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Aluminum High Energy Arc Fault (HEAF) Particle Size Characterization Test Plan

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SAND2018-0706 O

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

OVERVIEW OF TEST PLAN

This test plan covers a series of small-scale enclosure tests sponsored by the Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) and performed at Sandia National Laboratories (SNL). These tests are designed to better understand localized particle dispersion phenomena resulting from high energy arc fault (HEAF) fire-induced failure modes. The purpose of these tests is to better characterize aluminum particle size distribution, rates of production and morphology (agglomeration) of high energy arc faults (HEAFs), near the arc. More specifically, this effort will evaluate how ejected particles can transfer electricity for dispersion, where this investigation will characterize particle properties and morphology near the arc for HEAF models. The results and measurements techniques from this investigation will be used to inform an energy balance model, to predict additional energy from aluminum involvement. The experimental setup was developed based on prior work by KEMA and SNL [1] for phase-to-ground and phase-to-phase electrical circuit faults. The small-scale tests are not full-scale tests and the results should not be expected to be equivalent to the hazards associated with full-scale HEAF events. Here, the test voltages will consist of three different levels: 480V, 4160V and 6900V, based on those realized in nuclear power plant (NPP) HEAF events [2]. For these evaluations, HEAF physical phenomena will be assessed with respect to three main objectives:

- Investigate particle parameters of conductor arc-discharge materials including:
    - Particle density and conductivity
    - Particle size distribution
    - Arc-distribution
    - Particle morphology with respect to: 1. Composition, 2. Diameter, 3. Charge, 4. Symmetry, 5. Product Decomposition Path, etc.
- Investigate system physical parameters of a HEAF measured including:
    - System temperatures
    - Incident energy heat flux
    - Heat release rate (HRR)
    - Physical damage and mass loss
- Gather HEAF experimental data that can be used to better understand the HEAF phenomena and risk insight as applied to NPP safety.
    - Particle emission characteristics
    - Electrical data

The scope of this Investigation is to:

- Identify and explore how to instrument and record meaningful experimental data pertaining to particle morphology and physical movement from a HEAF event experiments.
- Explore how the different parameters (e.g. voltage, bus gap spacing, current, etc.) impact HEAF phenomena and zone of influence.
- Use the results and lessons learnt to provide information to future HEAF experimental programs.

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ACRONYMS AND ABBREVIATIONS

AC	alternating current
ACD	Advanced Components Development
AWG	American wire gage
CPT	control power transformer
CVT	current-voltage transformer
DC	direct current
DP	distribution panel
EMI	electromagnetic interference
FOV	field of view
HEAF	high energy arc fault
HRR	heat release rate
ICCD	intensified charged coupled device
IR	infrared
IEEE	Institute of Electrical and Electronics Engineers
MCCB	molded case circuit breaker
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PMMA	Polymethyl methacrylate
RES	NRC Office of Nuclear Regulatory Research
SEM	scanning electron microscopy
SNL	Sandia National Laboratories
TC	thermocouple
TTL	transistor–transistor logic
XPS	X-ray photoelectron spectroscopy
ZOI	zone of influence

1 OBJECTIVES, TECHNICAL BACKGROUND AND APPROACH

1.1 Objectives

The objective of this research is to better characterize aluminum particle size distribution, rates of production and morphology (agglomeration) of high energy arc faults (HEAFs), near the arc. The measurements from these experiments will be used to support development of a HEAF/Aluminum combustion energy balance model to characterize the HEAF hazard. This modeling effort will support advancements to quantify hazards HEAF pose to nuclear power plant (NPP) risk. This small-scale investigation is not intended to understand the effects of vapor and HEAF byproducts remote from the arc. These tests are not qualification tests and do not follow any national consensus standard, as none exist for the specific purpose of this testing.

This test plan has been developed by Sandia National Laboratories (SNL) and sponsored by the US Nuclear Regulatory Commission (NRC), Office of Regulatory Research (RES) Fire and External Hazards Analysis Branch. While the test plan is intended to focus and direct the testing, it is a working document and may be changed per the direction of the NRC/RES as the testing progresses and information gained support changes to achieve the objectives of this research.

1.2 Technical Background

Within NPP facilities, massive electrical discharges, referred to as HEAFs, have primarily impacted switching components. Specifically, switchgear components provide a means to isolate and de-energize specific electrical components including buses to clear downstream faults and perform routine maintenance. These protective technologies may be categorized by their insulating medium, such as air or oil. Additionally, switchgear components are classified as low, medium, and high voltage (< 1 kVAC, to > 35 kVAC) which have previously been evaluated [3] by industry, where the majority of studies have primarily focused on exposure to personnel safety. Low and medium voltage represent the majority of equipment classifications found in the plant. According to [2], the zone of influence (ZOI) for switchgear HEAF events is assumed to capture the damage generated during the energetic discharge phase

In general, a HEAF in electrical equipment is initiated in one of three ways: poor physical connection between the switchgear sprouts and the breaker main connections, 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 near the event.

NPPs within the United States (US) widely use medium voltage bus bars which are typically 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 [4] where incidents, like that shown in Figure 1, occurred due to HEAFs within bus ducts or rated cabinets.

Figure 1. HEAF damage to bus bars within a rated electrical cabinet [2].

According to Lopez et al. [2], there are major differences between "arc flash" and "arc blast" events. 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 program are focused on arc blasts.

Previous testing performed by the NRC/RES found notable results when equipment composed of aluminum was subject to HEAF conditions. This included thin-walled switchgear utilizing aluminum bus bars, as well as copper bus bars inside an aluminum bus duct enclosure, where both events observed a ZOI to be larger than the NUREG/CR-6850 guidance. Any non-conservatisms could mean that the current baseline risk models at plants that have aluminum components may actually underestimate risk. Prior NRC testing has also shown that there is a potential issue that current HEAF models are non-conservative, where recommendations have been provided [5] to revise the guidance in addressing larger ZOI events, where HEAF hazard levels could be more extensive. This will require further investigation for the ZOI that includes more fundamental and rigorous modelling and test validation of incident energy, as well as arc-path selection, shock waves and electromagnetic interference (EMI), where the definition of ZOI can be expanded to include non-mechanical destructive forms as well, such as thermal heat, induction field coupling and electromagnetic pulse. A possible experimental program would address the uncertainty associated with energetic arc faults to improve prediction models for plasma discharge path selection, intensity, incident energy prediction, ZOI and quantify fire hazard effects and EMI destruction at common, as well as elevated voltage levels. Understanding plasma discharge phenomena from the standpoint of thermal and mechanical exposure effects is relevant to determining ZOI. Quantifying the impacted operations region from a HEAF is important when analyzing arc effects also on material product formation associated with ejected particles and their post-HEAF hazards, which can be critical for re-operation and safety.

The NRC has asked SNL to design an investigation to study the effects from medium voltage (480V, 4160V and 6900V) HEAFs to better understand the risk associated with these incidents. For this investigation, SNL shall perform small-scale experiments to characterize the aluminum particle size distribution, rates of production and morphology (agglomeration) of HEAFs involving aluminum conductors. These experiments will use SNL's arc generation resources, such as the SNL Lightning Simulator to subject aluminum switchgear to arc fault conditions. Measurements from these experiments shall provide particle count size distribution, mass particle size distribution normalized by the total mass gasified, and microscopic analysis of the morphology of the particles. Variations of experimental parameters will be performed (e.g., voltage and AC configuration) that affect the particle size characteristics. These small-scale experiments will also provide information to determine fundamental equipment failure criteria (e.g., ignition, functionality) for high temperature, short duration exposures of secondary targets (e.g., electrical cable). This will be carried out using high-speed imaging within the arc initiation region. The results of this work will be used to support development of HEAF/Aluminum simulation models to characterize the HEAF hazard. This modeling effort will support advancements to quantifying the hazards HEAF pose to nuclear power plant fire risk.

1.3 General Approach

To meet the objectives of this test program, experiments will be conducted to explore aluminum particle size distribution, rates of production and morphology of HEAF product materials. The tests are intended to supplement previous HEAF testing performed at KEMA high energy test facility from 2014-2016 [3]. SNL will perform a series of tests involving the following variables: AC scaled current (0.35 to 29.0 kA), bus bar material (aluminum and copper) and arc configuration, which will include two parallel bus bars containing a shorting wire, at varying voltages (480V, 4160V and 6900V). These experiments will be conducted at SNL's lightning simulator that will subject bus bar specimens to phase to ground arc fault conditions. The experiments will be conducted to explore the basic configurations and effects of HEAF events. Since the switchgears and other equipment necessary for testing is expensive, this work relies on a simple two-bus-bar configuration.

Measurements from these experiments will provide particle count size distribution, mass particle size distribution normalized by the total mass gasified, and microscopic analysis of the morphology of the particles. These measurements will be captured from high speed imaging and microscopy. Small scale experiments will also provide information or data to determine equipment failure criteria (e.g., ignition, functionality) for high temperature, short duration exposures. The tests described in this test plan focus on characterizing failure events for a simplified electrical configuration. The tests are designed to characterize product formation phenomena with respect to ejected particles, transient analysis, and thermal-mechanical phenomena based on electrical failures due to reliability. The tests are intended to supplement previous NRC testing performed on electrical cabinets and to advance the state of knowledge, which has been determined to be low from a phenomena identification and ranking table exercise (NUREG/CR-7150, Volume 1 [6]). For the purposes of this test, data will be collected with high-sampling frequencies that will coincide with high-speed photography for particle tracking and destruction distribution. The measurements from these experiments will be used to support development of a HEAF/aluminum combustion energy balance model to characterize the HEAF hazard. This modeling effort will support advancements to quantify hazards HEAF pose to nuclear power plant (NPP) risk.

2 TEST APPARATUS AND EXPERIMENTAL SETUPS

2.1 HEAF Advanced Components Lab/Lightning Simulation Facility Overview

Several SNL test sites were considered for this test series [7]. While many experiments, including the DESIREE-Fire and KATE-Fire tests, have been performed at the SNL Thermal Test Complex and other facilities, the type of experiments being considered for this project fit the unique capabilities of the Advanced Components Development (ACD) Laboratory within the SNL Lightning Simulation Facility. In addition to the power considerations, another necessity is a structure or enclosure that can contain the shrapnel that may be created during the HEAF event. This enclosure is also necessary to maintain a controlled environmental condition during the initial blast and fire scenario. The structure also needed to facilitate the direct measurement of species for oxygen calorimetry and heat release rate estimation.

The SNL ACD Laboratory will be used for facilitating the arc-flash experiments and for electrically and physically characterizing discharges under varying voltage levels. The team can utilize a versatile atmospheric, variable-voltage test platform to measure current/voltage waveforms during breakdown/flashover and obtain simultaneous time-gated optical imagery of flashover paths. The ACD lab can perform DC, AC and pulsed (lightning waveform) tests with currents from 1kA-200kA, with applications such as:

- Electrical Component Performance and Breakdown Mechanism Diagnostics
- Experimental Electromagnetics and Thermal Diagnostics
- Electron and Bulk Temperature Particle Diagnostics
- Thermal Plasma Physics Capabilities
- High-Temperature Radiation Diagnostics and Experimentation Capabilities

The Advanced Components Development Lab facility test bed architecture may comprise open shutter and/or microsecond-scale, triggered integrated charge coupled device (ICCD) cameras for flashover path imaging, and current transformer and voltage probe monitors for arc flash voltages and current paths as a function of time. Current sources include a MacroAmp AC and DC voltage supply, HILO 20kV/12kA current and voltage sources as well as Glassman 100kV power supplies. The test enclosure allows breakdown testing as a function of gas composition and atmospheric/surface contaminants (e.g. humidity, saltwater spray, oil vapors and other atmospheric contaminants).

2.2 Experimental Setup

Twenty tests will be performed. The test configuration, illustrated in Figure 2, contains a 1" polymethyl methacrylate (PMMA) cabinet, composed of two long busbars in a Molded Case Circuit Breaker (MCCB) configuration. The PMMA cabinet is 21" x 21" x 50" and the bus bars are centered in the middle of the cabinet. The high-speed cameras are directly outside of the cabinet, one camera on the side and one camera taking a top-down view of the experimental setup. Various coupons of aerogel and carbon tape will be mounted approximately 1-in. from the bus bars, centered with the shorting wire to collected ejected particulate samples. Two high-speed cameras will be mounted above and to the side of the PMMA configuration for image collection. Although this is a simplified configuration, the results from this type of test will help inform physical phenomena found in real NPP cabinets, like the one shown in Figure 3.

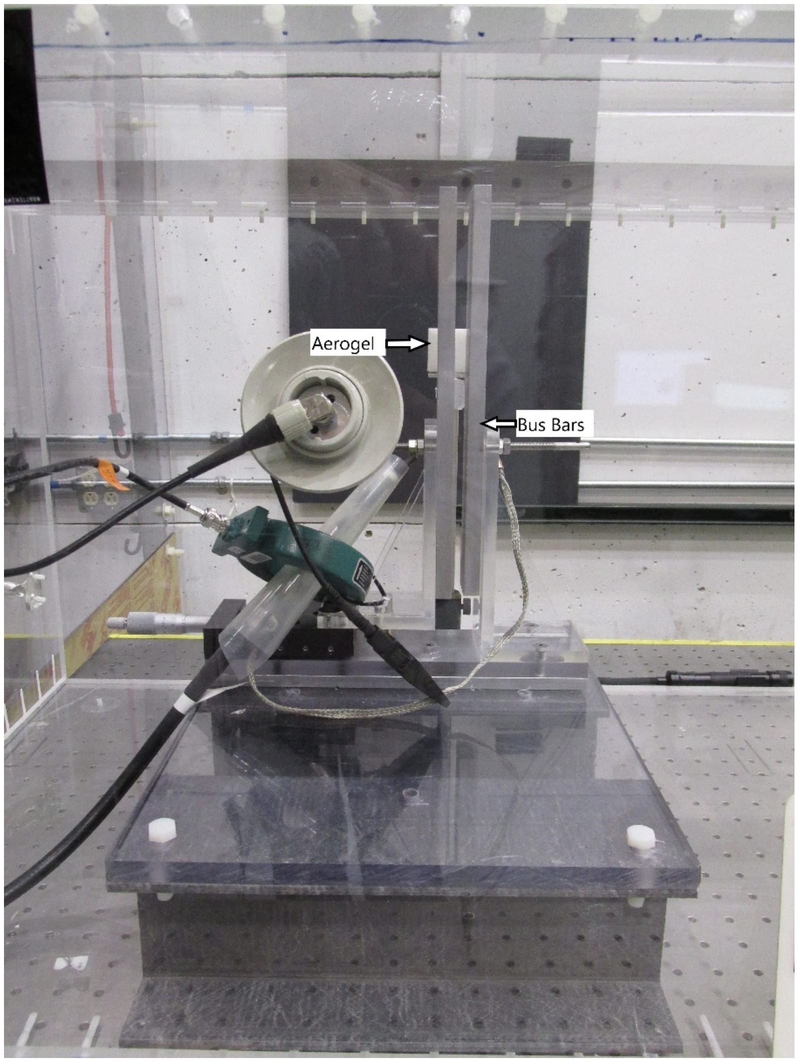

Figure 2. The 2-phase small mock-up bus experiment layout with aerogel. The bus bars and aerogel are contained within a PMMA enclosure where the arc-discharge is facilitated by a shorting wire positioned across the two bus bars.

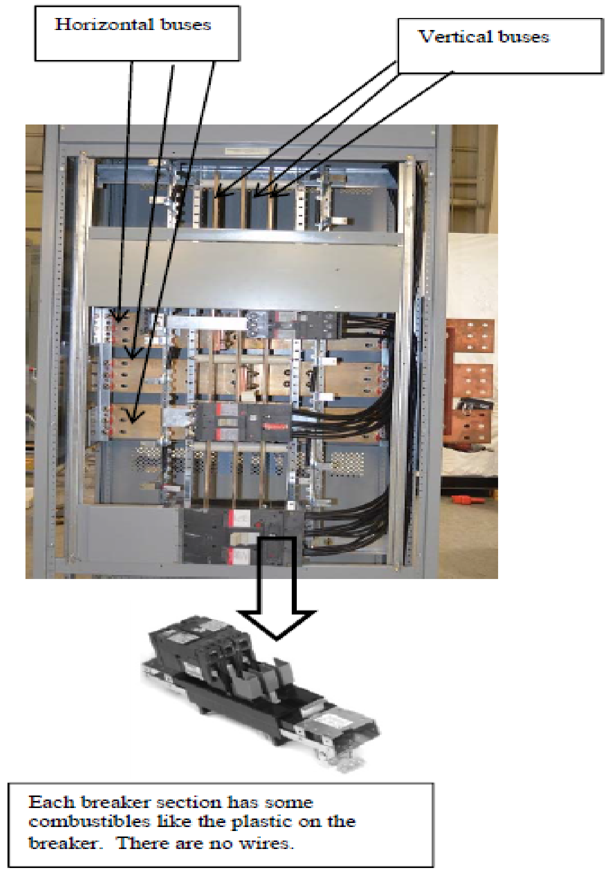

Figure 3. Distribution panel test with 3-molded case circuit breakers.

2.3 Instrumentation Circuits

AC voltage waveforms will be supplied from existing Macroamp power supplies (480V) and from arbitrary waveform generators, amplified by Trek amplifiers for 4160V and 6900V testing. The power supply for the 480V system will be a Cummins DSGAA 100 kW/125 kVA system. These tests will be instrumented with Tektronix voltage monitors, Pearson current-voltage transformers (CVTs). Voltage and current waveforms for both pre-breakdown and breakdown/arc transient voltage and current will be acquired and recorded for both single phase and phase to phase arc experiments. Current transients recorded on CVTs will be used to trigger 100,000 frames per second and/or 1 million frame per second cameras, as well as to trigger and/or integrated CCD cameras with microsecond resolution to capture initial stages of arc development. Additionally, optical and physical characterization of the arc studies are described below. For the DC tests, an arc welder will be used to provide 300 amp arcs.

Shorting wire for voltage tests will be connected at the top of the 2-phase buses to facilitate the arc. Test involving aluminum buses will use a copper shorting wire and tests using copper buses will use an aluminum shorting wire to allow for distinction in post-test analysis. This shorting wire is used to initiate the arc and will vaporize instantaneously when power is applied.

Temperature and heat flux measurement methods will be chosen to maximize the response time while being robust enough to survive the anticipated environment of the HEAF event. The following are potential instrumentation components that will be considered for employment in the SNL-NRC HEAF experiments:

- Micro-Raman spectroscopy measurement of energy loss of graphite/carbon under laser illumination
- E-type thermocouples (TCs) and high-temperature pressure measurement devices.
- The heat release rate (HRR) using spectroscopy and high-speed infrared (IR) thermal imaging. Previous work has shown that the use of a single neutral density filter may not be able to cycle through the temperature ranges as quickly as the arc developed to capture quantitative results. Here, an employed IR camera will have a significantly large dynamic range or with the ability to rapidly deploy neutral density filters. Additionally, thermal image videos will also qualitatively depict fire growth within the enclosure. They will also aid in identifying the progression of the arc within the enclosure and the directionality of the arc plasma and energy expelled during the arcing event.

2.4 Test Parameters

The test parameters for this work are listed in Table 1. For this investigation, four voltage levels will be tested with the phase-to-ground configuration. These AC voltage levels, with a nominal frequency of 60 Hz, will be 480V, 4160V, and 6900V. The arc-location will be consistent in all tests with a shorting wire positioned across the two bus bars. All tests will use a 3mm(w) by 1mm(t) size bus bar in either aluminum or copper. Additionally, the switch gear PMMA enclosure will always remain in the closed configuration.

The bus bar spacing will be varied between 5mm and 10mm. In UL1699B, 5mm is the standard gap used in arc fault testing. Based on previous SNL arc fault experience, 10mm was also selected because it’s been seen in industry and is an extreme distance between components that could still satisfy an arc discharge.

In order to obtain high enough resolution to develop representative information on the arc, data will be collected at a frequency of 100MHz.

Table 1. HEAF Test Matrix and Experimental Parameters

Test	DC Current [A]	Voltage [V]			AC Scaled Current [kA]						Target Arc-Duration [ms]		Bus Bar Gap (mm)		Bus Bar Material		Comment
	300	480	4160	6900	0.35	1.4	5.0	7.0	12.0	29.0	4	8	5	10	Al	Cu	
1		X			X							X	X		X		
2		X			X							X	X			X	
3		X				X					X		X		X		
4		X				X					X		X			X	
5				X				X				X	X		X		
6				X				X				X	X			X	
7				X						X	X		X		X		
8				X						X	X		X		X		Repeat of Test 7
9				X						X	X		X			X	
10				X		X					X		X		X		Test 3 voltage comparison
11				X				X				X		X	X		Test 5 gap comparison
12				X				X				X		X	X		Test 6 gap comparison
13				X						X	X			X	X		Test 7/8 gap comparison
14				X						X	X			X		X	Test 9 gap comparison
15			X					X				X	X		X		Test 6 voltage comparison
16			X							X		X	X		X		Test 7 voltage comparison
17	X											X			X		
18	X											X			X		
19	X											X				X	
20	X											X				X	
21				X					X			X	X		X		Optional Test
22				X			X					X	X		X		Optional Test

2.4.1 Voltage

Three voltages will be used during testing. In the low voltage classification, 480V will be used as this is the most common low voltage level found in US NPPs. While 480V does not bound 600V, it is expected that for a constant bus gap spacing the arc voltage would be comparable between the two low voltage levels. For medium voltage, two voltage levels will be tested, 4.16kV and 6.9kV. Most of the testing will be performed at 6.9kV because this level is also the primary test voltage for the full-scale testing to be performed by the NRC and the OECD (not part of the small-scale test program). Several 4.16kV tests will be included for comparison to the 6.9kV results.

2.4.2 Current

Also, with regard to IEEE Std. C37.20.7-2007 [8], the AC calibration test values for the short-circuit current in the metal-enclosed switchgear with respect to arcing will be set within a (+5,–0%) tolerance. If the applied voltage is equal to the rated maximum voltage, this tolerance applies to the prospective current [8].

For the tests, the current should remain constant. If the capability of the test configuration does not permit this constancy, the test will be extended until the integral of the ac component of the current equals the value specified within a tolerance of (+10, –0%). In this case, the current shall not be less than the specified value at least during the first three half-cycles and shall not be less than 50% of the specified value at the end of the test. The duration of the short-circuit current should not exceed 125% of the rated arcing duration [8].

2.4.3 Arc Initiation

A fine filament shorting wire of 1.33 mm^2 in cross-sectional area will be used as a means of arc initiation. Tests using aluminum bus bars will use a copper shorting wire, whereas tests using copper bus bars will use aluminum shorting wire. This will aid in post-test particle analysis. The wire is only intended to initiate the arc and will be rapidly vaporized when power is applied. The shorting wire will be installed between the two bus bars at the end farthest from the power supply connection to the bus bars. A small hole drilled in both bus bars will allow the shorting wire to be installed in a consistent and secure manner.

2.5 Electrical System Performance Monitoring

Time dependent voltage and current will be recorded for all phases under test during experimentation using voltage monitors and current-voltage transformers to record V(t) and I(t) prior to and during arc transient events. CVTs of multiple sensitivities will be used to capture both arc behavior during initiation and stable HEAF.

2.6 Thermal Response Monitoring

High-speed infrared (IR) imaging systems will provide thermal video of the experiments at approximately 100 to 1000 Hz. Due to the large variation in temperature during each HEAF event (ambient to over 1,500°C) and the IR camera operating characteristics, only qualitative information may only be reported. The thermal imaging video will provide an indication of arc progression during the experiments and development of any ensuing fires and secondary product formation effects. Each of the stationary IR imaging cameras will provide a view of the front of the test cell. Several models of high-speed IR imaging systems were used during these experiments. All of these systems will have the capability to measure temperatures up to approximately 1,500°C. However, the IR cameras may require a filter be in place to avoid saturating the IR images.

2.7 Placement of Switchgear Components

Switchgear components will be contained in custom PMMA isolation boxes, equipped with power supply relay interlocks. The isolation boxes will provide both a physical barrier to provide an interlocked, electrical safety exclusion area, as well as to facilitate collection of generated particles, ventilate the test region, and control potential debris.

2.8 Particle Capture Setup

To collect arc-generated particles for analysis of particle size, composition and state of oxidation, plates of porous SiO_2 aerogels and strips of carbon tape will be utilized as particle collectors. Aerogel plates have previously been used for collection of solar dust, due to their chemical purity (99.999% SiO_2), low density and low thermal conductivity. These methods enable collection of molten particles with minimal change in particle morphology and strong chemical contrast with collected particles. Following particle collection, the morphology (size and size distribution) and chemical state of collected particles from aluminum arc-faults will be analyzed. Automated particle size distribution software and chemical analysis will be used to determine particle size. This may include energy dispersive x-ray analysis (EDXA) and/or electron energy loss spectroscopy (EELS). These will also be used to determine if particles are droplets of metallic Cu or Al, or have oxidized, a potential source of added energy during arc flash.

2.9 Gas Capture Setup

Gas composition following arc discharge will be analyzed by ion trap residual gas analysis (RGA), illustrated in Figure 4, to determine molecular species released during the arc flash event, potentially including reduced gas species and metal or metal oxide nanoparticles. This method has 10-100 millisecond resolution and ability to temporally monitor changes in local gas composition (O_2, O_3, CO_2, CO, H_2O and H_2) generated during arc flash and other electro-thermal processes. Additionally, clean room particle counters will be investigated as a means to quantify arc-released particle concentration.

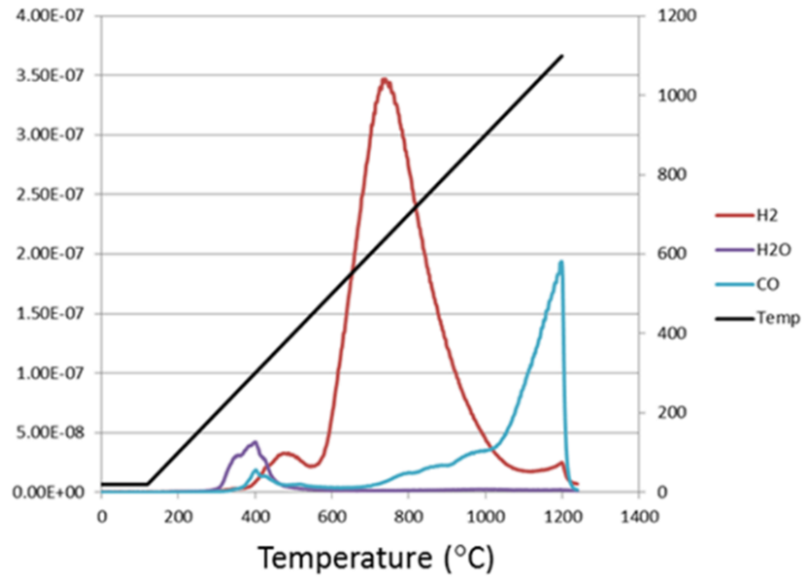

Figure 4. Ion trap residual gas analysis (RGA) data, shown here for the thermal desorption; arc-induced species may also be analyzed by collecting gas from the arc flash region for RGA analysis.

2.10 Materials for Testing

One of the most prominent aluminum alloys used for electrical conductors in power facilities [9] is AL 6061, and therefore AL 6061 will be the material used for the aluminum bus bars. The copper bus bars will use a copper 110 alloy which is a standard alloy used in high-voltage electrical equipment.

2.11 High-Speed Imaging/Photography

SNL has world-class, high-speed, high-fidelity photography capabilities on the order of millions of frames per second, with a suite of computational dynamics and other physics-based simulation tools for rapid characterization of explosions including plasma discharge tests. The lightening simulator laboratory will use in-house &/or ICCD cameras for nanosecond-timescale imaging to evaluate initial arc inception and discharge phenomena. To capture micro-second and larger time-scales SNL will use:

1. 2 orthogonal quantitative high-speed views of close in dynamics at roughly 100,000 FPS to see debris, with a fidelity level of 1280p x 720p. Goal is to measure debris speeds in-plane. Interested in initial 100 µs portion of arcing and potentially into ms range. Field of view ~1 ft. x3 ft.
2. 1 or 2 wide overall high-speed videos in color of event. Record entire arcing event. Field of view ~3 ft. x7 ft.
3. Single view at 1,000,000 FPS to see initial arcing dynamics. Likely small field of view (FOV) ~1 ft.

An in-house laboratory transistor-transistor logic (TTL) will be used to synchronize and trigger the various imaging tools, such as two v2512BW, 2x v1212C, Blackmagic cameras. This work may also include spectral imaging, for assessing in-situ product formation at different time-scales using various spectrally-sensitive filters. The analysis will also include post-process photometrics analysis using data fusion to characterize:

- Measurements of rigid body motion, strain, deformation, relative component motions, object tracking & quantification, acceleration & velocity measurement
- Explosive particle projectile tracking and velocity measurements
- Fireball/plume evolution

The data fusion capabilities will also be used to assess component tracking with respect to overall debris spread and impact forces. This will be accomplished using the mobile instrumentation unit (MIU), which provides site diagnostic high-speed photography and analytical instrumentation, encompassing 96 fully redundant/196 non-redundant channels including:

- Primary path: Precision filters signal conditioners, 24-bit, 250 kHz VTI digitizers
- Secondary path: Spectral Dynamics VXI signal conditioner/digitizers – 16-bit, 5 MHz

The photography equipment can be sealed within protected enclosures and can be made with protective shells that include quartz and sapphire windows for high-intensity explosive tests. The rugged camera technology, for 100,000 fps imaging is capable of image capturing up to a distance of up to 80 ft. though for this work they will be placed just outside the PMMA enclosure, at a distance of 5 ft. from the right and top respective panels. Depending on the final setup, highly-reflective angled mirrors may be employed to capture hard-to-reach explosion images that would otherwise facilitate destruction to photography systems.

2.12 Test Procedures

The steps for each test will be:

1. Assemble and prepare the respective test unit in the SNL Lightening Simulator assembly test area. Place the aerogel circumferential band in front of the lower cabinet section, approximately 1 ft. in front of the starter wire.
2. Place high-speed camera equipment and angled mirror assemblies above and to the side profiles of the cabinet.
3. Place measurement instruments in position and check for alignment.
4. Place 1” PMMA panel enclosure approximately 2 ft. from each face of the cabinet.
5. Connect cabinet to bus, energize system and create the arc; allow the secondary fire to burn as long as possible as long as the situation is safe. The burn time will not be limited in the actual tests.
6. Observe post-test conditions and collect material samples for processing. Take damage photos and notes on damage zone. Document and measure collected bus bar fragments (parts and pieces).
7. Disassemble and remove test unit.
8. Compile results and raw data. Perform a quality assurance check on the results.

2.13 Timeline and Milestones

Figure 5 illustrates the timeline and milestone estimates for the project. The final report will be submitted to the NRC no later than September 30, 2018.

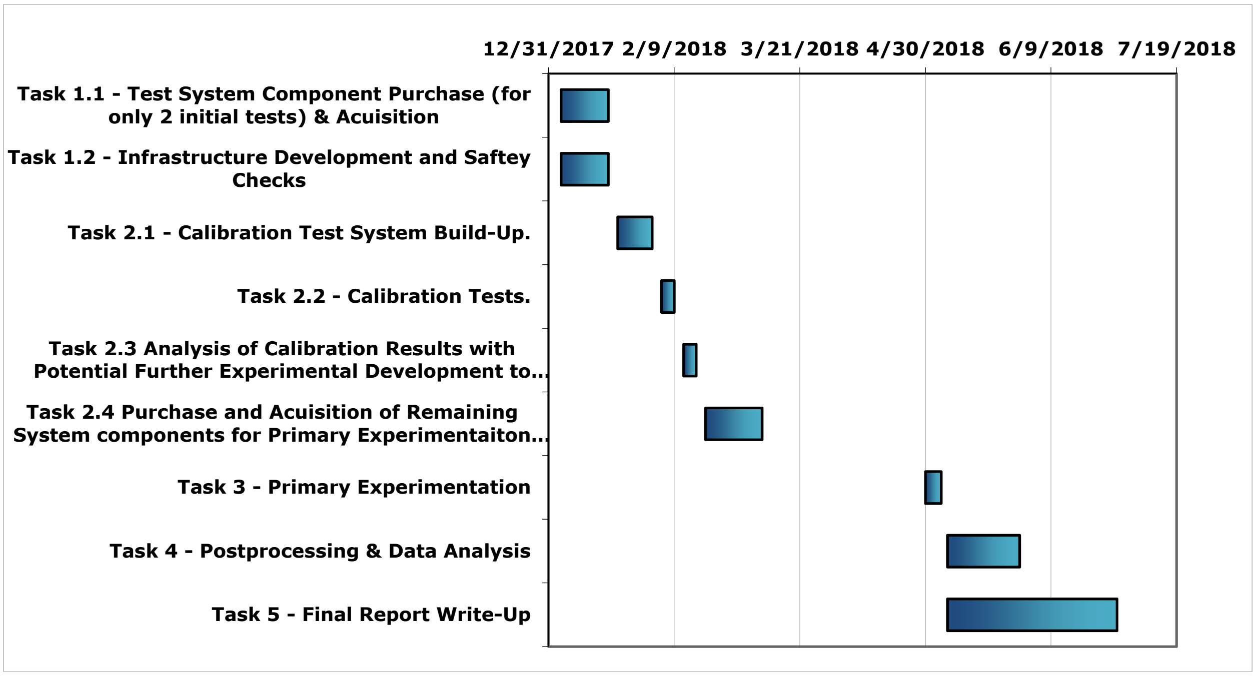

Figure 5. Project Timeline and Milestones

2.14 Reporting

A report of test will document the results from this testing program. The report will describe the experimental setup including characteristics of the power supply, description of the tests performed, quantitative results, observations, and any general conclusions or findings. The report will not specify new methods for assessing risk to plants from HEAF events.

3 POST-MORTEM FORENSICS ANALYSIS

3.1 Overview

Following experimentation, the captured aerogel particles will be processed at SNL to then be evaluated through post-forensics studies. Here, among the various material analysis techniques shown in Figure 6, scanning electron microscopy (SEM), Raman and X-ray photoelectron spectroscopy (XPS) will be used for study in this investigation.

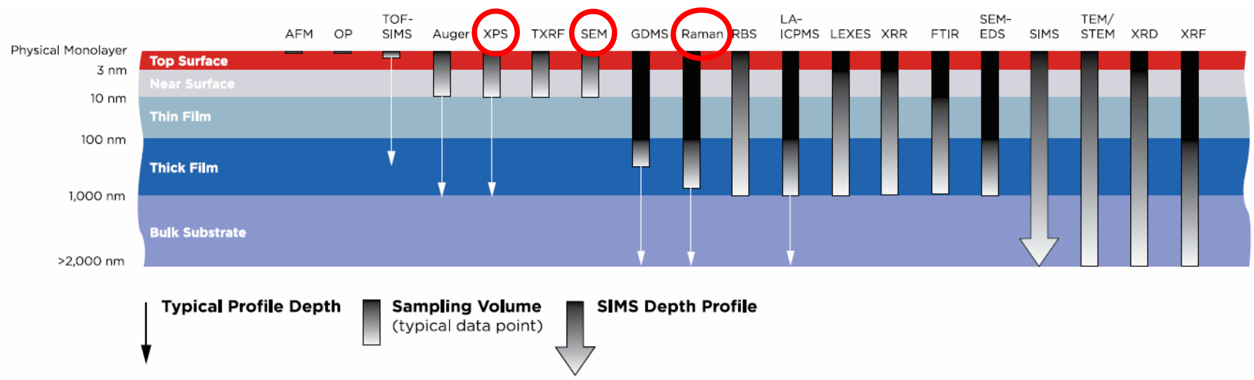

Figure 6. Typical analytical depth range based on technique.

Low- and high-magnification analysis using light microscopy and SEM enables the characterization of a tested component, where this study will evaluate particle size and geometry. Identifying deformation, corrosion product, wear marks, cracks, or other markings is an important step in diagnosing the cause of failure. Additionally, SNL may employ multi-beam SEM for high throughput imaging to rapidly analyze large topology areas for chemical analysis and feature characterization of a large sample set. Multi-SEM represents a new imaging paradigm where researchers no longer have to search for the significant features or ideal areas for analysis. High-throughput imaging will allow true statistics of a sample to be determined over large areas while maintaining excellent resolution. With this approach, 61 focused electron beams are focused on a surface at a resolution of 4 nm, where images are collected in parallel (1.22 GPixels/s). This instrument has been used to image relatively large surface areas, while searching for challenging-to-find irregularities or specific areas of interest. In addition, now statistics for each sample can be reliably calculated.

Another technique that will be employed here is Raman spectroscopy, where its capabilities allow the interrogation of large surfaces in a controlled environment (vacuum and temperature control from 80-500K), facilitating assessment of changes in materials (polymers, glasses, and ceramics) that can be impacted by arc evolution over time. Any change altering the energy of a vibration—strain, temperature, phase change—or the lifetime of that vibration (i.e., defects) will alter the Raman spectrum. The rastering of the Raman laser over the surface creates a "map" that can be utilized to assess the quality and degradation of materials, which is critical for understanding the HEAF thermal evolution of the system materials over time.

Finally, XPS will also be performed to evaluate the types of reactions that were facilitated by the respective arc-discharge tests, considering temperature, pressure and oxidation levels, among others. XPS is an electron based technique utilizing soft X-rays to eject core electrons from elemental species. Elemental species and local environmental conditions determine the kinetic energies of the ejected electrons. Therefore, XPS can provide quantitative elemental surface analyses along with information on the oxidation state (bonding, valence) and local environment of elemental species. The state-of-the-art XPS imaging can provide chemical mapping at resolutions down to 3μm. Additionally, with UV illumination we can quantify the work function and ionization potential of conducting samples with extreme surface sensitivity.

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