High Energy Arcing Faults in Electrical Equipment

Phase 2

Draft Test Plan

Prepared
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1. Background

International nuclear power plant (NPP) operating experience data clearly show that a significant number of high energy arcing fault (HEAF) events have occurred worldwide in operating plants. A report published by the Organisation for Economic Co-operation and Development, Nuclear Energy Agency, (OECD/NEA) in June 2013 [1] documents 48 different HEAF fire events reported by the twelve member countries of the OECD/NEA Fire Incidents Records Exchange (FIRE) Project. This number, which has further increased in recent years, represents approximately 10 % of the entire fire events reported to the FIRE Database.

Although much of the fire physics and fire dynamics is readily understood for the typical NPP fire event, the same cannot be said about the HEAF phenomena. In 2009, an OECD/NEA IAGE Task Group defined a "High Energy Arcing Fault (HEAF)" [1]

> *"High Energy Arc Faults (HEAF) are energetic or explosive electrical equipment faults characterized by a rapid release of energy in the form of heat, light, vaporized metal and pressure increase due to high current arcs between energized electrical conductors or between energized electrical components and neutral or ground. HEAF events may also result in projectiles being ejected from the electrical component or enclosure of origin and result in fire.*
>
> *The energetic fault scenario consists of two distinct phases, each with its own damage characteristics and detection/suppression response and effectiveness.*
>
> - *First phase: short, rapid release of electrical energy which that may result in projectiles (from damaged electrical components or housing) and/or fire(s) involving the electrical device itself, as well as any external exposed combustibles, such as overhead exposed cable trays or nearby panels that may be ignited during this energetic phase.*
> - *Second phase (i.e., the ensuing fire[s]): is treated similar to other postulated fires within the zone of influence.*
>
> *An arc is a very intense abnormal discharge of electrons between two electrodes that are carrying an electrical current. Since arcing is not usually a desirable occurrence, it is described as an "arcing fault." The arc is created by the flow of electrons through charged particles of gas ions that exist as a result of a vaporization of the conductive material."*

Another factor that becomes readily apparent about HEAF events with respect to safe NPP operation is that the HEAF events tend to create challenges that complicate the plant's ability to safely shut down the reactor and maintain it in a safe condition. The electrical disturbance initiating the HEAF often causes loss of essential electrical power and physical damage, while the products of combustion pose significant challenges to the operators and fire brigade members handling the emergency. In the United States, for example, internal fire risk is one of the most dominant hazard contributors for many plants. A preliminary examination of the risk assessment information from ten U.S. NFPA 805 nuclear power plants found that HEAF-initiated scenarios were significant contributors to the overall fire risk. The range of fire risk contributed by HEAF initiated fire scenarios ranged from 1 % to 27 % on a unit basis. The average per unit risk contribution was approximately 15 % [2].

Two full-scale HEAF research programs related to the hazards posed by HEAF events in NPP electrical equipment have been recently completed. One sought to understand the HEAF events that occurred at the Onagawa NPP in Onagawa, Miyagi, Japan during the earthquake of 11 March 2011 [3]. The second recently completed HEAF research program is Phase 1 of the OECD/NEA/CSNI HEAF experimental research program [4]. Both research programs illustrated that more severe physical damage occurred to equipment where aluminum was consumed during the HEAF.

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) conducted a PIRT exercise in February of 2017 [8]. The PIRT exercise was performed via a facilitated expert elicitation process. In this case, the expert panel was comprised of six international HEAF experts and the panel was facilitated by NRC staff. The objective of this PIRT exercise was to develop an ordered list of phenomena involved in HEAF events. This list will be ordered by priority; the more important a phenomena is judged to be, and the poorer its state of knowledge is judged to be, the higher its priority. This information was used to inform this test plan creation and aided to focus testing and instrumentation choices.

The PIRT panel covered three distinct HEAF scenarios. The first was a HEAF occurring in an electrical enclosure with a cable tray passing over the enclosure. The second was a HEAF occurring in a bus duct passing over an electrical enclosure. The third was a HEAF occurring in an electrical enclosure situated in a bank of similar enclosures.

As a result of the process, “level one” phenomena were identified. The level one phenomena are those that were ranked with high importance and low state of knowledge. These represented the key parameters and research priority. The level one phenomena identified by the panel included the following:

- Electrical arc characterization: thermal and magnetic effects of the arc, arc ejecta (smoke, ionized gas, conductive particulate), arc location, and migration;
- Pressure effects: mechanical shock, projectile impact, and degradation of the compartment pressure boundary;
- Arc mitigation: the use of HEAF-resistant equipment, thermal insulation, or “HEAF shields” to minimize damage incurred as a result of a HEAF;
- Target characterization: establishing the sensitivity of target equipment to various failure mechanisms, and associated damage criteria;
- Internal ensuing fire: the likelihood, impact, and phenomenology of an enclosure fire ignited by a HEAF event

The results of the PIRT and previous research efforts have been used to guide work discussed in this proposed test plan.

2. Current HEAF PRA Guidance

Currently, there are two available methods to model HEAF events. Electrical enclosure guidance is contained in NUREG/CR-6850 “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities Volume 2: Detailed Methodology,” Appendix M [5]. This model is very limited in the fact it was largely derived from empirical evidence from one single well-documented HEAF event that occurred at the San Onofre Nuclear Generating Station (SONGS), Unit 3, on February 3, 2001. A second method that focuses on bus duct HEAF events can be found in “Fire Probabilistic Risk Assessment Methods Enhancements, Supplement 1 to NUREG/CR-6850 and EPRI 1011989,” Section 7, “bus duct (counting) guidance for high-energy arcing faults (FAQ 07-0035)” [6].

Both methods employ a “one size fits all” zone of influence (ZOI) methodology which prescribes a damage zone around an initiating component. These ZOIs prescribe damage to potentially vulnerable electrical or electromechanical components nearby such as cables, transformers, ventilation fans, other cabinets, etc. The international OECD/NEA experimental HEAF Project was created in an attempt to take an exploratory scientific approach to better understand the HEAF phenomena and produce data that could be used to better inform fire modeling techniques for postulating HEAF scenarios.

3. Objective

The objective of this study is to quantitatively characterize the thermal conditions, pressure conditions, and deposits on nearby surfaces created by HEAFs occurring in electrical cabinets[*] and bus ducts, and provide qualitative illustrations of the impact of HEAFs on typical switchgear room targets such as electrical cable and nearby equipment. HEAFs in cabinets containing aluminum bus bars are of particular interest since they may produce more severe effects than HEAFs in cabinets containing copper bus bars. When combined with target damage criteria, the HEAF experimental data may be used by the NRC GIRP to determine the adequacy of existing HEAF ZOIs in NUREG/CR-6850 Chapter M for electrical cabinets with aluminum bus bars and bus ducts containing aluminum.

4. Experimental Approach

Previous work in Phase 1 examined a variety of electrical cabinets encompassing several manufacturers, manufacture dates, materials, and configurations [4]. While the tested cabinets provided an important view of the performance of available equipment, there were too many variations to fully understand the importance of specific variables on the severity of the HEAF.

To better understand the importance of variables such as bus bar material, operating voltage, current, and arc duration on the conditions produced by the HEAF, electrical enclosures and bus ducts will be selected so that repetitive and repeatable tests can be performed using the same enclosure configurations. The enclosure configuration will be chosen based on typical plant design and preliminary tests will be performed to ensure the arc will not extinguish until the power supply to the cabinet is turned off. The bus bar configuration will be chosen based on the desire for a known and repeatable arc location and plasma ejection direction. Real-time measurements of voltage and current during the arc will provide data for calculation of arc energy and arc power for comparison to thermal and pressure measurements. The use of a common electrical cabinet and bus duct should increase repeatability between experiments. No testing to be performed will subject any equipment to conditions that exceed equipment ratings.

4.1 Arc Initiation / Location

Low and medium voltage arcs will be initiated using a 2.6 mm diameter (10 AWG) stranded copper wire, strung across the three phases of power within the electrical cabinet or bus duct [15], at the desired initial arc location. Each initial arc will be created when the three-phase electrical supply to the cabinet or bus duct is energized, causing a direct short circuit at the desired position for the HEAF. Operating experience from HEAF events will be used to select representative arc locations within the enclosure. The arc locations will be across breaker stabs, at enclosure power supply entry locations, or along bolted connections within the enclosure/bus duct that could be subject to fatigue failures.

The use of a shorting wire is necessary during testing to provide predictable arc initiation at the desired position within the electrical enclosure or bus duct. Within microseconds of energy delivery, the shorting wire usually vaporizes, becoming a column of ionized gas and plasma, as would be found in a typical arc column.

Operating experience from HEAF events illustrates that faults can be initiated as single phase-to-phase or phase-to-ground arc, but may quickly progress to involve all phases as the ionized gasses and vaporized materials migrate within the electrical enclosure. This is evident from several LERs:

- The Kewaunee HEAF event (LER 87-009-00) involved a phase-to-ground fault, which "progressed to a phase-to-phase fault which accounted for the extensive bus damage."

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[*] In this proposed test plan, the term electrical cabinet includes electrical enclosures such as motor control centers (MCC), electrical switchgear (SWGR), distribution panels (DP), distribution switchboards, and similar equipment.

- The Prairie Island HEAF event (LER 01-05-00) involved a “C-phase ground arcing event, which quickly involved all phases.”
- The Zion HEAF event (LER 94-005-01) where the “failure started as a single phase to ground fault which rapidly evolved into a three phase to ground fault.”
- The Shearon Harris HEAF event (LER 89-017-01) that involved multiple phases, even in an isolated phase bus duct:

> *“The initiator of the ground faults has been identified as aluminum debris in the isolated phase bus duct, which was deposited in the bus duct from previous failures of the duct cooling system dampers. Arcing from the aluminum debris in the bus led to a double phase to ground fault at the "B" main power transformer. Magnetic forces from this fault broke insulators in "A" phase and "B" phase of the isolated phase bus duct. The "A" phase conductor contacted the bus enclosure creating another ground fault. These faults elevated the voltage at the generator neutral and led to another ground fault in the neutral grounding transformer cubicle.”*

4.2 Arc Current /Voltage

The KEMA Laboratories – Chalfont test facility will provide the electrical voltages and currents selected for sustained arcing within the subject enclosures independent of the local electric grid. KEMA will also provide the electrical measurement results required to quantify the characteristics of the power supplied to the enclosures during the arcing experiments.

NRC and Sandia National Laboratories (SNL) performed a literature and operational history review [7], which yielded very little information to inform the typical fault currents associated with HEAF events. This parameter is readily known at the time of the event, but rarely reported in licensee event report (LER) information of actual HEAF events. Therefore, the arc currents were selected to replicate fault capacities of typical electrical distribution systems within NPPs considering the ratings of the breakers.

The arc voltage will be selected to replicate typical power distribution systems commonly found within NPP’s. The test program will split testing for electrical enclosures between low voltage equipment and medium voltage equipment. The low voltage range is defined as less than 600 V.

The nominal current and voltage directly contributed to the total arc energy released during the event and were identified as key parameters for future model input in a recent international HEAF Phenomena Identification and Ranking Table (PIRT) expert elicitation exercise [8].

4.3 Duration

Operating experience has shown that protective devices have not always worked as designed. Incorrect breaker settings and fuse sizing due to design errors can increase the likelihood of a HEAF and allow for extended duration HEAF events. Operating experience has also indicated that faults can be initiated in locations not protected by fault clearance devices, allowing for extended fault exposure times. The HEAF event that occurred at Diablo Canyon on May 15, 2000 (ADAMS Accession No. ML003725220), for example, exhibited successful openings of the switchyard and main generator field breakers immediately at the start of the event. Coast down of the main generator, however, continued to feed the arc fault on the 12 kV bus.

Protection coordination, when properly implemented, would limit the duration of an arc fault to a just a few cycles; however, many of the HEAF events that contribute to the HEAF frequency involve one or more breaker malfunctions that fail to clear the fault. The durations selected for the HEAF tests will be a controlled parameter based on a review of operating experience where arc hold time information was readily available from fault recording devices or could be inferred by breaker response indications. However, little information is usually available regarding HEAF durations from operating experience because this information is rarely included in LERs. Table 1 includes duration information for four HEAF events. Based on these events, arc hold times between two and twelve seconds were identified as reasonable values.

Table 1. HEAF duration from U.S. operating experience

Plant Name	Date	Arc Duration
Robinson	03/27/2010	8 s to 10 s
Diablo Canyon	05/15/2000	11 s
Prairie Island	08/03/2001	>2 s
San Onofre	02/03/2001	>2 s
Fort Calhoun	June 7, 2011	42 s (required operator intervention)

The Robinson and Diablo Canyon NPP HEAF events listed in Table 1 occurred at 4160 V and 12000 V, respectively, and at much higher currents than KEMA's generators can provide for these extended arc durations. Therefore, a true representation of the Robinson and Diablo Canyon events cannot be created due to power limitations. KEMA's largest generator can deliver 2200 MVA to a bolted-fault. Voltage, current, and frequency all factor into the maximum duration of energy delivery. Based on the arc durations in Table 1, and KEMA capabilities, the selected experimental arc durations are 4 s and 8 s for low voltage equipment, and 2 s and 4 s for medium voltage equipment (KEMA power limitations restrict durations to 4 s at medium voltages).

4.4 Measurements

A list of measurements and the corresponding measurement devices is contained in Table 2. The thermal environment around the cabinet during the HEAF experiments will be characterized by measurements of temperature, time varying and average heat flux, and incident energy. The time varying and maximum pressure inside of the cabinet will also be measured during the experiments. HEAF generated deposits will be collected on vertical coupons, and analyzed for composition and conductivity after the experiments.

The extent of the arc plasma and fire will be characterized using optical (visible and IR spectrum video) means. IR imaging will provide information as to the extent of the arc plasma and fire, as well as cabinet surface temperature information.

Table 2. Metrology

Measurement	Device
Temperature	Thermocouple (TC), Plate Thermometer (PT), IR imaging
Heat flux (time-varying)	Plate Thermometer (PT)
Heat flux (average)	Plate Thermometer (PT), Thermal Capacitance Slug (T_{cap} Slug)

Measurement	**Device**
Incident energy	Slug calorimeter (slug)
Cabinet internal pressure	Piezoelectric pressure transducer
Compartment internal pressure**	Piezoelectric pressure transducer
Arc plasma / fire dimensions	Videography, IR filter videography, IR imaging
Surface deposit analysis	Energy dispersive spectroscopy, electron backscatter diffraction

There are many possible variations in equipment, cabinet installation, and operating conditions. Some of the possible variations are listed in Table 3, and shown in flow chart format in Figure 1 and Figure 2. Based on the results of the Phase I project, and the resources available for this experimental series, the experimental test matrix will be limited to variations in bus bar material, bus duct material, voltage, current, and arc duration as shown in

Table 4 and Table 5. Choosing to use a generic commercial cabinet fixes many of the possible variations, but the cabinet has yet to be determined. Thirty-six (36) experiments are needed to explore the five (5) main variables, as shown in Table 6 and Table 7, including replicate testing. Replicates, which are important for establishing experimental repeatability and uncertainty.

Table 3. Potential experimental variables

Potential Variable	**Potential Values**
Equipment Type	Cabinet, Bus Duct
Bus bar material	Aluminum, Copper
Bus duct material	Steel, Aluminum
Voltage	480 V, 4160V, 6900 V
Current	I_1, I_2
Frequency	60 Hz
Power configuration	Delta, Wye
Equipment grounding	Grounded, Ungrounded (Floating)
Arc duration	100 ms to 10 s
Arc Energy	Dependent on other variables
Arc location	
Bus bar insulation	Insulated, Uninsulated
Bus bar spacing (arc length)	
Bus bar size	
Bus bar thickness	
Enclosure thickness	

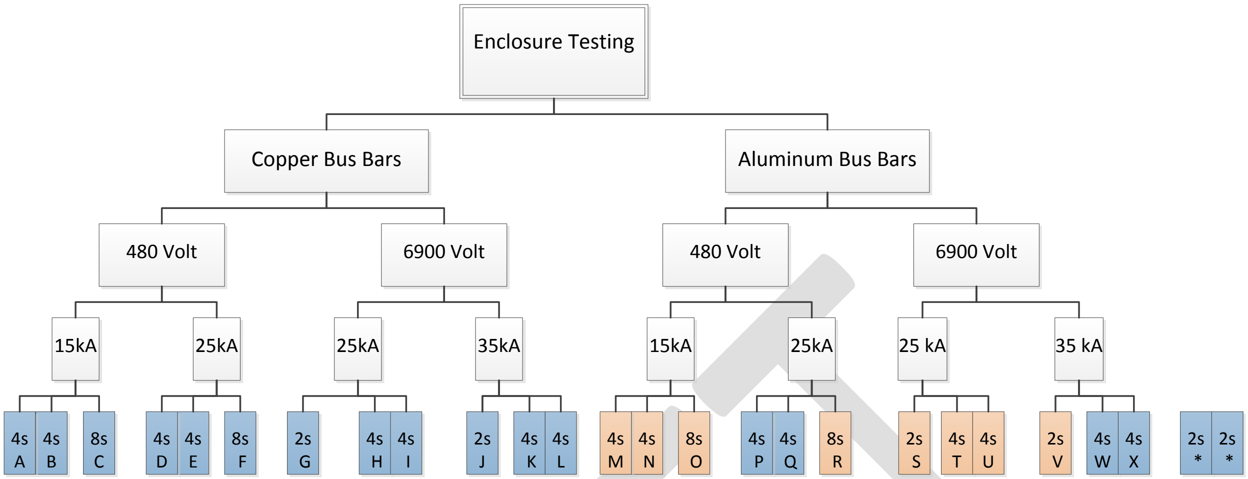

Figure 1. Electrical cabinet experimental combinations.

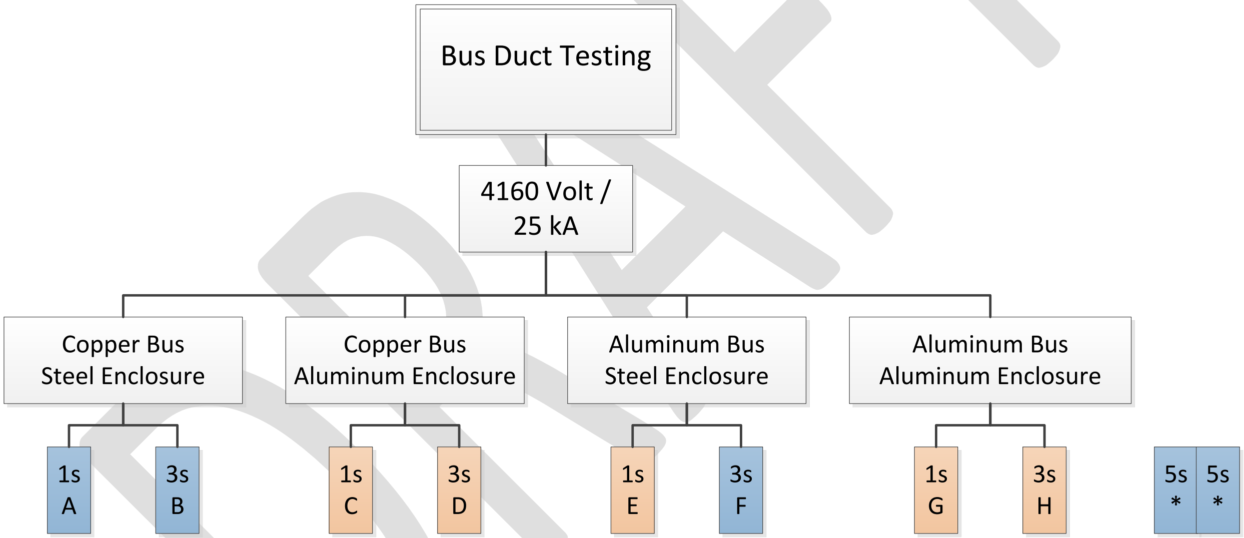

Figure 2. Bus duct experimental combinations.

Legend

🟦 OECD Test Contribution

🟧 U.S. Specific Supplemental Testing driven by GI Program

Undetermined Tests to explore unanticipated results/enhance repetition

Table 4. Experimental variables – electrical cabinets

Variable	**Values**
Bus bar material	Aluminum, Copper
Voltage	480 V, 6900 V
Current	23 kA, 35 kA
Arc duration	2 s, 4 s, 8 s

Table 5. Experimental variables – bus ducts

Variable	**Values**
Bus bar material	Aluminum, Copper
Bus duct material	Aluminum, Steel
Voltage	4160 V
Current	25 kA
Arc duration	1 s, 3 s

Table 6. Total number of experiments – electrical cabinets

Variable	**Variations**
Bus bar material	2
Voltage	2
Current	2
Arc duration	2
Total experiments:	**24** (replicate cases run at 4 s, see Figure 1) +2 potential extra tests for unanticipated results

Table 7. Total number of experiments - bus ducts

Variable	**Variations**
Bus bar material	2
Bus duct material	2
Voltage	1
Current	1
Arc duration	2
Total experiments:	**8** +2 potential extra tests for unanticipated results

5. Experimental Facility

The experiments will be performed at KEMA Laboratories Chalfont, in Pennsylvania, USA. The Phase 1 experiments were also performed at this facility. Low voltage experiments will be performed in Test Cell 7, where the previous Phase 1 experiments were performed. Test Cell 7 is approximately 9 m wide, 7 m deep, and 8 m high, and is illustrated in Figure 3. Medium voltage experiments will be performed in Test Cell 9. Test Cell 9 is approximately 10 m wide, 10 m deep, and 11 m high, and is illustrated in Figure 4. Test Cell 9 is a new facility that is better equipped for medium voltage experiments, but does not have an enclosed hallway behind the cell for staging and protection of equipment.

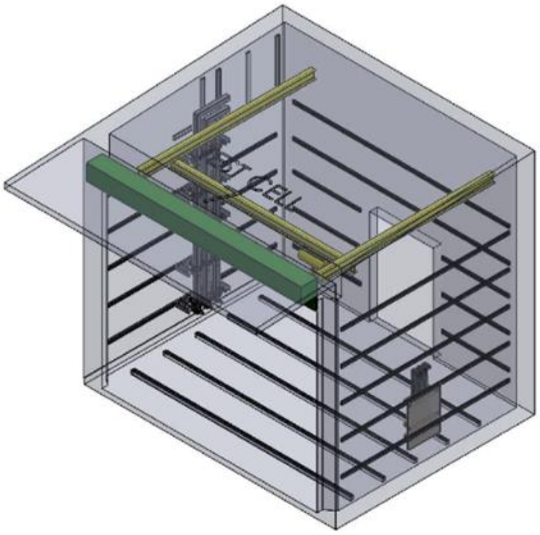

Figure 3. Test Cell 7 - Low voltage experiments.

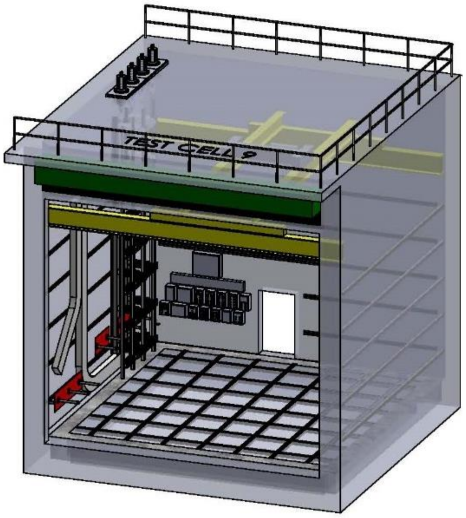

Figure 4. Test Cell 9 - Medium voltage experiments.

The KEMA facility can provide a combination of electrical voltage, current, and arc duration based on the limitations of the on-site equipment. In previous experiments, the low voltage bus provided a combination of approximately 40 kA at 480 V for 8 s. The medium voltage bus provided a combination of approximately 25 kA at 4.160 kV for 4 s.

Details of the KEMA facility are presented in the Phase 1 Report [4].

6. Electrical Cabinets

NRC has specified that commercial cabinets be used instead of functional cabinet mockups. An example cabinet with the desired bus bar configuration is shown in Figure 5. Since the experiments seek to examine the arcing phase of the HEAF, the cabinets will be populated with minimal additional equipment, wiring, or cable. The cabinets will have non-functional breakers installed to mimic the loading configurations of typical electrical enclosures and ventilation conditions. The breakers will be non-functional as the breaker performance is not a goal of the test program.

The arc wire will be installed as shown in Figure 6. If the arc is not sustained for the desired duration, the arc wire may be moved to another location.

Figure 5. Electrical cabinet bus bar example.

Figure 6. Example arcing wire location.

7. Instrumentation and DAQ

Many of the measurement techniques utilized in Phase 1 will continue. The combination of shielding, grounding, isolation, and data acquisition to reduce the impact of electromagnetic interference (EMI), as shown in Figure 7, will be applied to all the thermal and pressure measurements. Improvements will be explored to increase the data acquisition rate and reduce the impact of malfunctioning or destroyed sensors.

7.1 Data Acquisition

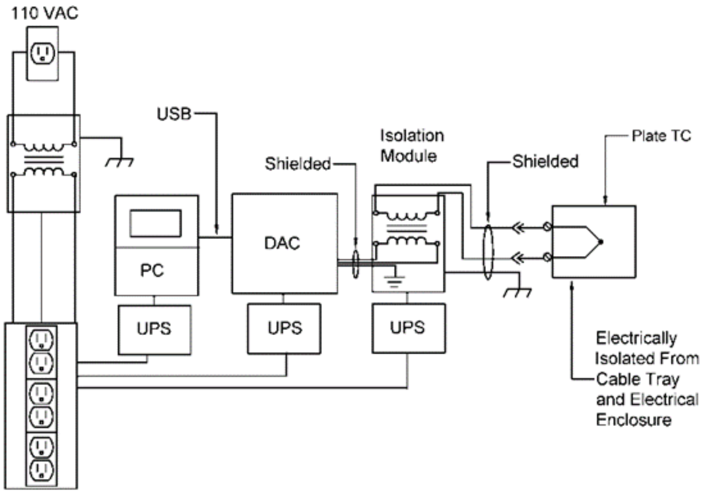

Figure 7. EMI resistant wiring concept.

7.2 Slug Calorimeter

Incident energy will be measured using an arc energy style slug calorimeter (slug) [9], due to its common use in the study of arc flash effects on protective clothing (Figure 8). Slug calorimeters located near the HEAF are expected to over-range, however, so additional measurement methods are needed to characterize the HEAF.

Figure 8. Slug calorimeter installed on a test stand.

7.3 Plate Thermometer

Modified plate thermometers [10] will measure the temperatures during the HEAF experiments, as used in Phase I (Figure 9 and Figure 10). Time-varying and average heat fluxes are calculated from the PT temperature data. Plate thermometers can operate in more severe thermal environments than slug calorimeters, but may also over-range when located in the HEAF plasma. Potential modifications of plate thermometer (plate and TC) are being explored to provide higher temperature and heat flux capabilities.

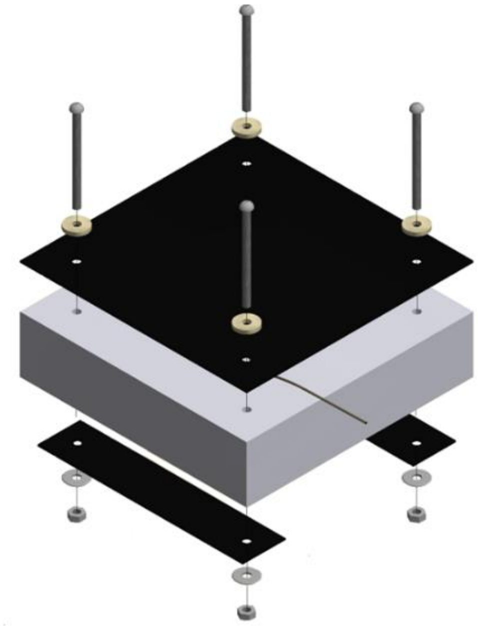

Figure 9. Modified plate thermometer.

Figure 10. Modified plate thermometer. Side view.

7.4 Thermal Capacitance Slugs

Thermal capacitance slugs (T_{cap} slug) will be used to measure the average heat flux produced by the HEAF. A cross section of a T_{cap} slug is shown in Figure 11, which is a modified example of the thermal capacitance slug described in ASTM E457-08 [11]. It is anticipated that the slug will be composed of an insulated tungsten or molybdenum rod. These two metals have much higher melting points than copper or Inconel, while having similar thermal inertia and higher thermal conductivity than Inconel. These properties will increase the survivability of the slug in the HEAF thermal environment.

The length of the slug will be designed based on direct exposure to the HEAF for the entire expected arc duration. The T_{cap} slug will be modeled with the Fire Dynamics Simulator (FDS) [12] to determine the optimal length of the metal cylinder. Cone calorimeter [13] experiments will validate the performance of the modified Thermal Capacitance Slugs (T_{cap} slug). The goal is to provide a large enough ΔT for reasonable levels of measurement uncertainty while not over-ranging the attached thermocouple. The addition of a modified T_{cap} slug will improve measurement capabilities in severe environments, such as the HEAF and aluminum combustion seen in Test 23 of Phase 1.

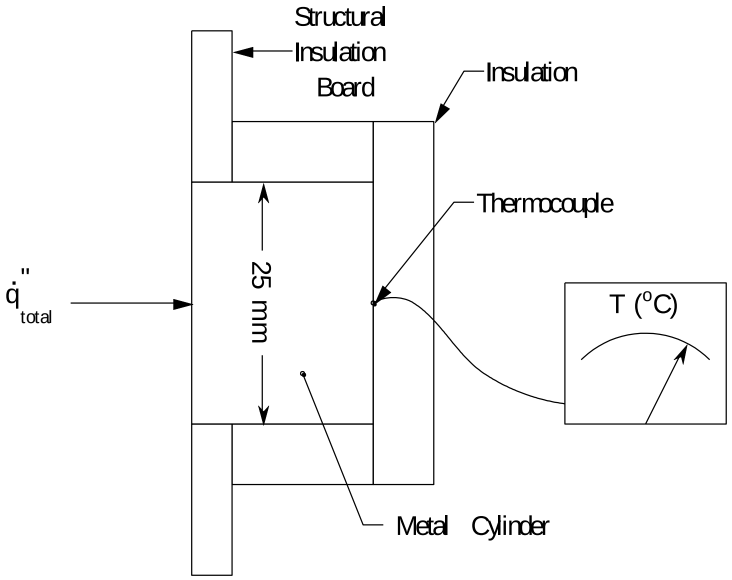

Figure 11. Cross section of thermal capacitance style slug. Not to scale. Length not yet determined.

7.5 Pressure Measurement

Pressure measurement will be improved to reduce the electro-magnetic interference (EMI) experienced in Phase 1. Piezoelectric style pressure transducers will be used instead of the strain gauge type in Phase 1.

7.6 Compartment Pressure Measurement **

**In addition to the in-cabinet pressure measurements, an attempt will be made to evaluate the pressure rise inside of a sealed compartment. Piezoelectric style pressure transducers will be used and a mock sealed compartment of a known volume will be built to enclose the target electrical enclosure. Due to the sealed nature of this arrangement limited instrumentation and video data will be collected. This proposed evaluation is not currently included in the test matrix and will constitute additional testing if deemed necessary by the HEAF project members.

7.7 Video / Thermography

The size of the arc plasma and fire ejected during the HEAF will be studied using optical means. A portion of the HD video cameras will be equipped with IR pass filters to better image the plasma / fire from the HEAF. IR filter equipped cameras will be located in the test cell with orthogonal lines of sight in three dimensions.

7.8 Physical Damage, Deposits, and Conductivity of Representative Targets

Steel or other material coupons will be installed to collect samples of HEAF deposits for later analysis of chemical composition and conductivity. Cables samples will be installed to examine the effects of the HEAF on typical NPP switchgear room targets.

8. Experimental Setup

8.1 Electrical Cabinet Setup

The setup of a typical electrical cabinet experiment is shown in Figure 12 and Figure 13. The cabinet is in the test cell approximately 1 m to 2 m from the power supply bus mounted on the wall. Thermal transducers and samples are mounted on steel vertical test stands. Due to the configuration of the power supply bus bars, test stands are located on three of the four sides of the cabinet.

The primary arc plasma and fire are expected to eject from the rear of the cabinet, so instrument stands are located at 0.9 m, 1.8 m, and 2.7 m from the rear panel of the cabinet (Figure 13 and Figure 15). Single instrument stands are installed on the sides of the cabinet, 0.9 m from each side. Sensors and target samples are mounted on the test stands in configurations designed to reduce the shadow effect of the sensors closer to the cabinet on the sensors farther from the cabinet. Plate thermometers (PT), slug calorimeters, and T_{cap} slugs are installed on the test stands to provide quantitative thermal data. It is anticipated that the PTs will provide measures of time varying heat flux and average heat flux over the arc duration. The arc energy slug data will be analyzed to provide the incident energy. The T_{cap} slugs will be analyzed to provide another measure of arc energy and average heat flux over the arc duration. Alternative sensor materials will be explored with the goal of increasing the maximum measurable temperature, heat flux, and incident energy.

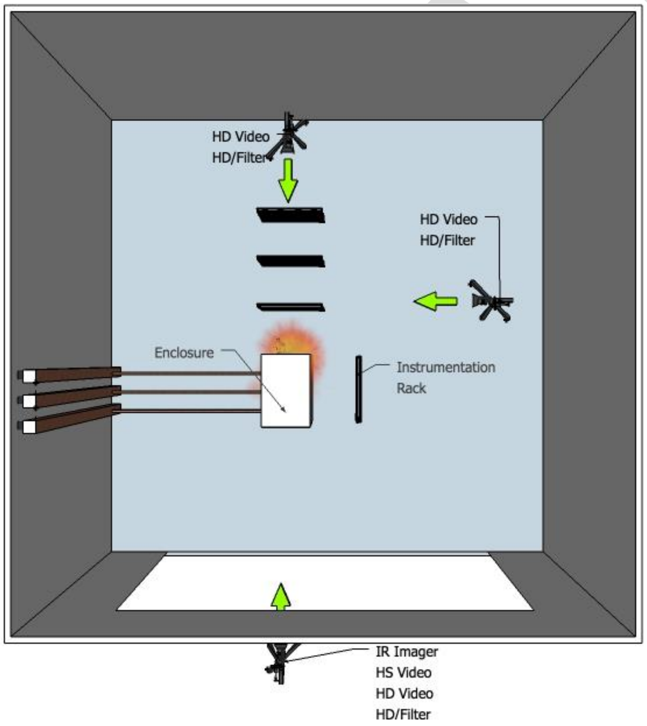

Figure 12. Electrical cabinet experiment. Plan view of camera layout in test cell. Infrared (IR) imaging video, high speed (HS) video, high definition (HD) video, and high definition video with filter (HD / Filter). Not to Scale.

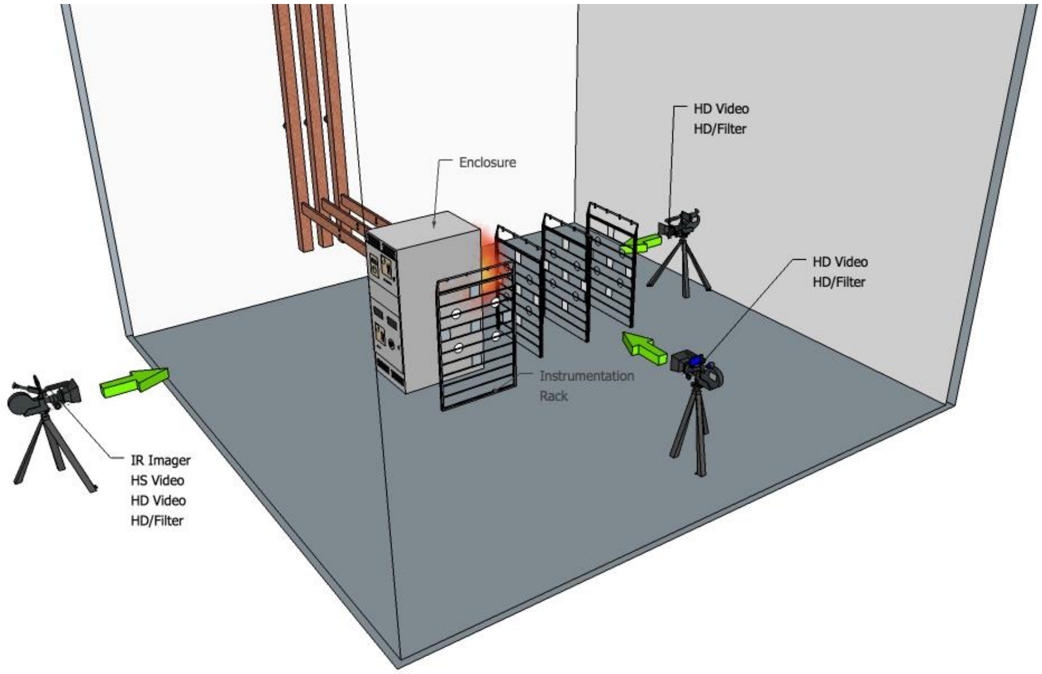

Figure 13. Electrical cabinet experiment. Side elevation view of electrical cabinet and instrument stands. (Not to scale)

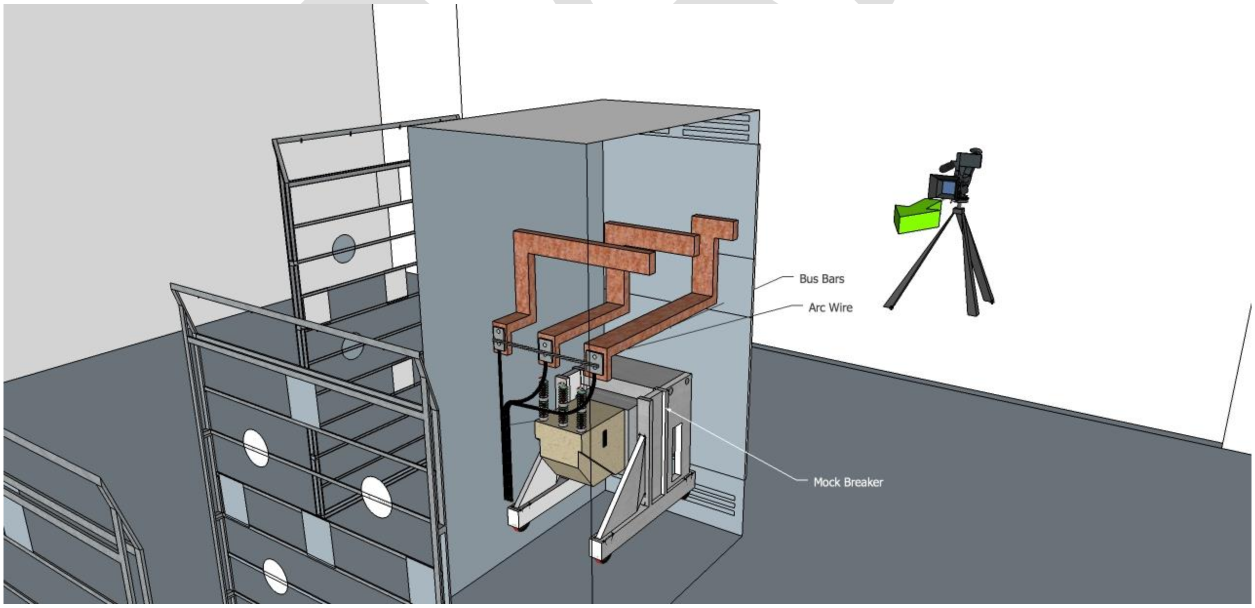

Figure 14. Internal view of electrical enclosure illustrating the shorting wire location and non-functional breaker "mock-up".

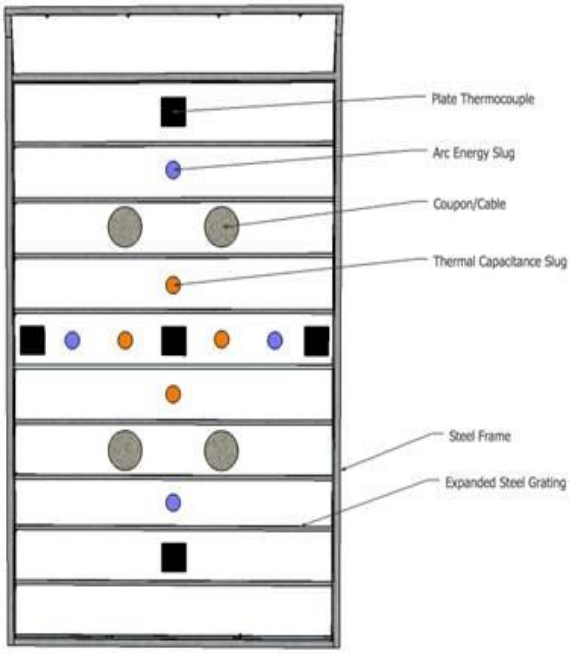

Figure 15. Example instrument stand. Elevation view. Not to scale.

Sample collection coupons are installed on the test stands to collect HEAF generated metallic and oxide deposits. Cable samples are installed on the test stands, including power cable, control cable, and instrumentation cable. The post-HEAF condition of the expanded metal portion of the test stands will provide a qualitative indication of the thermal conditions and extent of the plasma and fire ejected from the arc.

Pressure transducers will be installed to measure the time varying pressure within the cabinet during the HEAF. Due to the limitations of the measured pressures discovered in Phase 1, piezoelectric pressure transducers will be used instead of the strain gauge type. The piezoelectric type transducer provided improved pressure data in recent experiments for JNRA by Leidos and KEMA [14].

A combination of high definition video, high speed video, thermal imaging, and spectrally filtered high definition video will record the experiments. Figure 12 and Figure 13 show the locations of the various imaging devices.

8.2 Electrical Cabinet Setup – Multiple Cabinets

Multiple electrical cabinet configurations will also be investigated in several ways. There are two main scenarios involving multiple cabinets. One scenario involves two cabinet line-ups, facing one another, across an aisle. This scenario is approximated by the single cabinet scenario discussed in Section **Error! Reference source not found.** above. The target cabinet is represented by the instrument stand, which characterizes the incident exposure on the target cabinet(s) across the aisle.

The second multi-cabinet scenario involves two cabinets, representing part of a cabinet line-up, as shown in Figures 16-18. The purpose of this configuration is to investigate the propensity of a HEAF in one cabinet to spread and ignite a fire in an adjacent cabinet. During these experiments, the goal is to produce a HEAF in one cabinet that penetrates the adjacent cabinet, exposes the internals of the adjacent cabinet to HEAF products, and quantifies the exposure. The enclosed nature of the adjacent cabinet serves to trap some portion of the fire, heat, and HEAF products – physics that would not be captured by an instrument stand in the open air. Measurements of pressure, temperature, incident energy, and heat flux inside the adjacent (target) cabinet characterize the cabinet environment during and shortly after the HEAF event. Coupons inside the cabinet collect HEAF deposits for further analysis. Due to the challenges associated with electrically isolating instruments incorporating thermocouples, fiber optic instruments are under development for use inside the adjacent cabinet.

The instrument stands, video, and thermal imaging described in Section **Error! Reference source not found.** are also utilized in the multiple cabinet experiments.

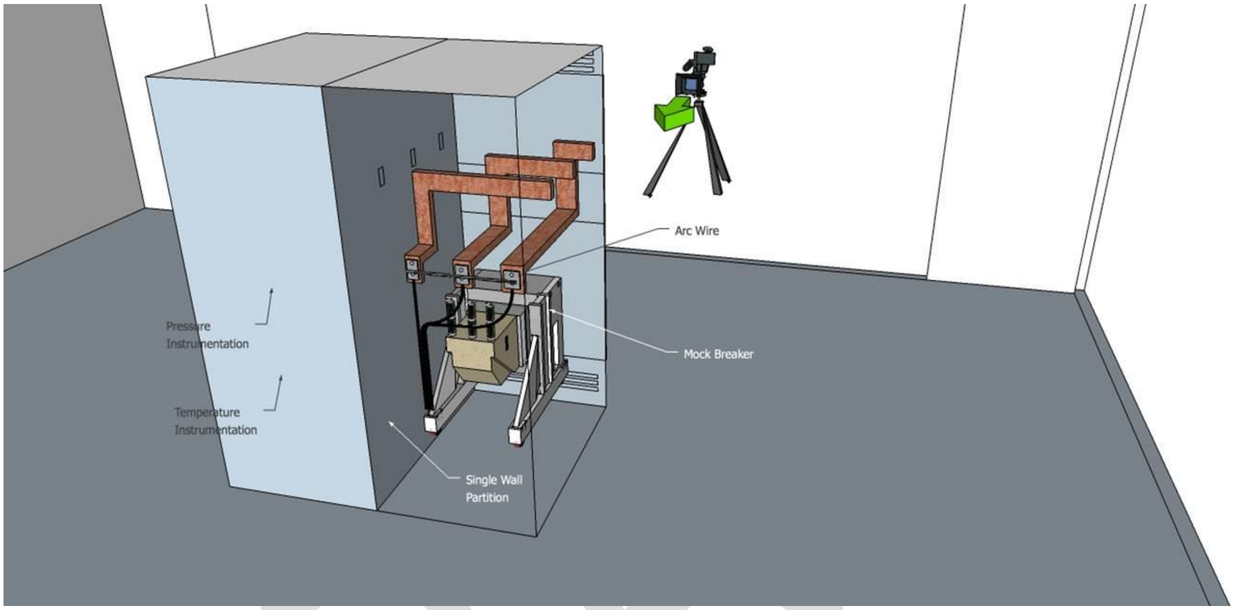

Figure 16- multi-cabinet scenario involves two cabinets, representing part of a cabinet line-up Internal view of electrical enclosure illustrating the shorting wire location and non- functional breaker “mock-up”. Both cabinets will have representative fuel loading conditions

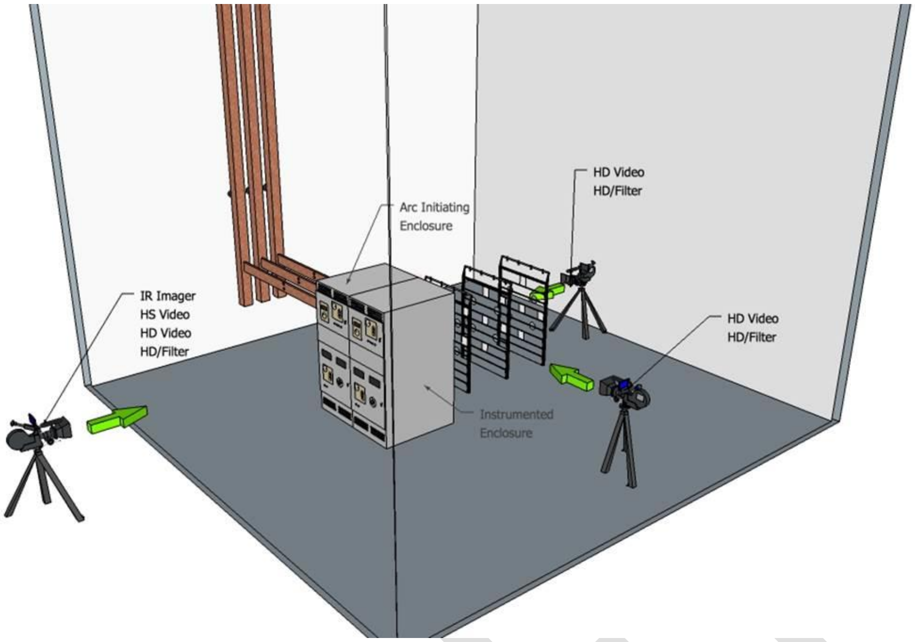

Figure 17 multi-cabinet scenario involves two cabinets, representing part of a cabinet line-up Side elevation view of electrical cabinet and instrument stands. (Not to scale)

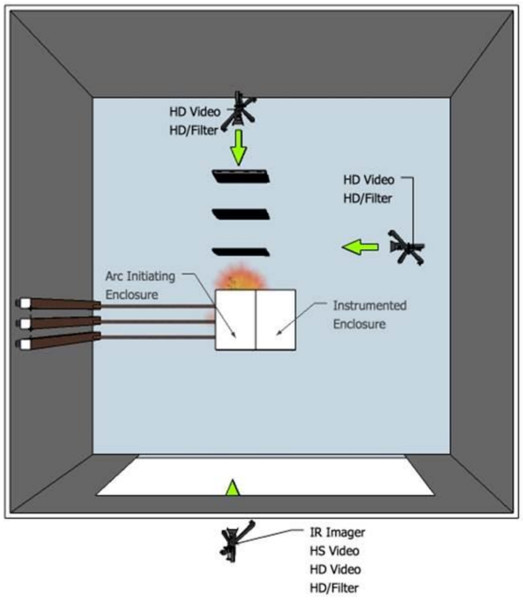

Figure 18- Multi-Cabinet Lineup Plan view of camera layout in test cell. Infrared (IR) imaging video, high speed (HS) video, high definition (HD) video, and high definition video with filter (HD / Filter). Not to Scale.

8.3 Bus Duct Setup

The setup of a typical bus duct experiment is shown in Figure 19 and Figure 20. The bus bars in the bus duct are attached to the power supply bus mounted on the wall and terminate at the electrical cabinet. A break is made to the bus bars between the supply bus and the electrical cabinet, with the arc wire attached to all three phases prior to the break location. The break in the bus bars prevents the arc from moving down the bus bars and into the electrical enclosure. Thermal transducers and samples are mounted on steel horizontal test stands located above and below the bus duct.

The primary arc plasma and fire are expected to eject from either the top or bottom of the bus duct near the location of the arc wire. The instrument stands are located at 0.9 m, 1.8 m, and 2.7 m from the top and bottom surfaces of the bus duct (Figure 19 and Figure 20). Sensors, target samples, and imaging techniques will be used in the same manner as in the electrical cabinet experiments.

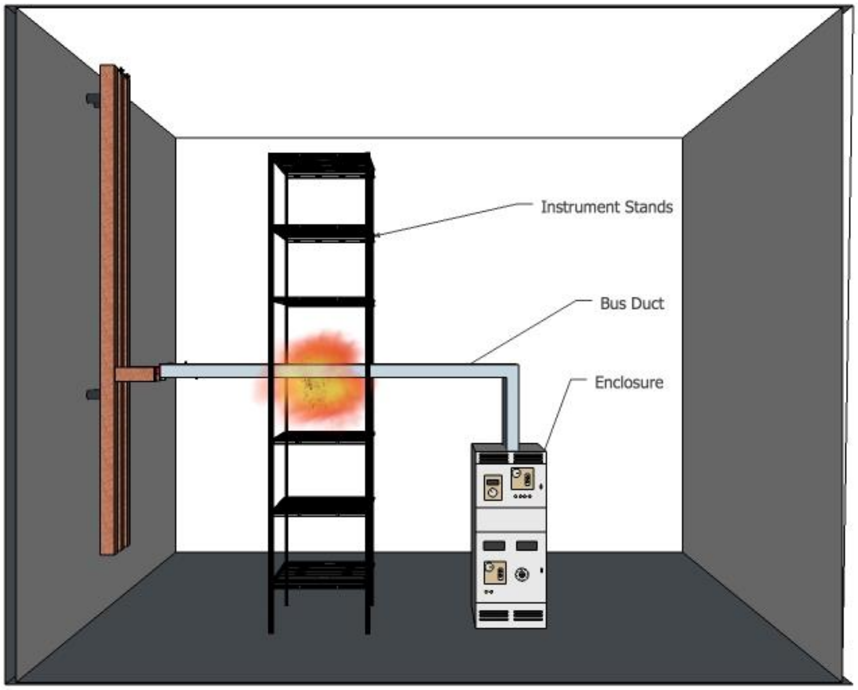

Figure 19. Bus duct experiment. Elevation view of bus duct and instrument stands. Not to scale.

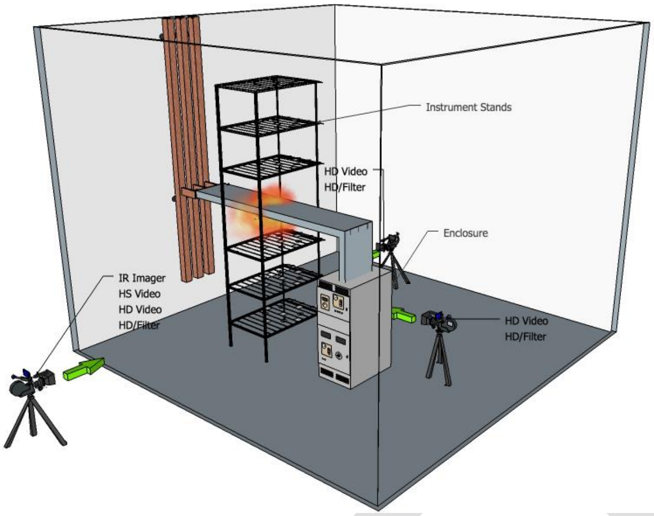

Figure 20. Bus duct experiment. Plan view of camera layout in test cell. Infrared (IR) imaging video, high speed (HS) video, high definition (HD) video, and high definition video with filter (HD / Filter). Not to Scale.

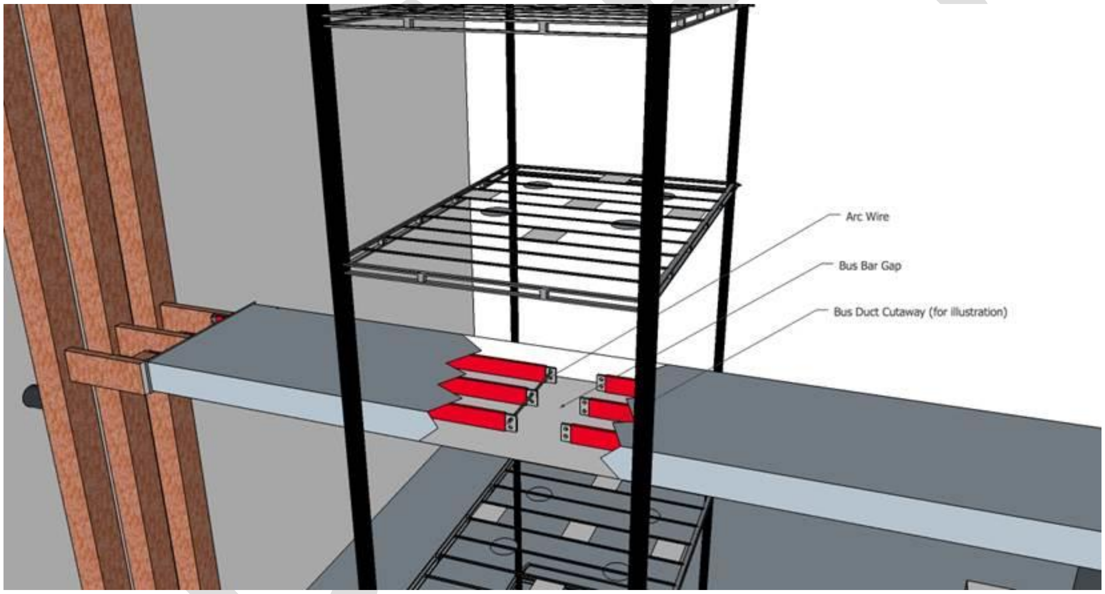

Figure 21. Internal view of bus duct illustrating the physical break in continuity of the bus duct

9. Experiments

The experiments will be performed in representative commercial electrical cabinets and bus ducts, which will be fully documented prior to the experiments. The documentation will include bus bar compositions, sizes, masses, and locations; the types, masses, and locations of ordinary combustibles such as wires, cables, and electrical components; ventilation openings; enclosure and bulkhead materials and thicknesses; and cabinet dimensions, geometry and configuration.

The experimental matrix associated with the first week of experiments is shown in Table 8. The matrix is subject to change based on the results of each experiment.

Table 8. Initial experimental matrix.

Test	Voltage (kV)	Current (kA)	Arc Duration (s)	Bus Bar Material
1 (T)	4.160	23	4	Al
2 (U)	4.160	35	4	Al
3 (H)	4.160	23	4	Cu
4 (I)	4.160	35	4	Cu
5 (W)	4.160	35	2	Al

After installation of the electrical equipment in the test cell, it will be hi-pot tested to ensure that arcing will initiate at the intended location. Prior to arc wire installation, the test facility will perform a bolted fault calibration. The arc will be formed in the same manner as Phase 1. A 2.6 mm diameter (10 AWG) stranded copper wire will be installed [15] across all three bus bar phases, the location documented, and equipment panels reinstalled.

The KEMA control room will energize the bus bars leading to the equipment with the nominal specified voltage and current, for a time period limited by the specified arc duration. The actual delivered voltage, current, and arc duration will not exceed those specified, but will vary from those specified as a result of the arcing behavior and equipment characteristics.

After each experiment, the condition of the equipment will be partially documented in the test cell. Once the equipment has sufficiently cooled, it will be disconnected, removed from the test cell, and transferred to one of the KEMA CAB fabrication bays for disassembly and full documentation. Once the equipment is fully documented and any samples cataloged, the equipment will be disposed of properly.

The experimental series will begin with one week of experiments at KEMA, and focus on HEAFs in electrical cabinets. Approximately five (5) experiments will be performed, with the basic schedule shown in Table 9. Electrical equipment and test stands will be setup and staged in the CAB the week before tests. The equipment will be moved into the test cell on Monday, and experiments performed through Friday. Friday afternoon will consist of tear-down and moving the equipment to the CAB. The post-HEAF damage and equipment condition will be documented in the CAB the week after the experiments. The actual number of experiments performed during the week may vary depending on the quantity of instrumentation destroyed during the experiments. Sufficient cabinets and equipment will be prepared for six (6) experiments.

Table 9. Basic schedule

Time	**Tasks**	**Location**
Week prior to experiments	Pre-HEAF documentation, assembly and staging	CAB

Time	**Tasks**	**Location**
Monday	Setup and Experiment 1	Test Cell
Tuesday	Experiment 2	Test Cell
Wednesday	Experiment 3	Test Cell
Thursday	Experiment 4	Test Cell
Friday	Experiment 5 and tear down	Test Cell
Week after experiments	Post-HEAF documentation	CAB

Further weeks of testing are needed to perform all thirty-two (32) experiments. The first week of experiments will inform the planning process for the remainder of the experiments, the number of which will depend on the total funding available.

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