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Sensitivity Analysis of Bus Duct Damage Limits

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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 switchgears 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. In NUREG-2262, the fragilities of equipment affected by HEAF were derived from the results of RIL 2022-01 [3], while the determination of the HEAF Zone of Influence (ZOI) was based on RIL 2022-09 [4].

The fire impact assessment methodology for HEAF (e.g., ZOI, damage thresholds) in nuclear power plants (NPPs) can be applied not only to fire PSA but also to deterministic fire safety evaluations. Deterministic fire hazard analyses, both domestic and international, require assessments of arc damage [5] and high-energy electrical faults [6]. RIL 2022-01 analyzed damage thresholds only for bus ducts with a thickness of 3 mm. However, consultation with the largest domestic cable company indicated that 2.5 mm steel bus ducts are also in use. Accordingly, this study extended the analysis to bus ducts with thicknesses of 2.5 mm and 3.5 mm. The damage thresholds of bus ducts were estimated using both analytical methods and fire simulations in accordance with RIL 2022-01.

2. Methods and Results

RIL 2022-01 applied three different methods to evaluate the fragilities of electrical bus ducts and proposed recommended fragility values. In this study, the Bounding Lumped Mass Approach (Method 1) and Fire Dynamics Simulator (FDS) simulations (Method 2) were employed in accordance with RIL 2022-01.

2.1 Bounding Lumped Mass Approach

This conservative/bounding method assumes that the bus duct cover exposed to a HEAF acts as a lumped mass on one side, with adiabatic conditions on the opposite side. In this method, the bus duct is treated as a lumped mass, and the damage threshold is calculated in terms of the total absorbed energy based on the failure mode. The bounding method considers two failure paths:

- Path 1: Tearing without melting, in which the duct heats to a temperature below the melting point, assumed to be 500°C for aluminum and 1300°C for steel, compared to the respective melting points of 660°C and 1500°C.
- Path 2: A combination of melting and tearing, in which the heat of liquefaction (376 kJ/kg for aluminum and 250 kJ/kg for steel) is added to the energy required to reach the temperatures in Path 1.

The damage thresholds for Path 1 and Path 2 were calculated using equations (1) and (2).

(1) $E = \rho \Delta x (c \Delta T)$

(2) $E = \rho \Delta x (c \Delta T + \Delta h_l)$

where, E is the energy in KJ/m^2, ρ is the density in kg/m^3, Δx is thickness in m, c is the average specific heat over the temperature rise in kJ(kg.K), ΔT is the bus duct temperature rise in K, and Δh_l is the heat of liquefaction. Using these equations, the absorbed energy of the bus duct wall was determined. Assuming that HEAF occurs within a very short duration and heat transfer occurs primarily via radiation, the absorbed energy was divided by the emissivity of the duct material (0.85 for steel and 0.4 for aluminum) to obtain the incident energy on the duct surface.

The required incident energy (MJ/m^2) for bus duct damage are shown in Table I and II. The "Report" column presents the results for a 3 mm duct from RIL 2022-01, while the "3 mm" column shows the reproduced calculation in this study. The incident energy for Path 2 was greater than that for Path 1.

2.2 FDS simulations

The phase-change model in FDS was applied with a grid size of 2.5 cm. Hot gases generated by HEAF were assumed to be discharged at 20 m/s toward the bus duct, consisting of an air–aluminum oxide (Al_2O_3) mixture with 0.1 kg/kg concentration. Sensors were installed at the duct walls to measure thickness reduction and heat flux. The cumulative incident heat flux at the point where the duct thickness first reached zero was used to determine the required heat exposure for duct failure.

Since RIL 2022-01 did not provide sufficient details for FDS simulations, the input data were reconstructed based on the duct geometry and HEAF zone described in the report. Considering the publication date of RIL 2022-01 (May 2022), FDS 6.7.6 (May 2021) [7] was used. Figure 1 a schematic diagram of the fire simulation of bus duct damage.

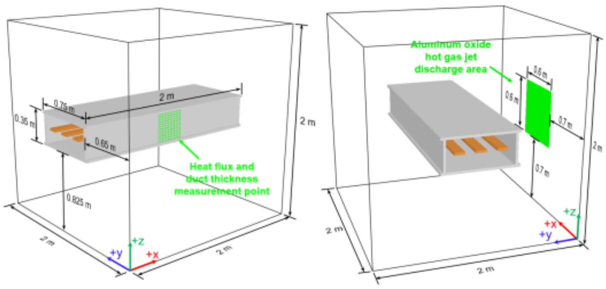

Fig.1. Schematic Diagram of the fire simulation

The sensitivity analysis of the required incident energy for duct damage is summarized in Table III. In this study, critical temperatures were expressed in Celsius (℃), whereas RIL 2022-01 reported them in Kelvin (K). Using the critical temperatures from the bounding lumped mass approach, the reproduced results (3 mm case) showed somewhat higher energies than those in RIL 2022-01. Overall, the required incident energy increased with duct thickness. Higher emissivity led to reduced required incident energy, whereas higher critical temperature resulted in increased incident energy. Fig.2 presents the sensitivity analysis results for Case 11 in Table III.

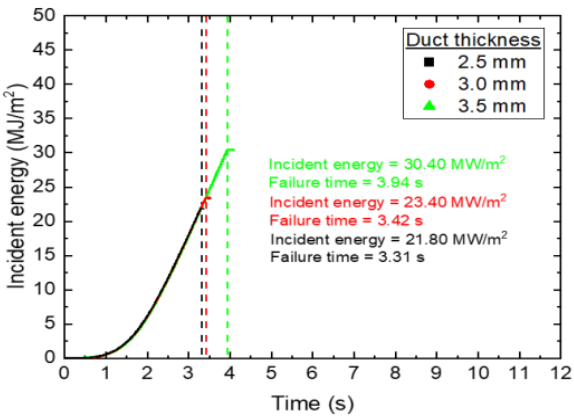

Fig.2. Sensitivity analysis result for Case 11

2.3 Determination of Bus Duct Damage Limits

The damage limits of bus ducts based on the sensitivity analysis results were determined following the approach in RIL 2022-01. In RIL 2022-01, the required incident energy for steel was at least 31.8 MJ/m² under Method 1 and at least 29 MJ/m² under Method 2. The damage threshold was therefore determined as 30 MJ/m². At an incident energy of 29 MJ/m² in Method 2, the critical temperature was 1100°C, which is more than 200°C lower than in other scenarios. For aluminum, the required incident energy was at least 17.5 MJ/m² under Method 1 (Path 2), and at least 14 MJ/m² under Method 2, leading to a damage threshold of 15 MJ/m². At 14 MJ/m² in Method 2, the critical temperature was 450°C, more than 50°C lower than in other cases.

Comparison with the reproduced results shows that, for steel, RIL 2022-01 reported an incident energy of at least 29 MJ/m², while this study reproduced 32.4 MJ/m². Thus, setting the damage threshold at 30 MJ/m² is considered appropriate. For aluminum, RIL 2022-01 reported at least 14 MJ/m², while this study found 15 MJ/m², confirming the validity of the 15 MJ/m² threshold.

For the 2.5 mm bus duct, the required incident energy for steel was 26.2 MJ/m² (Method 1) and 26.7 MJ/m² (Method 2). Based on these, the damage threshold was determined as 27 MJ/m². For aluminum, the required values were 14.4 MJ/m² (Method 1) and 12.6 MJ/m² (Method 2), leading to a threshold of 13.5 MJ/m².

For the 3.5 mm bus duct, the required incident energy for steel was 36.7 MJ/m² (Method 1) and 38.4 MJ/m² (Method 2), and the damage threshold was set at 35 MJ/m². For aluminum, the required values were 20.2 MJ/m² (Method 1) and 17.5 MJ/m² (Method 2), leading to a threshold of 17.5 MJ/m².

3. Concluding Remarks

A sensitivity study for the damage thresholds of bus ducts was conducted to provide more realistic estimates. The results of this study confirmed that damage thresholds are proportional to duct thickness. The thresholds proposed in this study are expected to contribute to more realistic HEAF fire safety assessments. Applying duct thickness-dependent damage thresholds in HEAF evaluations will enable more accurate fire safety assessments for domestic NPPs, ultimately supporting advancements in regulatory fire protection technology and enhancing licensee response capabilities to the regulatory body.

Acknowledgments

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Table I: Sensitivity analysis results using bounding lumped mass approach (Path 1)

Bus Duct Cover	Path 1(without emissivity)				Path 1(with emissivity)			
	Report	3mm	2.5mm	3.5mm	Report	3mm	2.5mm	3.5mm
steel	21.1	20.9	17.4	24.4	24.8	24.6	20.5	28.7
aluminum	3.9	3.9	3.2	4.5	9.8	9.7	8.1	11.3

Table II: Sensitivity analysis results using bounding lumped mass approach (Path 2)

Bus Duct Cover	Path 2(without emissivity)				Path 2(with emissivity)			
	Report	3mm	2.5mm	3.5mm	Report	3mm	2.5mm	3.5mm
steel	27.0	26.7	22.3	31.2	31.8	31.4	26.2	36.7
aluminum	7.0	6.9	5.8	8.1	17.5	17.3	14.4	20.2

Table III: Sensitivity analysis results using FDS simulations

Bus Duct Failure Conditions					Report	3 mm	2.5mm	3.5mm
Metal	Case No.	HEAF Temp. (K)	Emissivity	Critical Temp. (℃)	Incident Energy (MJ/m^2)	Incident Energy (MJ/m^2)	Incident Energy (MJ/m^2)	Incident Energy (MJ/m^2)
Steel	1	4000	0.85	1300	35.1	37.6	31.2	43.9
	2	5000	0.85	1300	33.5	36.8	30.2	43.7
	3	6000	0.85	1300	34.5	38.9	32.1	52.8
	4	5000	0.8	1300	35.6	38.8	31.9	46.1
	5	5000	0.9	1300	31.6	34.9	28.6	41.6
	6	5000	0.85	1100	29	32.4	26.7	38.4
	7	5000	0.85	1500	37.9	41.3	33.8	49.3
Al	8	4000	0.4	500	17.4	17.5	16.1	22.4
	9	4500	0.4	500	17.4	19.8	16.6	23.1
	10	5000	0.4	500	17.5	20.2	16.9	23.6
	11	4500	0.3	500	23.1	23.4	21.8	30.4
	12	4500	0.5	450	14	15	12.6	17.5
	13	4500	0.4	450	16.3	18.6	15.6	21.7
	14	4500	0.4	550	18.6	21	17.6	24.5