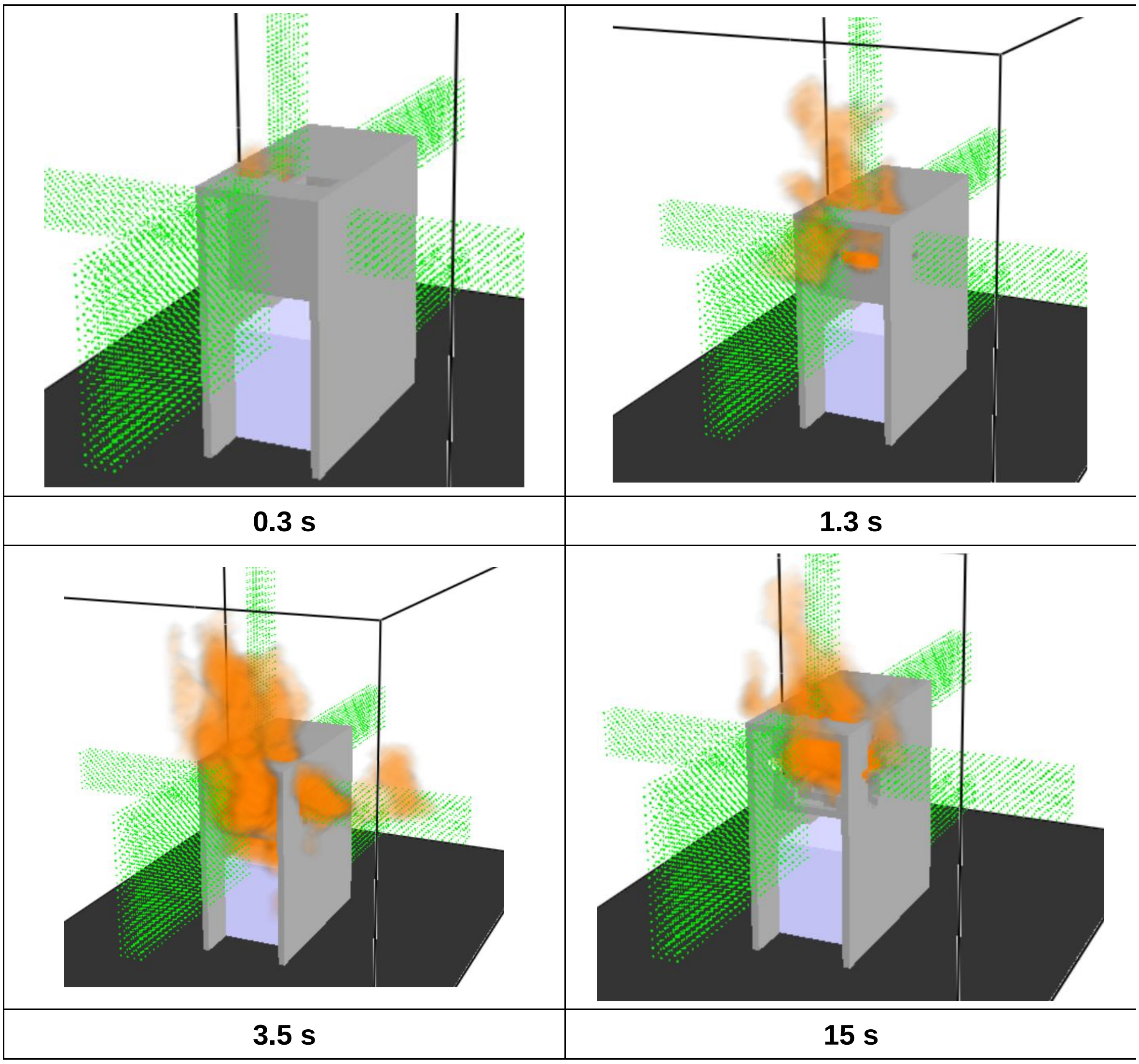

Figure 7 FDS Results for a 226 MJ HEAF thermal plume (medium voltage switchgear cabinet**)**

This information allowed the determination of the distance at which the 15 MJ/m^2 and 30 MJ/m^2 target fragilities would be exceeded (which is used to determine the HEAF zone of influence). Figure 8 shows the results for medium voltage switchgear cabinet with an arc initiated at the main bus bars using a 15 MJ/m^2 fragility threshold.

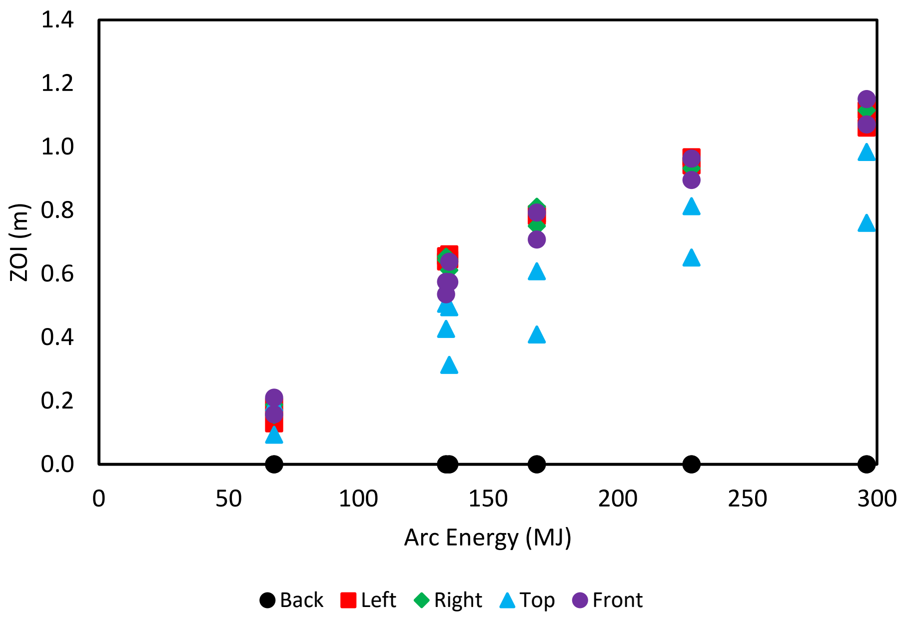

Figure 8 Example ZOI for 15 MJ/m^2 fragility (medium voltage switchgear)

Zones of influence for other simulated conditions were obtained in a similar manner. Reference [16] provides a tabulation of the ZOI results for all FDS simulations. Several key insights were identified during this work:

- The dominant factor for medium voltage switchgear ZOIs was total arc energy. The results for medium and voltage switchgear were also sensitive to equipment geometry and orientation. [7], [8].
- The ZOIs for low voltage switchgear are lower than those provided in NUREG/CR-6850 and its supplement.
- The ZOIs for medium voltage switchgear are lower than the NUREG/CR-6850 guidance for some configurations, but greater for others (e.g., up to 1.24 m for a fragility threshold of 15 MJ/m^2).
- The composition of non-iso phase bus duct housings (aluminum vs. steel) has a significant impact on the ZOI, with aluminum increasing the ZOI by approximately 0.15 m. The maximum ZOI is 1.41 m for a 15 MJ/m^2 fragility threshold. However, the ZOI results were not sensitive to electrode composition, with copper and aluminum electrode results lying within the 95 % confidence interval.

CONFIRMATORY ZOI CALCULATIONS

To provide additional confidence in the ZOIs calculated using the FDS model, the NRC staff also developed a modified model based on IEEE guide 1584-2018, “IEEE Guide for Performing Arc-Flash Hazard Calculations” [18]. This IEEE standard was developed to estimate incident energy at various distances from an arc flash event for the purpose of electrical safety. The NRC’s model differed from the IEEE arc flash model and its application in several ways, including fault current input (arc current rather than bolted fault current), inclusion of an enclosure breaching time, and solving for incident energy to determine a ZOI based on plant specific target fragilities [19]. Specific differences include the following:

- Arc current and voltage: The IEEE model is based on use of a bolted fault current (which is a short circuit condition that assumes zero impedance at the point of the fault). However, determining the appropriate bolted fault current requires analysis of the characteristic of the specific electrical distribution system. Since this information was not available, the staff iterated on bolted fault current to determine a value that yielded the desired arc current. Arc voltage is needed to determine total arc energy and was estimated based on use of the CIGRE-602 model [20] with a correction factor based on previous medium voltage switchgear and open box testing results [12], [13].
- Enclosure breaching time: The IEEE arc flash model is intended to address electrical safety and does assume there is a barrier (such as an electrical enclosure) between the arc and target. However, actual HEAF events that initiate within an enclosure will need to breach the enclosure before incident energy is received by the target. Therefore, a model was developed to account for the time to breach and enlarge the opening of the enclosure. The time to breach is dependent on enclosure material with aluminum enclosures breaching approximately four times faster than a steel enclosure of equivalent thickness and fault current.
- Arc energy decay due for generator fed faults – Because some faults cannot be isolated from the main generator, the arc energy was adjusted to reflect generator coast down following a turbine trip and associated energy decay.
- A spherical zone of influence, centered on the arc location, was determined by identifying the distance at which the incident energy for the simulated HEAF event is equivalent to 15 MJ/m^2 and 30 MJ/m^2.

Application of the modified arc-flash model yielded the following results:

- Low-voltage switchgear: No results exceeded the 0.9 m ZOI provided in NUREG/CR-6850 and its supplement.
- Medium voltage: The maximum ZOI obtained from the modified arc flash model is slightly greater the maximum FDS calculated ZOI for both the 15 MJ/m^2 fragility level (1.6 m versus 1.3 m) and the 30 MJ/m^2 fragility level (1.1 m versus 0.97 m).
- Non-isophase bus ducts: The maximum ZOI obtained from the modified arc-flash model is 1.2 m, which is slightly less than the maximum FDS ZOI of 1.4 m.

The results of the modified arc-flash empirical model are consistent with the more detailed FDS analysis and appropriately reflect the influence of key factors such as arc energy, and enclosure material. Therefore, the modified arc-flash model provides additional confidence in the CFD-derived ZOIs.

CONCLUSIONS

The development of updated fragility thresholds for thermoplastic and thermoset cabling and the use of the FDS computational fluid dynamics computer code, which allows for detailed examination of a variety of electrical equipment configuration and arc characteristics, is expected to further improve the realism of Fire PRA. The use of a joint working group supported by both the NRC and EPRI allowed thorough consideration of a diverse spectrum of perspectives and enabled the development of consensus positions for a number of challenging issues. Further, the NRC use of a modified arc-flash model provided additional confirmation of the results of the FDS calculations and further support NRC confidence in the results of this process.

ACKNOWLEDGEMENTS

This work would not have been possible without the collaboration of staff from the Electrical Power Research Institute, Sandia National Laboratories, KEMA Labs, Brandon Stanton Inc., and the U.S. National Institute of Standards and Technology. The NRC gratefully acknowledges the support from the following individuals:

- U.S. Nuclear Regulatory Commission Working Group members, including Thinh Dinh, J. S. Hyslop, Kenn Miller, Charles Moulton, Reinaldo Rodriguez, David Stroup, Sunil Weerakkody, Jen Whitman, and Antonios Zoulis:
- Electric Power Research Institute: Ashley Lindeman, Marko Randelovic, Tom Short, and Fernando Ferrante. In addition, the following individuals provided substantial support to EPRI during this project: Jason Floyd, Dane Lovelace, Sean Hunt, Ken Fleischer, P. Shannon Lovvorn, and Victor Ontiveros:
- U.S. National Institute of Standards and Technology: Kevin McGrattan, Anthony D. Putorti, Scott Bareham, Edward Hnetkovsky, Christopher Brown, Wai Cheong Tam, Erik Link, Michael Selepak, Philip Deardorff, and Andre Thompson:
- Sandia National Laboratories: Chris LaFluer, Paul Clem, Byron Demosthenous, Austin Glover, Raymond Martinez, Anthony Tambakuchi, Kenneth Armijo, Alvaro Augusto Cruz-Cabrera, James Taylor, Rana Weaver, and Caroline Winters
- OECD Nuclear Energy Agency High Energy Arcing Fault Project participants, including the project Secretariat Markus Beilmann and participating countries including Belgium, Canada, France, Germany, Japan, Korea, the Netherlands, Republic of Korea, and Spain;
- KEMA Labs: Frank Cielo and the staff at KEMA Labs;
- Brandon Stanton, Inc.: Rob Taylor and the staff at BSI:

REFERENCES

[1] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI): OECD FIRE Project – Topical Report No. 1, Analysis of High Energy Arcing Fault (HEAF) Fire Events, NEA/CSNI/R(2013)6, Paris, France, June 2013, http://www.oecd-nea.org/documents/2013/sin/csni-r2013-6.pdf.

[2] Raughley, W., and G. F. Lanik: Operating Experience Assessment Energetic Faults in 4.16 kV to 13.8 kV Switchgear and Bus Ducts that Caused Fires in Nuclear Power Plants 1986–2001 (ADAMS ML021290358), U.S. Nuclear Regulatory Commission, Washington, DC, USA, 2002.

[3] Rodriguez, R., and S. Weerakkody: High Energy Arcing Faults LIC-504 Team Recommendations (ADAMS ML22200A272), U.S. Nuclear Regulatory Commission (NRC), Washington, DC, USA, 2022

[4] National Fire Protection Association (NFRA): NFPA 805, Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition, Quincy, MA, USA, 2001.

[5] Office of the Federal Register: Voluntary Fire Protection Requirements for Light Water Reactors; Adoption of NFPA 805 as a Risk-Informed, Performance-Based Alternative, 69 FR 33536, June 16, 2004,https://www.federalregister.gov/d/04-13522.

[6] United States Nuclear Regulatory Commission (U.S. NRC): Regulatory Guide 1.205, Risk-Informed, Performance-Based Fire Protection for Existing Light-Water Nuclear Power Plants, Revision 2, Washington, DC, USA, 2021.

[7] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI): Fire PRA Methodology for Nuclear Power Facilities, Final Report, EPRI/NRC-RES, NUREG/CR-6850 (EPRI 10191989), Washington, DC, and Palo Alto, CA, USA, 2005, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/index.html.

[8] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI): Fire PRA Methodology for Nuclear Power Facilities, Supplement 1: Fire Probabilistic Risk Assessment Methods Enhancements, EPRI/NRC-RES, NUREG/CR-6850 (EPRI 10191989), Washington, DC, and Palo Alto, CA, USA, 2010, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/s1/index.html.

[9] United States Nuclear Regulatory Commission (U.S. NRC): High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components, Information Notice 2017-04, Washington, DC, USA, August 21, 2017, https://www.nrc.gov/docs/ML1705/ML17058A343.pdf.

[10] United States Nuclear Regulatory Commission (U.S. NRC): HEAF Cable Fragility Testing at the Solar Furnace at the National Solar Thermal Test Facility, Research Information Letter (RIL) 2021-09, (SAND2021-11327), Washington, DC, USA, September 2021, https://www.nrc.gov/docs/ML2125/ML21259A256.pdf.U

[11] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI): Experimental Results from the International High Energy Arcing Fault (HEAF) Research Program Testing Phase 2014 to 2016, NEA/CSNI/R(2017)7, Paris, France, 2017, http://www.oecd-nea.org/documents/2016/sin/csni-r2017-7.pdf.

[12] United States Nuclear Regulatory Commission (U.S. NRC): Report on High Energy Arcing Fault Experiments - Experimental Results from Medium Voltage Electrical Enclosures, Research Information Letter (RIL) 2021-10, (NIST TN 2188, SAND2021-12049 R), Washington, DC, USA, December 2021, https://www.nrc.gov/docs/ML2133/ML21334A196.pdf.

[13] United States Nuclear Regulatory Commission (U.S. NRC): Report on High Energy Arcing Fault Experiments - Experimental Results from Open Box Enclosures, Research Information Letter (RIL) 2021-18, (NIST TN 2198, SAND2021-16075 R), Washington, DC, USA, December 2021, https://www.nrc.gov/docs/ML2136/ML21361A176.pdf.

[14] United States Nuclear Regulatory Commission (U.S. NRC) and Electric Power Research Institute (EPRI): Target Fragilities for Equipment Vulnerable to High Energy Arcing Faults, Research Information Letter (RIL) 2022-01, (EPRI 3002023400), Washington, DC, and Palo Alto, CA, USA, May 2022, https://www.nrc.gov/docs/ML2213/ML22131A339.pdf.

[15] McGrattan, K., et al.: Fire Dynamics Simulator User's Guide, NIST Special Publication 1019, National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, 2022.

[16] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI): Determining the Zone of Influence for High Energy Arcing Faults Using Fire Dynamics Simulator, Draft Research Information Letter for Public Comment, (ML22095A237), Washington, DC, USA, 2022, https://www.nrc.gov/docs/ML2209/ML22095A237.pdf.

[17] McGrattan, K., et al.: Fire Dynamics Simulator Technical Reference Guide Volume 3: Validation, Sixth Edition, NIST Special Publication 1018-3, U.S. Department of Commerce, National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, 2022.

[18] Institute of Electrical and Electronics Engineers (IEEE): IEEE Guide for Performing Arc-Flash Hazard Calculations, IEEE 1584-2018, ISBN:978-1-5044-5262-5, New York, NY, 2018November 2018, https://doi.org/10.1109/IEEESTD.2018.8563139.

[19] United States Nuclear Regulatory Commission (U.S. NRC): Predicting High Energy Arcing Fault Zones of Influence for Aluminum Using a Modified Arc Flash Model, Draft Research Information Letter, (ML22095A236),Washington, EC, USA, May 2022, https://www.nrc.gov/docs/ML2209/ML22095A236.pdf.

[20] Conseil international des grands réseaux électriques (CIGRÉ) Comité d'études A3: Tools for the simulation of the effects of the internal arc in transmission and distribution switchgear, CIGRE 602, ISBN: 978-2-85873-303-3, 2014.