Conceptual Test Plan for High Energy Arcing Faults Fire Experiments

PRELIMINARY DRAFT

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1 Background

Massive electrical discharges, referred to as High Energy Arcing Faults (HEAF), have occurred in nuclear power plant (NPP) switching components throughout the world. These incidents have been increasing as a result of the aging infrastructure and increasing energy demands. In general, HEAF in electrical equipment are initiated in one of three ways: poor physical connection between the switchgear and the holding rack, environmental conditions, or the introduction of a conductive foreign object (e.g., a metal wrench or screwdriver used during maintenance). A resulting HEAF would cause large pressure and temperature increases in the component cabinet, which could ultimately lead to serious equipment failure. After the energetic arcing, secondary fires have been observed to impact cables and other equipment in the vicinity of the event. The U.S. Nuclear Regulatory Commission (NRC), Office of Regulatory Research (RES), has asked Sandia National Laboratories (SNL) to design a testing program to study the effects from HEAF-induced fires to better understand the risk associated with these incidents.

2 Objective

High Energy Arcing Faults (HEAFs) have the potential to cause extensive damage to the failed electrical component and distribution system along with adjacent equipment and cables within the zone of influence. The significant energy released during a HEAF event can act as an ignition source to other components. The primary objective of this project is to perform experiments to obtain scientific fire data on the HEAF phenomenon known to occur in nuclear power plants (NPP) through carefully designed experiments. The goal is to use the data from these experiments and past events to develop a mechanistic model to account for the failure modes and consequence portions of HEAFs. These experiments will be designed to improve the state of knowledge and provide better characterization of HEAF in the fire probabilistic risk assessment (PRA) and NFPA 805 license amendment request applications. Initial impact of the arc to primary equipment and the subsequent damage created by the initiation of an arc (e.g., secondary fires) will be examined. The equipment considered in this study primarily consists of switchgears and bussing components.

3 Overview of Testing Needs

As defined by the Institute of Electrical and Electronic Engineers (IEEE), switchgear components are classified as low, medium, and high voltage which corresponds to less than 1 kVac, 1 to 35 kVac, and greater than 35 kVac, respectively. Testing of these components has occurred throughout the switchgear industry as well as at the research level; however, these latter experimental series were primarily focused on exposure to personnel and worker safety. The proposed testing to be conducted at Sandia National Laboratories is driven by a need to better understand the HEAF phenomenon within a NPP systems framework and the effects on secondary combustibles (e.g., electrical control cables). The experimental program seeks to resolve the uncertainty associated with the energetic arcing fault and subsequent fires in order to quantify the fire effects at common voltage levels.

For the initial HEAF impact, data are required for the blast affects, including the pressures, temperatures, and heat flux created within the switchgear component during the event. The initial impacts are important in understanding the structural integrity of the component during overpressure as well as the potential for catastrophic equipment failure for different manufacturer's specifications (e.g., Class 1E, non-Class 1E, NEMA rating). Understanding the heat exposure effects is relevant to determining the zone of impact. Quantifying influenced zone from a HEAF is important when analyzing the arc effects on secondary combustible materials (e.g., transient combustibles, adjacent equipment, electrical cabling). This provides the basis for subsequent damage, which may result from an ensuing fire. From these data, the NUREG/CR-6850 model may be refined to more accurately represent HEAF events.

3.1 NUREG/CR-6850

NUREG/CR-6850 is a joint publication between NRC and EPRI on the fire probabilistic risk assessment methodology for nuclear power facilities, which was originally released in September 2005. This work is separated into Volume 1, *Summary & Overview*, Volume 2, *Detailed Methodology*, and Supplement 1, *Fire Probabilistic Risk Assessment Methods Enhancements*.

When looking at the detailed methodology found in Volume 2, Appendix M for Chapter 11 discusses the analysis of HEAF and surrounding combustibles as well as the relevant assumptions applied during the analysis. The assumptions were developed from different incidents and previous studies. The majority of the events occurred in 4160 V switchgear/bussing equipment; however, other failures occurred in 480 V and 6900 V. The impacts of HEAF varied. It was found that damage was contained within 480 V compartments, but damage could be more extensive for high voltage ratings with fires lasting for tens of minutes outside of the compartment of origin before being extinguished. For the more intense arcing incidents, adjacent cabinets and secondary combustibles (e.g., cables) were impacted by the HEAF. Additional insights on the HEAF events may be found in Appendix M of Volume 2 for NUREG/CR-6850.

The zone of influence (ZOI) for HEAF events is intended to capture the damage generated during the energetic phase. What follows is a summary list of assumptions for switchgear.

- The initial arcing fault will cause destructive and unrecoverable failure of the faulting device.
- The 1st upstream over-current protection device will trip open.
- The release of copper plasma and/or mechanical shock will cause the next directly adjoining/adjacent switchgear and/or load center cubicles within the same bank to fault.
- Subsequent fires will burn consistent with a fire intensity and severity as described in the methodology.
- Unprotected cables that drop into the cabinet will ignite.
- Any unprotected cables in the first overhead cable tray will be ignited concurrent with the initial arcing event provided that the tray is within 1.5 m vertical distance of the top of the cabinet.
    - Fire will spread to other trays consistent with the treatment of cable tray fires described in the methodology.
    - This assumption also applied to trays located 0.3 m in any horizontal direction of the impacted cabinet or duct.
    - Cables in fire wrap or conduit are considered protected.
- Any vulnerable component within 0.9 m horizontally in front or in the rear of the cabinet will suffer physical damage and functional failure.

  - This includes operable structural elements like fire dampers and fire doors, equipment such as cables and transformers, and oil feed lines less than 1” diameter.
  - This excludes structural elements such as walls and floors as well as large components and purely mechanical components such as pumps and valves.

The following assumptions were made for HEAF in bus ducts.

- The entire length of the bus duct is considered damaged.
- Any cable or combustible immediately adjacent to the bus duct is considered damaged or has been ignited.
- Equipment connected to the bus duct has been damaged.
- Fire damage is limited with the presence of fire barriers.

The assumptions made in NUREG/CR-6850 are to be verified during the experimental process and the results from the test series will be used to refine the models within the fire PRA methodology.

4 Experimental Approach

To meet the goals of this test program, experiments will be conducted to explore the basic configurations, failure modes, and effects of HEAF events. Since the switchgears and other equipment necessary for testing is very expensive, this program relies on donated samples through the NRC and Energy Power Research Institute (EPRI) Memorandum of Understanding (MOU) as well as international collaboration. Therefore, at this stage, the testing program is flexible while the components to be tested are identified. As such, the proposed test matrix, testing facilities, and instrumentation is to be considered nominal and subject to change.

4.1 Test Facilities

Several SNL test sites have been considered for this test series. Two of the sites are the Nuclear Energy Work Complex (NEWC) and the Thermal Test Complex (TTC). Additionally, there is an unused power substation that is located in a remote area within the Kirtland Air force Base, which is where SNL is located, that could also be used for the tests. The NEWC and the TTC will need a power drop capable of providing the necessary voltage and current for these experiments. While many experiments, including the DESIREE-Fire and KATE-Fire tests, have been performed in these and other test sites at SNL, the type of experiments being considered for this project are unique. In addition to the power considerations, a structure or enclosure that can contain the shrapnel that may be created during the HEAF event would be necessary regardless of which facility is selected to conduct the experiment. This enclosure is also necessary to maintain a controlled environmental condition during the initial blast and fire scenario. The structure will also be needed to facilitate the direct measurement of species for oxygen calorimetry and heat release rate estimation. Further project planning for site selection, infrastructure protection, and safety considerations is needed for this particular test series. Once the test facility has been chosen and the testing equipment has been committed to the program, specific details will be added the test plan.

4.2 Test Matrix, equipment, and set-up

The preliminary test matrix proposed for this program is presented in Table 1. The number of tests and type of components can vary and highly depend on the number of items that can be provided to SNL. This table also shows a suggested test sequence. Details on each component to be tested and their set-up are included in the subsection following the table.

Table 1. Proposed matrix for HEAF fire tests

Test	Conduit	Bus Bars			Switchgear		Notes
		Duct	Cabinet (doors closed)	Cabinet (doors open)	Cabinet (doors closed)	Cabinet (doors open)	
1	X						
2	X						
3	X						
4	X						
5		X					
6		X					
7		X					
8		X					
9*			X				480 V
10*			X				4160 V
11*			X				6900 V
12*				X			480 V
13*				X			4160 V
14*				X			6900 V
15†					X		480 V
16*					X		4160 V
17*					X		6900 V
18*						X	480 V
19*						X	4160 V
20*						X	6900 V
Contingency 1*							
Contingency 2*							
Contingency 3*							
Contingency 4*							

* Tests will be dependent on resource availability and donations to the program.
† Test will involve a 480 V switchgear donated by SNL to the program.

4.2.1 High Voltage Cables

The recent HEAF event at H.B. Robinson Steam Electric Plant was a direct result of high voltage cable insulation failure. The cables that initiated the arcing event were located inside a conduit attached to the bus enclosure. Electrical shorting to the conduit resulted from a lack of strain relief, which aided in the deterioration of the cable insulation. After the HEAF event, a secondary fire continued to burn the trays located directly above the bus enclosure.

Given the detail on the Robinson incident, the initial tests will seek to produce a HEAF event within conduit. These tests are being included to help quantify the effects of a high voltage arcing incident within conduit, as a proof of concept with initiating an arc, and to acquire preliminary data on fault duration associated with fuse size. As shown in Figure 1, the damage of the conduit was non-trivial and warrants additional consideration.

Figure 1: Photo of the conduit damage above a switchgear

The plan for initiating an arc within conduit will be simplistic. Similar to the event depicted in Figure 1, electrical cables will be partially striped of insulation and connected together using a piece of copper wire. This copper wire will simulate a short within the conduit. In Figure 2, the cables to be shorted are illustrated in red. The nominal voltage to be tested will be 4.16 kV.

Sample, multi-stage cages designed to house common items such as cotton, paper, cables, leather, wood, and oiled rags will be positioned near the test cabinets to gather ignition power data. The intent is to analyze the impact of the heat released from an arc on these types of materials to investigate ignition potential. The cage will also contain instrumentation such as thermocouples and heat flux gages. Multiple cages can be used in each experiment and are not limited to the area above a cabinet; they will be positioned at different points of interest. In essence, each cage is a complex measuring probe, which can allow for consistent measurements techniques (and relative probes position) between tests.

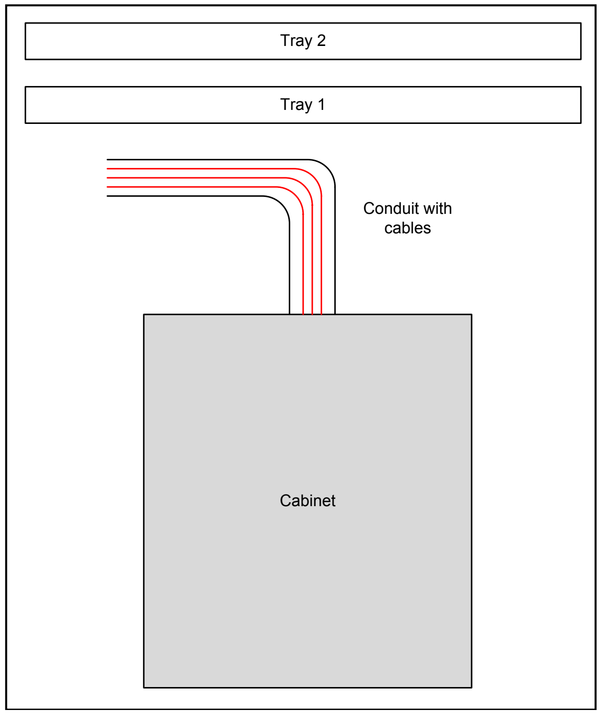

Figure 2: Diagram illustrating the intended conduit test layout

4.2.2 Bus Bar Equipment

Bus bars are widely used throughout NPP within the US. Typically, the bus bars are housed within a bus duct or a rated cabinet. Through maintenance errors, malfunctioning equipment, and general wear on the system, arcing faults have been observed in US NPP. As shown in Figure 3, incidents involving arcing faults within bus ducts have been observed. Similarly, HEAFs have occurred within rated cabinets, as shown in Figure 4. The intention of this series of experiments is to study the effects arcing on components and obtain the necessary data to improve fire risk models.

Figure 3: HEAF inside cable duct

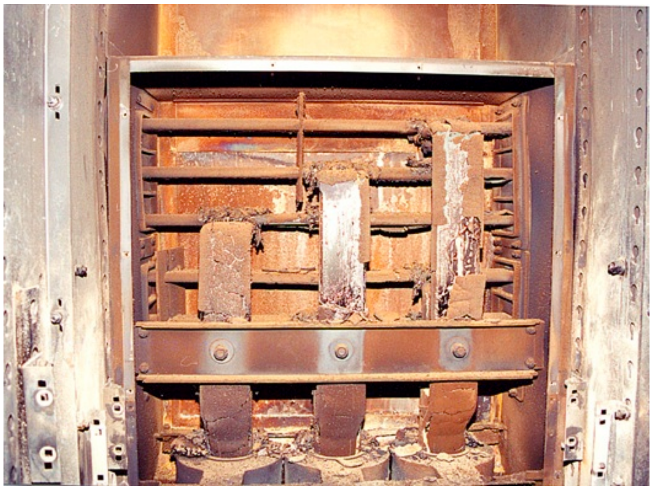

Figure 4: Damage to bus bars within a cabinet

To gain a fundamental understanding of the HEAF in bus bar configurations, tests will be conducted which include the duct and cabinet (open and closed) designs. For the tests involving the ductwork, sample cages will be located above the bus duct, but may be reconfigured as deemed appropriate. As depicted in Figure 5, the red bus bars are contained within a section of ducting. To create an arc, a piece of copper wire will be placed to initiate a short upon energizing the system.

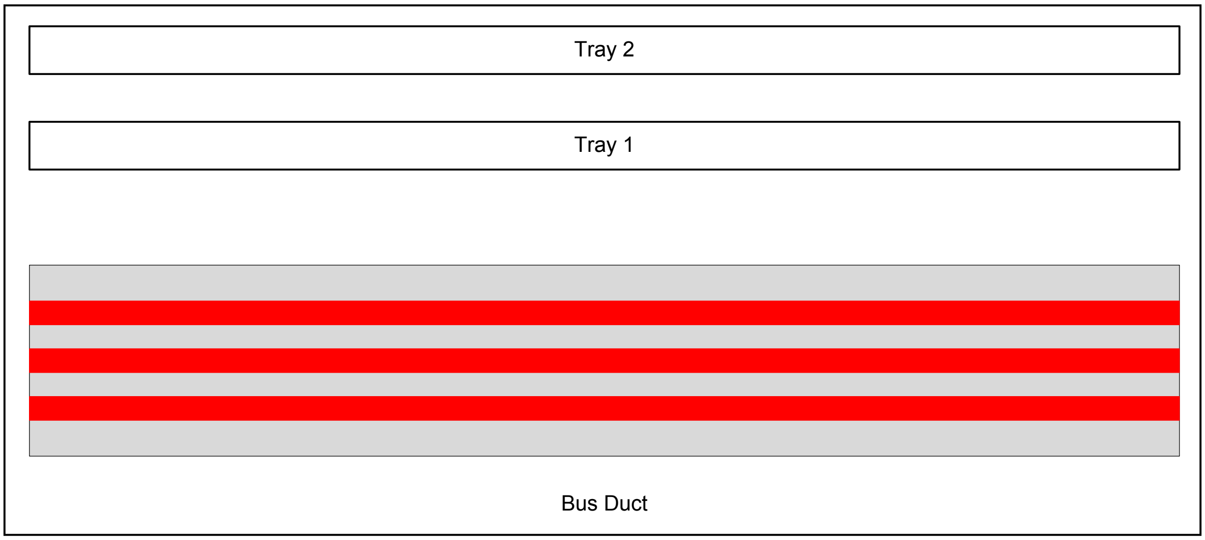

Figure 5: Diagram of bus bars within ducting

For the tests involving the cabinet configuration, it is anticipated that the method of initiating the arc will be explored. Two options appear to be the most feasible: connecting a bare wire between the bus bars prior to energizing them and, alternatively, introducing a conductive material after the equipment is energized. Target cabinets will be located adjacent to the cabinet being subjected to the arc incident, as depicted in Figure 6. After the initial scoping tests are conducted for the bus bar equipment, target combustible materials representative of those found in a typical NPP will be strategically located to investigate fires resulting from the arc event. An example of the location of the combustibles may be found in Figure 7.

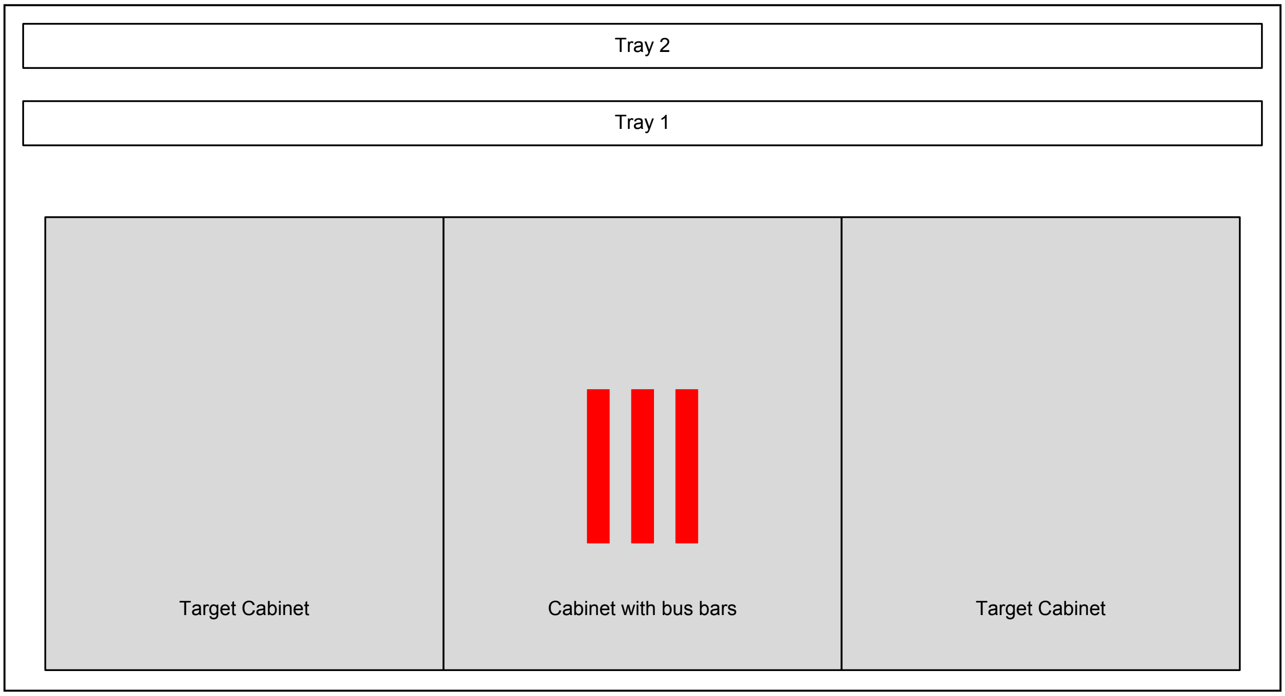

Figure 6: Draft test configuration for the bus bars within a cabinet

Figure 7: Combustible targets within the cabinet

4.2.3 Switchgear

Arcing events are known to occur within switchgear components. The switchgears donated to the program are expected to be low or medium voltage and, as such, the electrical feed system will need to accommodate low and into the medium voltage range. From the main feed, redundant safety systems (e.g., fusing, circuit breakers) are required to protect against site power losses. These safety systems are to be representative of those typically installed in NPP applications. The arc, once initiated, will persist until the safety system actuates (e.g., a fuse clear, breaker trip). Figure 8 and Figure 9 are photos from HEAF incidents inside switchgears.

Figure 8: Impact of HEAF event on the switchgear cabinet

Figure 9: Internal view of a HEAF incident along the posts

It is anticipated that the insights gathered from the bus bar tests will influence the method of inducing an arc within the switchgear. In order to initiate an arc, the use of a conductive material (e.g., bare copper wire, metallic tool) to simulate a ground fault is anticipated. Other methods, such as improper connection between the switchgear and housing cabinet, for HEAF initiation have been discussed and are still being developed. Similar to the bus bar tests, cabinets may be left open or closed to investigate the impact of the arc. Of additional interest are the effects of the NEMA rating on cabinet performance.

Secondary combustibles will be included in the testing in a similar fashion to the bus bar configuration. Impact to the internal components is of additional interest. The donated switchgear should include the electrical harnesses associated with the equipment to provide a representative configuration, as depicted in Figure 10. In addition to the cables within a conduit, trays will be placed above the cabinet as shown in Figure 11. The sample cages described previously in this document may also be of some interest, primarily to investigate the impacts of the arc at different locations.

Figure 10: Combustible components within the switchgear

Figure 11: Combustible targets above a cabinet structure

4.3 Secondary Combustibles

In an attempt to quantify the effects of the HEAF on other materials, common secondary combustibles will be staged and monitored. Within an NPP, it is common to have cabling run above bus cabinets or switching equipment. Tests including overhead cable trays will be integrated into the testing matrix. Primarily, the sample cage may be used to investigate the impacts of the arc on common combustible materials. However, actual materials (e.g., waste paper basket, brooms, rags) may also be included.

4.4 Instrumentation and Data Acquisition

Appropriate instrumentation will be required for the two distinct areas of interest; namely, the HEAF and the secondary fire. The data gathered are essential to characterize and quantify the effects of the incident in order to properly model a HEAF scenario. To capture the high-speed transients from an arcing event, data acquisition equipment needs to function at high frequency and the instrumentation must perform similarly. Instrumentation to obtain pressure, temperature, and heat flux exposure values will be included. Electrical data for the HEAF event would be collected. Data of particular interest will be:

- Arc intensity
- Arc duration
- Target damage as a result of the arc
- Fire damage

4.4.1 Arc event

The electrical arc within a component is the initiating event occurring during the HEAF scenario. General characteristics of the arc may be obtained for the different initial voltages (i.e., 480, 4160, and 6900 V). Pressure transducers and heat flux gauges may be used within the structures to gather relevant data. Personnel involved with the IEEE HEAF events have suggested that data should be collected at approximately 20 milliseconds or lower to obtain high enough resolution to develop representative information on the arc event. Thin-skin calorimeters can provide the speed and precision necessary for the experiments and subject matter experts (SMEs) are available to further develop the instrumentation and data acquisition methods for the experiments. Directional flame thermometers (DFT) will also be used to estimate the heat flux from the arc. These items are relatively inexpensive and have been used in quick response measurements of heat flux for propellant burns. Noise in the data collected is of great concern. To minimize the effects of noise, fast recovery DC amplifiers and inverse filter functions are being considered.

4.4.2 Enduring fire

Data on the enduring fire after the HEAF will also be collected. It is desired to quantify the effects of the arc on the cabinet and components within the cabinet as well as on secondary combustibles. Type-K thermocouples may be used in conjunction with specifically located heat flux gauges to obtain the relevant data in the region of the instrumentation cages are placed and in specific locations around the interior and exterior of the compartment.

5 Arc flash versus arc blast

There are major differences between “arc flash” testing and “arc blast” testing. During an arc flash the voltage can drop to about 10% of the original while current is maintained. However, to obtain an arc blast, both voltage and current need to be maintained for a relatively prolonged period of time (1 to 2 seconds). Therefore, the power load of an arc blast is much larger and is very difficult to maintain under a testing environment without causing power problems. The intensity of an arc flash is therefore less than that of an arc blast. The test series in this testing program are focused on arc blasts. If arc blasts are not feasible in the testing environment, the possibility exists that an equivalent heat-releasing surrogate be used to expose the NPP components to a transient heating that will also help improve current fire PRA methods.