

Development of a Procedure for Evaluating the High Energy Arcing Fault Zone of Influence in Nuclear Power Plants

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1. Introduction

High Energy Arcing Faults (HEAFs) are defined as faults that result in the rapid release of electrical energy in the form of heat, vaporized metal, and mechanical force [1]. According to the OECD/NEA fire event report [2], 48 HEAF events have been recorded, accounting for approximately 10% of all reported fire events. Since 2014, the USNRC and OECD/NEA have conducted HEAF experiments on low- and medium-voltage (MV) switchgears (SWGR) and bus ducts. Recently, a new research report, NUREG-2262 [1], focusing on the fire probabilistic safety assessment (PSA) of HEAF events, has been published.

A HEAF event is modeled in two phases: the energetic phase and the ensuing fire. Therefore, when evaluating the HEAF zone of influence (ZOI), defined as the distance within which a HEAF can cause damage or failure of a target, both the energetic phase and the ensuing fire phase should be considered. For the HEAF ZOI during the energetic phase, NUREG-2262 provides ZOI values according to HEAF zone and equipment type. However, practical application of NUREG-2262 to a specific nuclear power plant (NPP) can be challenging for analysts because understanding and applying the methodology requires multidisciplinary engineering knowledge, including electrical engineering, fire PSA, and fire dynamics. Therefore, this study developed a procedure for analyzing the HEAF ZOI based on NUREG-2262 to facilitate HEAF ZOI analyses in NPPs. The developed procedure adopts a progressively refined approach, beginning with conservative evaluations and gradually advancing toward more realistic assessments of the HEAF ZOI. The developed procedure can be applied to both fire PSA and deterministic fire safety analyses.

2. Methods and Results

2.1 Overall Procedure

As shown in Fig. 1, the HEAF equipment and zones to be analyzed are first identified. Fig. 2 and Table I show the equipment and HEAF zones subject to HEAF analysis. As shown in Fig. 3, the HEAF ZOI for bus ducts (BDs) is evaluated by considering two components: the energetic phase and the waterfall phase. The energetic BD ZOI is applied along the bus duct at the location where the fault is postulated. The waterfall phase is intended to evaluate the exposure of vulnerable

equipment located beneath the bus duct where the fault is postulated. For MV SWGR and 480 V load centers (LC) located in Zones 1, 2, and 3 in Fig. 2, the ZOI is determined by selecting the larger value between the ZOI during the energetic phase and that during the ensuing fire phase.

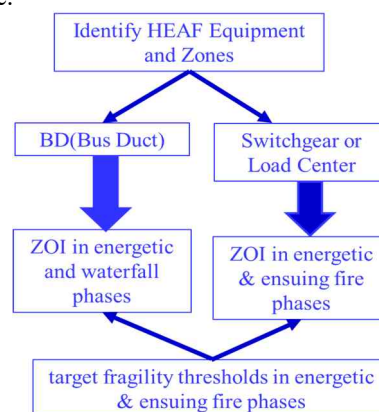


Fig. 1. Overall evaluation procedure of the HEAF ZOI

Once the ZOI has been determined, target damage is considered during the energetic phase, whereas both target damage and ignition are considered during the ensuing fire phase. All targets located within the ZOI are assumed to be damaged. Therefore, identifying all targets within the ZOI is necessary for the safety analysis. However, if three-dimensional information on equipment and cables within a fire area is not available, identifying all targets can require considerable effort. For the ensuing fire phase, fires involving secondary combustibles must also be considered.

Table II: Damage criteria for electrical cables

HEAF Phase	Thermoplastic(TP)	Thermoset(TS)
Energetic Phase	15 MJ/m ²	30 MJ/m ²
Ensuing Fire Phase	205°C, 6 kW/m ²	330°C, 11kW/m ²

When performing a fire PSA, if a generator circuit breaker (GCB) is installed, the frequency of HEAF scenarios involving generator power supply, such as IPBD and BDUAT, can be significantly reduced. Therefore, the PSA quantification is initially performed conservatively by assuming that all equipment and cables within the fire area where the HEAF occurs is damaged. If the resulting quantification is considered excessively conservative, the HEAF ZOI is subsequently

evaluated. The criteria for equipment damage to targets during the energetic phase and ensuing fire phase are presented in Table II [1,3].

2.2 Energetic phase

As shown in Fig. 4, the ZOI during the energetic phase is initially determined by selecting the maximum ZOI obtained from the screening or detailed analysis results provided in NUREG-2262. Table III presents the maximum ZOIs obtained from the screening and detailed analyses. If the post-HEAF ensuing fire ZOI is greater than the maximum HEAF energetic phase ZOI, no additional evaluation of the energetic phase ZOI is performed. The ZOIs presented in Table III do not consider factors such as the target material, including whether the target is a TP or TS cable, the power source associated with the HEAF, or the material of the bus duct. If factors affecting the determination of the ZOI are identified, an alternative ZOI value may be selected from the relevant tables in NUREG-2262, if necessary. If the ZOI previously determined for a bus duct or MV SWGR is considered overly conservative, the fault clearing time (FCT) is estimated to determine an appropriate ZOI. For isolated-phase bus ducts (IPBDs), NUREG-2262 does not provide separate fire-modeling results; therefore, no additional analysis is performed. For load centers, FCT estimation is not required because a single arc energy value is used. Because the ZOI varies depending on the FCT, only the relevant tables from NUREG-2262 are provided in Table IV.

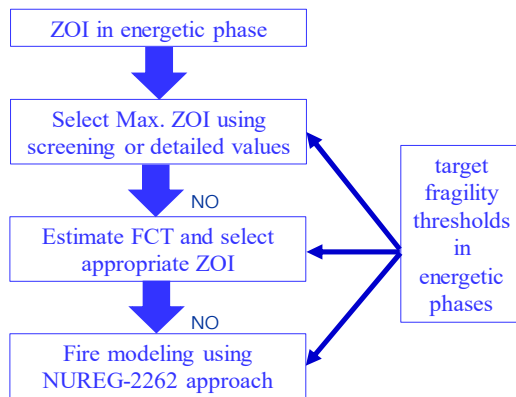


Fig. 4. Evaluation procedure of the energetic HEAF ZOI

In the third step, if determining the HEAF ZOI using NUREG-2262 is considered inappropriate, the ZOI is determined through direct fire modeling. The fire-modeling approach used for this purpose follows the methods and procedures described in NUREG-2262, as shown in Fig. 5. The ZOIs presented in NUREG-2262 were developed based on RIL 2022-09 [4], which documents the evaluation of HEAF ZOIs using the Fire Dynamics Simulator (FDS) [5]. Because the predicted ZOI increases as the grid size increases [7], a grid size of 0.08 m or less is used for SWGR and load centers, consistent with RIL 2022-09, while a grid size of 0.02 m

or less is used for bus ducts. The configuration and physical input parameters of the equipment under analysis are reviewed, and the FDS program provided in RIL 2022-09 is modified and used when necessary. Because arc energy and the opening condition of the enclosure have a significant effect on the ZOI, particular attention should be paid to estimating the arc energy. The enclosure is assumed to be open due to ventilation openings or physical damage. The final ZOI is determined by applying a bias factor of 0.596, specified in RIL 2022-09, to the ZOI obtained from the FDS analysis. The arc energy is calculated as follows [1]:

- Arc Energy = Arc Power × Arc Duration = $\sqrt{3} \times I \times V(L-L) \times \text{Arc Duration}$
I = arc current, V(L-L) = line-to-line voltage
- For bus ducts and MV SWGR, NUREG-2262 estimates the line-to-line voltage for equipment rated at 4.16 kV, 6.9 kV, and 13.6 kV as 650 V. For load centers rated at 400 V and 600 V, the voltage is estimated as 375 V. These values are used as the estimated voltages for the plant under analysis.
- NUREG-2262 uses an arc current of 30 kA for MV HEAF events. For generator-supplied faults, the arc current is assumed to decay exponentially from an initial value of 20 kA. The arc duration is determined by identifying the arc current and FCT through an analysis of the protection and coordination calculation scheme for the plant under analysis, with reference to the arc current values provided in NUREG-2262.

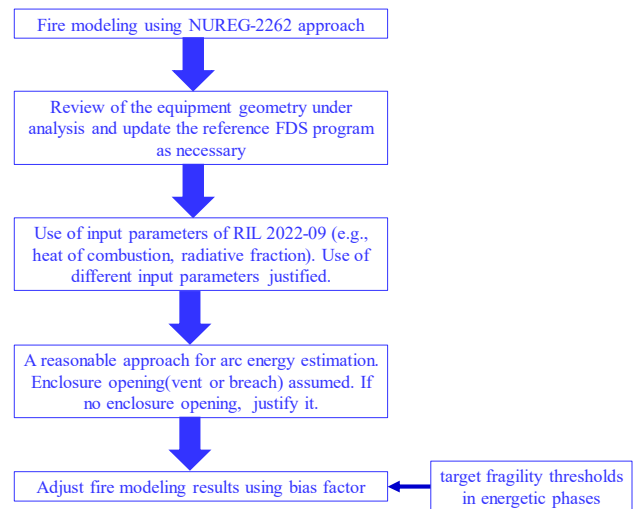


Fig. 5. Evaluation procedure of the energetic HEAF ZOI using direct FDS modeling

2.3 Ensuing fire phase

As shown in Fig. 1, the ensuing fire must be considered when determining the ZOI for MV SWGR and LCs. Fire modeling for the ensuing fire follows the methods and procedures described in Section 6.5 of NUREG-2262, together with the general fire-modeling procedure [6]. For LCs, fire spread is not considered,

whereas fire spread from MV SWGR is considered. The fire-modeling conditions for the HEAF ensuing fire are as follows:

- The fire source for the HEAF ensuing fire is located 0.3 m directly above the SWGR, and the heat release rate (HRR) is 170 kW.
- The HEAF ensuing fire has a growth time of 0 min, because the fire is assumed not to undergo an additional growth phase after the HEAF. A constant burning period of 8 min and a decay time of 19 min are assumed.
- Because the fire occurs following a HEAF, obstructions that would suppress the plume or radiation from the ensuing fire are not considered.
- If fire spread is possible, fire spread is assumed to occur in both directions.
- The arc energy required for fire spread from a MV SWGR to an adjacent SWGR is 101 MJ or greater for a vertical surface separated by a single steel barrier and 202 MJ or greater for one separated by a double steel barrier.
- When the HEAF ensuing fire spreads to the vertical section of an adjacent SWGR, the HRR is assumed to have the fire characteristics of a typical electrical enclosure fire. The assumed growth time is 12 min, followed by a constant burning period of 8 min and a decay time of 19 min.

A detailed analysis of fire spread is performed using the general fire-spread event tree shown in Fig. 6. Only a fire involving the meter and relay enclosure is assumed to have an HRR of 170 kW. If the meter and relay are not involved, the amount of combustible material is relatively small, and an HRR of 45 kW is assumed. The general fire-spread event tree shown in Fig. 6 consists of four fire scenarios. The HRR and fire-modeling location for each scenario are presented in Table V.

The ZOI for the ensuing fire is evaluated separately for the area where the HEAF occurs and the area to which the fire spreads. The hot gas layer temperature is evaluated by considering both the HEAF ensuing fire and the fire that spreads to an adjacent SWGR. Table 6-4 of NUREG-2262 provides separate data for the hot gas layer temperature based on a single HRR. However, because the data are not provided as a time-dependent HRR, they are difficult to use directly in fire simulations. Therefore, in this study, the HRR used to estimate the hot gas layer temperature is determined by considering both the HRR at the location where the HEAF occurs and the HRR at the location to which the fire spreads, as described above.

3. Concluding Remarks

In this study, a practical procedure for evaluating the ZOI of HEAF events in NPPs was developed based on NUREG-2262. The procedure was developed to facilitate the practical application of NUREG-2262 to NPP equipment, particularly for analysts who may not

have extensive expertise in electrical engineering, fire dynamics, and NPP electrical systems.

The developed procedure considers both the energetic phase and the waterfall or ensuing fire phase of a HEAF event. For the energetic phase, the ZOI is initially determined using the maximum values obtained from the screening or detailed analyses in NUREG-2262. If the resulting ZOI is considered excessively conservative, the ZOI can be refined using the FCT and, when necessary, direct FDS fire modeling. This stepwise approach allows the analyst to begin with a conservative evaluation and progressively refine the ZOI when a more realistic assessment is required.

For the ensuing fire phase, the procedure considers not only target damage but also ignition and fire spread. In particular, the ensuing fire of MV SWGR is evaluated by considering the HRR, fire duration, and conditions for fire spread to adjacent SWGR. The ZOI is evaluated separately for the HEAF-origin area and the area affected by fire spread. The proposed approach also considers the combined effects of the HRR at the HEAF location and the HRR associated with fire spread when estimating the hot gas layer temperature.

The proposed procedure can be applied flexibly depending on the purpose and conservatism required in the safety analysis. In a fire PSA, an initial conservative quantification can be performed by assuming that all equipment within the HEAF fire area is damaged. If the resulting risk contribution is significant or the quantification is judged to be overly conservative, the proposed ZOI evaluation procedure can subsequently be applied to refine the analysis. This approach can reduce unnecessary analytical effort while maintaining an appropriate level of conservatism.

Acknowledgments

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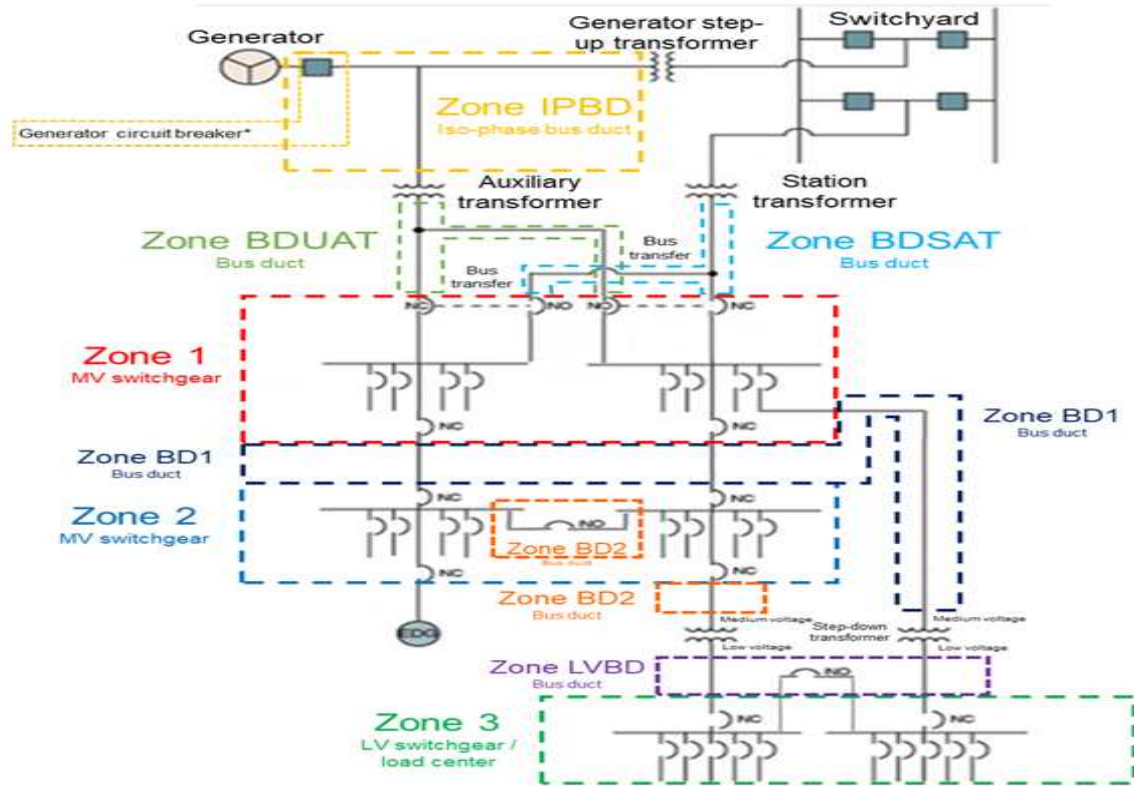


Fig. 2. HEAF zones for a simplified NPP electrical distribution system (EDS)

Table I: HEAF Zones

HEAF zone	Portion of the EDS	Ignition source bin	Equipment
IPBD	Iso-phase bus duct	16.2	Iso-phase bus duct connecting the station generator to the UAT (Unit Auxiliary Transformer) and generator step-up transformer.
BDUAT	Bus duct between UAT and Zone 1	16.1-1	NSBD (Non-segregated bus duct) that connects the UAT secondary (tertiary) windings to the first downstream SWGR.
BDSAT	Bus duct between SAT and Zone 1	16.1-1	NSBD that connects the SAT (Station Auxiliary Transformer) secondary (tertiary) windings to the first downstream SWGR.
1	MV SWGR	16.b	First SWGR downstream of the UAT or SAT. This may also be referred to as an “intermediate bus” if it feeds another downstream MV bus.
2	MV SWGR	16.b	Second SWGR bus downstream of the UAT or SAT (via an intermediate bus).
3	Load center	16.a	Load centers or LV (Low Voltage) SWGR (480 to 1000 VAC).
BD1	MV bus duct between Zone 1 and Zone 2 and Zone 1 and Zone 3	16.1-2	Region of the MV NSBD between the first MV SWGR and either of the following: <ul style="list-style-type: none"> • The high side of the second MV SWGR bus supply breaker (bus duct from Zone 1 to Zone 2) • The high side of the load center transformer (bus duct from Zone 1 to Zone 3)
BD2	MV bus duct between Zone 2 and Zone 3 and Zone 2 to Zone 2	16.1-2	Region of the MV NSBD between the second MV SWGR and either of the following: <ul style="list-style-type: none"> • The high side of the load center transformer • Another Zone 2 SWGR (bus-tie)
LVBD	LV bus duct between Zone 1 or Zone 2 to Zone 3, or Zone 3 to Zone 3	16.1-2	Region of the LV NSBD between the Zone 1 step-down transformer and the load center (Zone 1 or Zone 2 to Zone 3) or between load centers (Zone 3 to Zone 3).

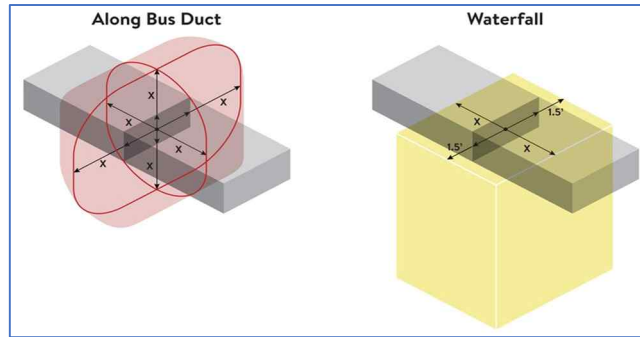


Fig. 3. NSBD ZOI showing energetic (red shaded) and waterfall (yellow box) components

Table III: Evaluation of the energetic HEAF ZOI using the maximum values of the NUREG-2262

	IPBD	BDUAT	BDSAT	BD1	BD2	BDLV	Load Center	MV SWGR
Max ZOI	1.5m	1.52m	1.07m	0.91m	0.46m	0.46m	0.76m	1.4m
Sources	Chapter 9 of NUREG-2262	Table 9-2 of NUREG-2262, Chapter 9 of NUREG-2262					Table 7-1 of NUREG-2262	Table 8-2 of NUREG-2262

Table IV: Evaluation of the energetic HEAF ZOI using NUREG-2262 and estimated FCT

	IPBD	BDUAT	BDSAT	BD1	BD2	BDLV	Load Center	MV SWGR
Sources	Chapter 9 of NUREG-2262	Table 9-2 of NUREG-2262, Chapter 9 of NUREG-2262					Table 7-1 of NUREG-2262	Table 8-2,3,4,5,6 of NUREG-2262

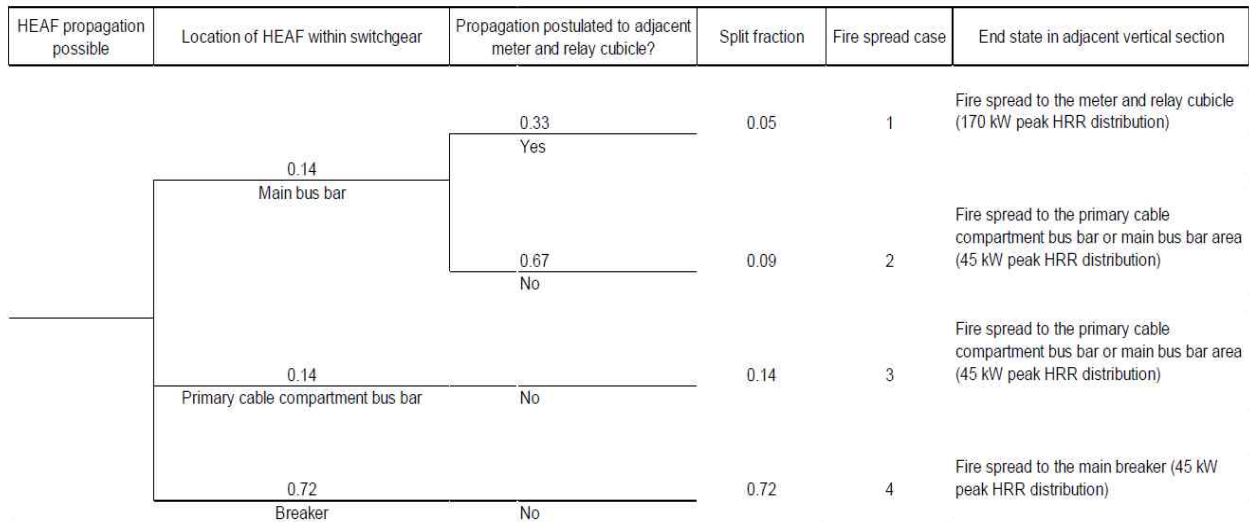


Fig. 6. Generic fire spread event tree (use for single wall at energies of 132 – 233 MJ and for double wall energy of 233 MJ)

Table V: Heat release rates and fire-spread locations for HEAF ensuing fire scenarios

Cases	Adjacent section	98th percentile peak HRR (kW)	fire base height
Case 1	meter and relay cubicle	170 kW	0.3 m below the top of the switchgear
Case 2/3	primary cable compartment bus bar or main bus bar area	45 kW	0.3 m below the top of the switchgear
Case 4	main breaker	45 kW	switchgear mid-height