Understanding High Energy Arcing Faults

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1. Introduction

Infrequent events such as fires at a nuclear power plant can pose a significant risk to safe plant operations. Licensees combat this risk by having robust fire protection programs designed to minimize the likelihood and consequences of fire. These programs provide reasonable assurance of adequate protection from known fire hazards. However, several hazards remain subject to a large degree of uncertainty, requiring significant safety margins in plant analyses.

One such hazard comprises an electrical arcing fault involving electrical distribution equipment and components. While the electrical faults and subsequent fires are considered in existing fire protection programs, recent research [1, 2] has indicated that elements of the electrical fault can exacerbate the damage potential of the event. The increased damage potential could exceed the protection provided by existing fire protection features for specific fire scenarios and increase plant risk estimated in fire probabilistic risk assessments (PRAs).

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) studies fire and explosion hazards to ensure the safe operation of nuclear facilities. This includes developing data, tools, and methodologies to support risk and safety assessments. Through recent research efforts and collaboration with international partners, a non-negligible number of reportable high energy arcing fault (HEAF) events have been identified as occurring in nuclear facilities [3]. HEAF events pose a unique hazard in nuclear facilities and additional research in this area is needed to ensure that the hazard is accurately characterized and assessed for its impact on nuclear safety.

1.1. Background

In June 2013, an Organisation for Economic Co-operation and Development (OECD) / Nuclear Energy Agency (NEA) report [3] on international operating experience documented 48 HEAF events, accounting for approximately 10 % of the total fire events reported. These HEAF events are often accompanied by loss of essential power and complicated shutdowns. Existing PRA methodology for HEAF analysis is prescribed in NUREG/CR-6850 “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities Vol. 2 [4],” and its Supplement 1 [5]. To confirm these methods, the NRC led an international experimental campaign from 2014 to 2016. This experimental campaign is referred to as “Phase 1 Experimenting.” The results of these experiments [6] uncovered a potential increase in the hazard severity.

In response to this new information, the NRC issued Information Notice 2017-004, “High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components (IN 2017-04)” detailing the relevant aspects of the licensee event reports and Phase 1 experiments was published in August of 2017 [2]. Additionally, RES staff proposed a potential safety concern as a generic issue (GI) in a letter dated May 6, 2016 [7]. During its review, the Generic Issue Review Panel (GIRP) determined that the pre-GI-018 no longer met the Criterion 5 of the NRC MD 6.4, concluding that the risk and safety significance of HEAFs involving aluminum cannot be adequately determined in a timely manner without performing additional, long-term research to develop the methodology for such a determination [8].

In a revised approach to resolving the knowledge gap, the NRC staff applied the BeRiskSMART framework. This approach consists of two coordinated tracks for (1) research activity in coordination with EPRI and (2) use of the NRC process LIC-504, "Integrated Risk-Informed Decision-making Process for Emergent Issues [9]," to apply best available information and NRC risk assessment tools to determine whether any regulatory action was needed. The NRC LIC-504 process was completed in July 2022, finding both increase and decreases in plant risk with a determination of no significant risk increase in total HEAF risk for the two plants evaluated [10].

Under the research approach with EPRI, the NRC developed tools to estimate the HEAF hazard [11, 12], a hazard-specific target fragility characterization [13] and an updated HEAF fire PRA method [1] to provide guidance for evaluating the risk from a HEAF. The NRC and EPRI presented their findings during a two-day public workshop held at the NRC Headquarters located in Rockville, Maryland in May 2023 [14].

Following the completion of this work, there were still several questions raised by the international member countries of the OECD HEAF 2 agreement. These include the post-HEAF fire growth and development assumptions of the ensuing fire and damage insights to equipment adjacent and near the HEAF initiation point. To fulfill the requirements of the operating agent under the HEAF 2 agreement, the NRC performed a series of experiments to help address these questions and close out the experimental campaign.

1.2. Objectives

The research objectives for this experimental series include: quantitatively characterize the thermal and pressure conditions created by HEAFs occurring in electrical enclosures (switchgear and bus ducts) along with characterizing the damage features of adjacent and nearby equipment; and document the experiments and results.

1.3. Scope

The scope of this research includes evaluating the HEAF hazard on low- and medium-voltage electrical switchgear and medium-voltage non-segregated bus ducts. This evaluation involves measurement and documentation of electrical and thermal parameters, along with physical evidence of the HEAF hazard. The results from this effort will be used to provide empirical evidence for use by the OECD HEAF 2 member countries and by NRC staff to evaluate the prediction capabilities of the recently developed hazard models [1]. Detailed data analysis for specific applications is beyond the scope of this report.

1.4. Approach

The approach taken for this work follows practices from past efforts [6, 15-18]. Specifically, the experimental device (switchgear and bus ducts) is faulted between the three phases. The laboratory provides electrical energy to the experimental device at specified parameters (system voltage, current, duration). Measurements internal and external to the test device are made using robust measurement devices fielded by the National Institute of Standards and Technology (NIST). Sandia National Laboratories (SNL) provided high-speed visual and thermal imaging and those results are presented in a separate report. Measurements were recorded, scaled, and reported. Feedback received during the developmental stage of this project was incorporated into the experimental approach. This included the arc locations, fault current magnitudes, and the durations of the experiments.

2. Experimental Method

This section provides information on methods used to perform the experiments[1], including experimental planning, overview of the experimental facility, the tested devices, and the various instruments that were used.

2.1. Experiment Planning

The original HEAF phase II matrix planned for a total of thirty-two experiments. Those experiments were selected to explore the 5 variables, namely; duration, current, voltage, conductor material and bus ducts housing material (for bus duct scenarios). In addition, replicate experiments were planned to evaluate experimental variability. The experimental matrix was separated into two distinct focus areas. The OECD/NEA driven experiments and experiments performed by the NRC with a focus on the effects of aluminum during HEAF events.

This program has evolved significantly since the international agreement was signed in 2019. The COVID-19 pandemic halted all experimental activities and preparations for a two-year period. During this time the NRC shifted all staff resources towards the NRC/EPRI working group to make analytical progress on modeling tools and methodologies which advanced the state of practice. The working group used data collected from pre-pandemic experiments and made significant advancements to update the methodology for modeling HEAFs in fire PRAs. These methods, tools, and data were made publicly available and can be accessed from the NRC HEAF homepage at https://www.nrc.gov/about-nrc/regulatory/research/fire-research/heaf- research.html.

Past work has reshaped the HEAF effort from an exploratory experimental campaign to a confirmatory one. As such, the experimental matrix is reconfigured to provide useful information and insights to the OECD/NEA member countries. The refocus of these experiments include filling data gaps and ensuring alignment with the international HEAF PIRT conducted in 2018 [19].

The significant time delay between the signing of the HEAF agreement also poses unique logistical challenges to completing the original scope of experiments. The supply chain interruption and general inflation experienced worldwide has impacted the ability to perform the same number of experiments without increasing resources. However, efficiencies gained during the performance of previous experimental series have resulted in improved and more efficient experimental methods.

The experimental plan was developed and shared with the OECD/NEA HEAF 2 member countries. Lessons learned from the Phase 1 and NRC focused generic issue experiments, results from the Phenomena Identification and Ranking Table (PIRT) exercise, information from the fire HEAF PRA update [1] and existing literature were used to develop the initial experimental plan. The experimental plan serves as a living document and has undergone several revisions over time as new information emerges. Review and feedback by the OECD/NEA were incorporated

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[1] The term ‘test’ implies the use of a standardized test method promulgated by a standards development organization such as the International Organization for Standardization (ISO), ASTM International, Institute of Electrical and Electronics Engineers (IEEE), etc. The experiments described in this report are not standard tests and were specifically developed to examine HEAF phenomena. The term ‘test’ is used in some contexts to preserve continuity with previous programs or to describe facilities where standard tests are frequently performed. Standard test methods, where they exist, are used for some measurements.

into the experimental plan. The central component of the plan is the experimental matrix which specifies the key parameters for each experiment. This matrix has evolved over time and some experiments originally on the matrix have been removed, others replaced, and some added as the knowledge base has advanced. A graphical matrix for electrical enclosures is presented in Fig. 1 and Fig. 2, while the bus duct matrix is shown in Fig. 3. These figures are annotated to identify the experiment parameters, the user group interests, and year completed.

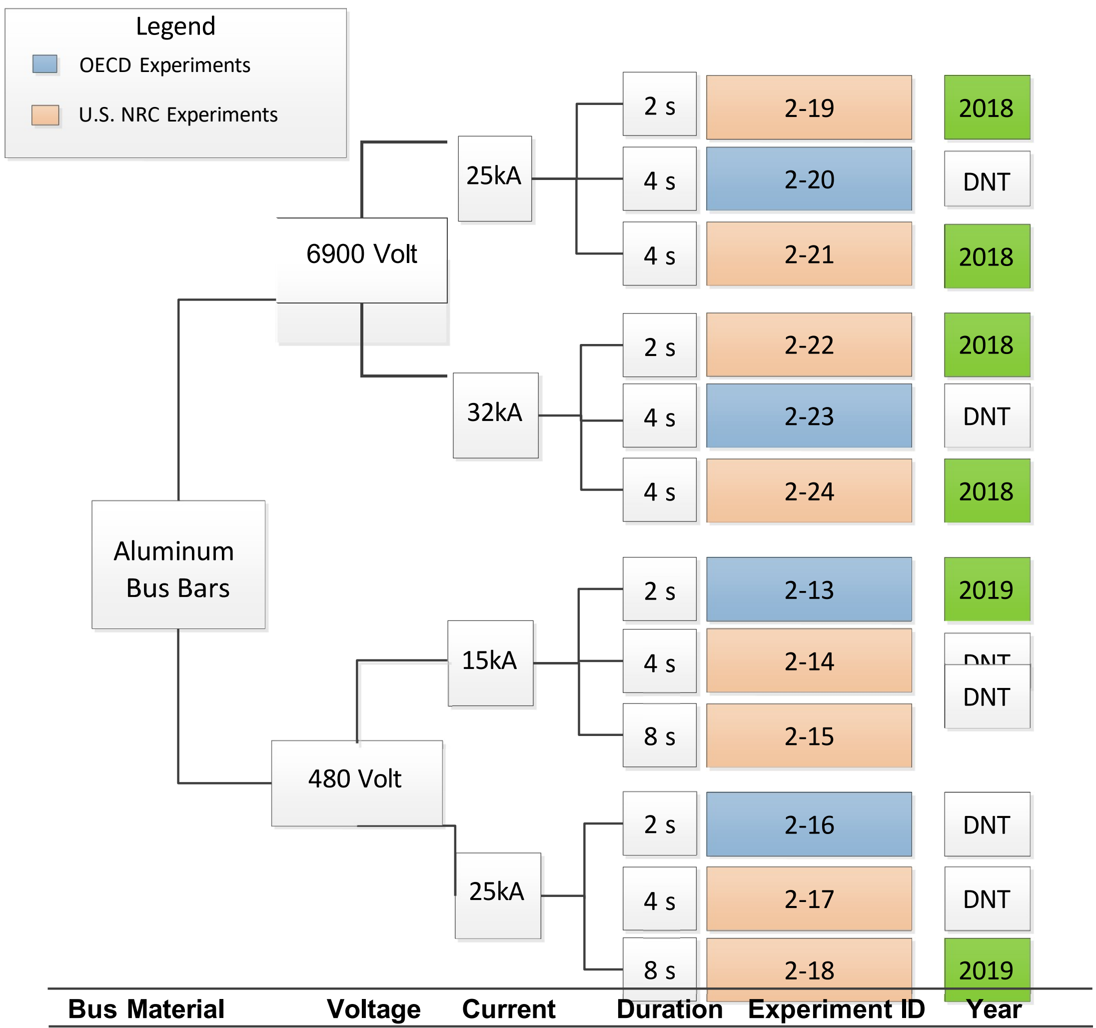

Fig. 1. Graphical Phase 2 Experimental Matrix for Electrical Enclosure – Aluminum Bus (included for completeness). These experiments are not documented in this report. (DNT, did not test)

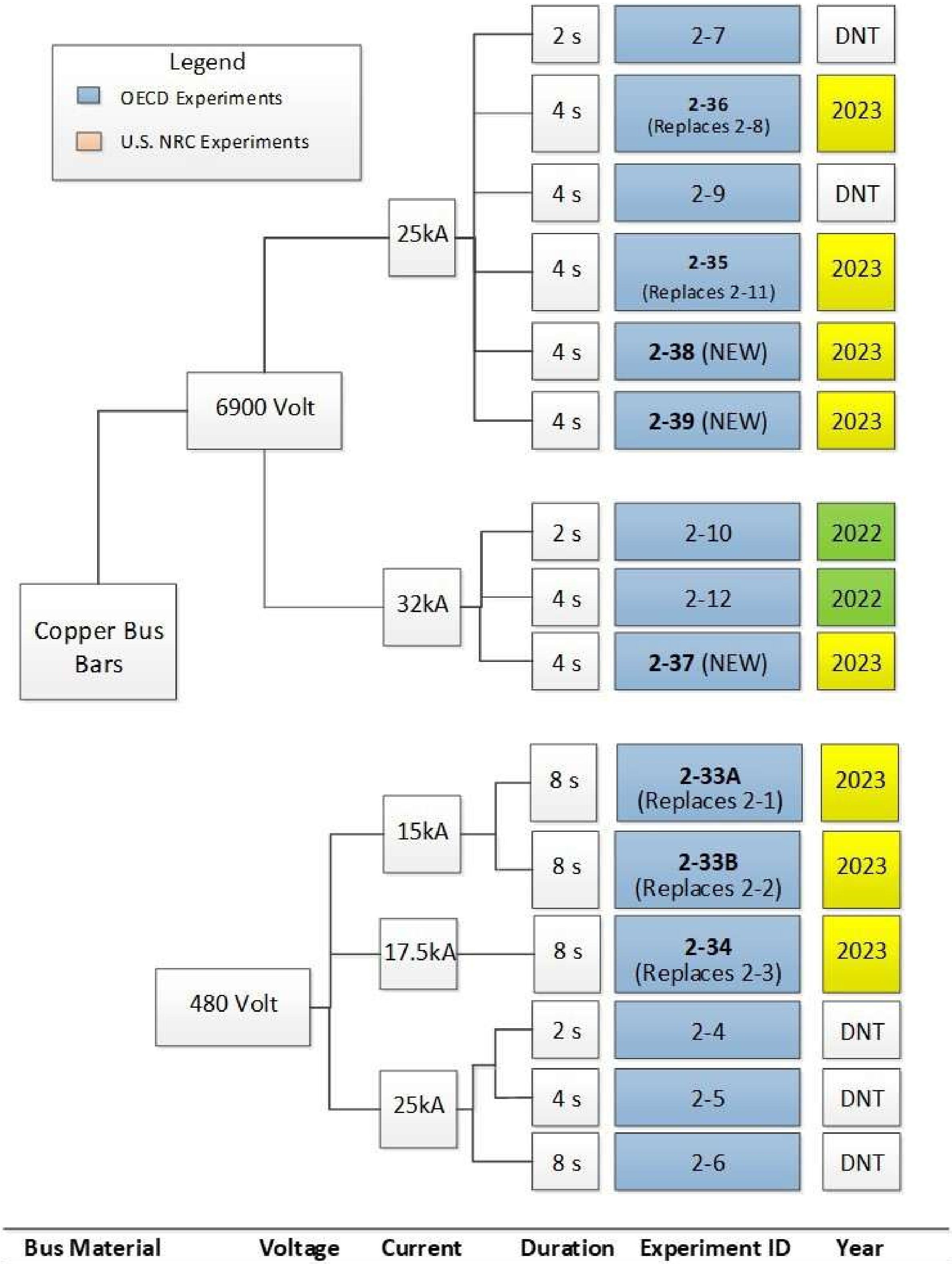

Fig. 2. Graphical Phase 2 Experimental Matrix for Electrical Enclosure – Copper Bus. Graphic shows voltage, arcing current, duration, experimental identification number and year experiment performed. (DNT, did not test)