High Energy Arcing Fault Research Project Plan

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CONTENTS

DISCLAIMER

This project plan was developed to provide the public and stakeholders with information on the NRC's high energy arcing fault research program. Although the Electric Power Research Institute (EPRI) has provided technical input to this program, the NRC is responsible for the planning and execution of all aspects of this program unless otherwise noted.

This project plan is not regulatory guidance and does not represent the NRC's regulatory position on any issue. Because this research program is ongoing, this project plan will be subject to additions and modifications, and should not be considered a final product.

EXECUTIVE SUMMARY

Overview
This document provides a description of the Nuclear Regulatory Commission's (NRC) research plan for developing updated tools and methods to assess the risk posed by high energy arcing faults (HEAFs) in support of PRE-GI-018.

Background
HEAFs are hazardous events in which an electrical arc leads to the rapid release of energy in the form of heat, vaporized metal, and mechanical force. The guidance for modeling HEAF events in fire probabilistic risk assessments (PRA) is documented in Appendix M of NUREG/CR-6850, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities." This guidance postulates that HEAFs can occur in switchgear, load centers, and bus ducts with a nominal voltage of 440V and above, and defines a zone of influence (ZOI) in which targets are assumed to be damaged.
An OECD/NEA report, published in June of 2013, documented 48 HEAF events, accounting for approximately 10% of the total fire events reports in the international fire records exchange program database. These events were often accompanied by loss of essential power and complicated shutdowns. To confirm the PRA methodology in NUREG/CR-6850, which was formulated based on limited observational data, the NRC led an international experimental campaign from 2014 to 2016. The results of these experiments uncovered an unexpected hazard posed by aluminum components in or near electrical equipment and the potential for unanalyzed equipment failures, which the current PRA modeling guidance does not address.

Initial NRC Actions
Upon discovery of the potential hazard posed by aluminum, the NRC's Office of Nuclear Reactor Regulation conducted an immediate safety evaluation and concluded that no immediate safety concern exists, but recommended that the NRC's Office of Nuclear Regulatory Research (RES) begin the generic issues (GI) process. Additionally, RES staff conducted a review of operating experience, and identified six events from the U.S. operating fleet where aluminum-related effects like those observed in testing were present. To inform licensees about the findings of this review and results of testing, the NRC issued Information Notice 2017-004.

Generic Issues Program
RES staff proposed this potential safety concern as a GI in a letter dated May of 2016. The Generic Issue Review Panel (GIRP) completed its screening evaluation for proposed Generic Issue (GI) PRE-GI-018, "High-Energy Arc Faults (HEAFs) Involving Aluminum," and concluded that the proposed issue met all seven screening criteria outlined in Management Directive (MD) 6.4, "Generic Issues Program." Therefore, the GIRP recommended that this issue continue into the Assessment Stage of the GI program. The assessment plan, published in August of 2018, requires the NRC to develop updated PRA tools and methods for HEAFs to be used in pilot plant studies and risk evaluation.

Update September 1, 2021:
NRC staff has determined that pre-GI-018, "High Energy Arcing Faults Involving Aluminum," no longer meets Criterion 5 of NRC Management Directive (MD) 6.4, "Generic Issues Program" (ML14245A048), for remaining in the Generic Issues (GI) program. The staff has concluded that the risk or safety significance of HEAFs involving aluminum cannot be adequately determined in a timely manner without performing additional, long-term research to develop the methodology for such a

determination. Therefore, Criterion 5 of the screening criteria in MD 6.4 is no longer being met.

Accordingly, the staff has exited the pre-GI-018 from the GI program (ML21237A360) and the staff is moving forward with a revised approach that supports a more efficient resolution of the issue by applying the *BeRiskSMART* framework.

The staff's revised approach for aluminum HEAF activities consists of two coordinated tracks for (a) research activities in coordination with EPRI and (b) use of LIC-504, "Integrated Risk-Informed Decisionmaking Process for Emergent Issues," Revision 5 (ADAMS Accession No. ML19253D401), to apply best available information and NRC risk assessment tools to determine whether any regulatory action is needed.

Consistent with the LIC-504 process, Phase 1 of the evaluation will reaffirm that no immediate safety issue exists given the time lapse since the GI process was entered in 2016. At the conclusion of Phase 2, the LIC-504 team will provide a publicly available memorandum that captures any recommendation(s) on longer-term regulatory actions. Agency management will consider the recommendation(s) and decide on any further regulatory actions needed, as appropriate. If necessary, such decisions will be communicated to internal and external stakeholders using NRC's existing processes.

HEAF Research Program

The objective of the NRC's HEAF research program is to develop tools and methods to assess the risk posed by high energy arcing fault events based on experimental data, operating experience, and engineering judgment. These tools and methods will account for the primary factors that influence the occurrence and severity of HEAF events, including the presence of aluminum and plant electrical configuration and protection schemes.

To leverage the expertise of collaborative partners, NRC-RES and the Electric Power Research Institute (EPRI) formed a joint working group under the NRC-RES/EPRI memorandum of understanding (MOU). The working group has outlined five tasks needed to achieve the program objective:

1) Development and Validation of a Multi-Physics HEAF Model (Task B)

Experimental evidence has shown that the behavior of a HEAF is highly variable, and depends on a number of factors, including: fault duration, system voltage, available current, equipment geometry, and electrode composition. The amount of physical testing required to comprehensively address the variation in these parameters across the nuclear fleet is prohibitively large. A multi-physics modeling approach will allow for the calculation of the HEAF hazard across a wide variety of configurations. Because this is a novel application for any model, this task includes validation of the selected model.

2) Survey of U.S. Nuclear Fleet (Task C)

To ensure that full-scale experiments are representative of in-plant configurations, and to better understand the location and configuration of equipment containing aluminum to support PRA method development, EPRI conducted a comprehensive survey of the U.S. nuclear fleet. The survey gathered information on equipment manufacturers, models, voltages, insulation, and the location of aluminum components.

3) Physical Testing (Task D)

Physical testing is needed for the development and validation of the multi-physics model. Although not every configuration of interest can be tested, a limited set of tests that span the range of critical parameters can be conducted to ensure that the development and validation of the model provide acceptable results.

Physical testing encompasses small, medium, and full-scale tests, with each series designed to investigate aspects of the HEAF phenomena that are best observed at that particular scale. Small-scale experiments will characterize the morphology and oxidation states of aluminum particles. Medium-scale experiments ("open-box" experiments) will characterize the spectral emissions of the arc and the conductivity of arc ejecta. Full-scale experiments will provide data on enclosure breach, pressure effects, and serve as the representative scenarios against which the model will be validated.

4) PRA Method Development (Task E)

In addition to the tools and methods to model the consequences of a HEAF, updated PRA methods are needed to improve the realism and fidelity of the hazard model. This task includes an evaluation of U.S. operating experience, updated fire ignition frequencies, and updated non-suppression probabilities. This task also incorporates the configuration of plant electrical distribution systems (EDS), which heavily influence the maximum fault durations—a key parameter in determining HEAF severity.

5) Fragility Testing (Task F)

Tasks one through four will provide PRA practitioners with the tools and methods needed to realistically model the frequency and severity of a HEAF event for a wide variety of configurations. The specific impact of a HEAF on a particular target, however, is unknown. Current HEAF guidance conservatively postulates that systems, structures, and components (SSCs) within the ZOI will be damaged. However, existing fire PRA target damage models were designed with a conventional fire in mind; HEAFs present a much shorter, higher energy source term, the effects of which have not been quantified. To address this gap, the response of common targets to short duration, high energy exposures will be evaluated in physical testing to develop a damage model. This damage model can be coupled with the hazard and PRA models to comprehensively and realistically assess the risk of HEAFs.

A simplified flowchart showing the relationships between these tasks and their products, as well as a tentative timeline, is shown in the figure below.[1]

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[1] The dates in this timeline refer to the completion of the technical work. Draft reports will typically be issued for public comment 2-3 months after the completion of the work. Final reports will be published after resolution of public comments.

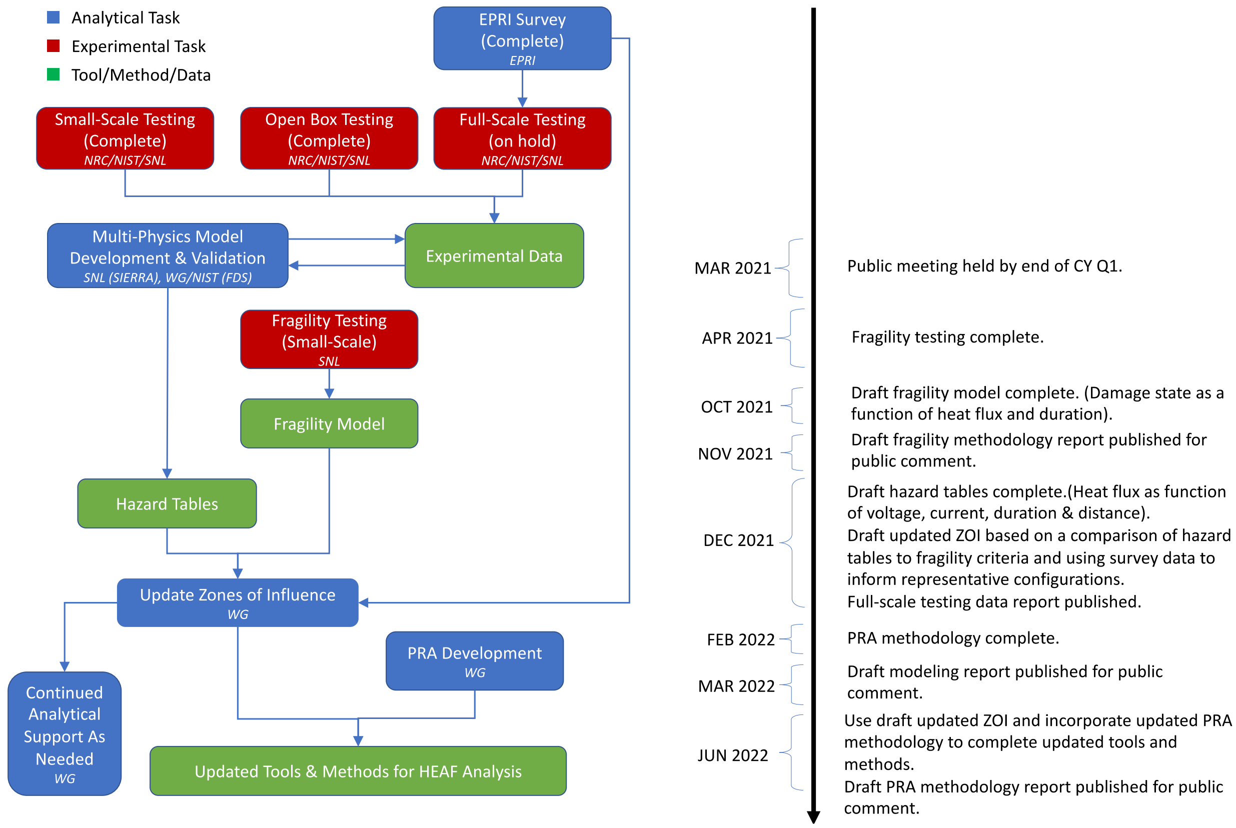


Figure 1 Simplified flowchart and timeline of major milestones.

Deliverables

Each task will culminate in one or more written reports. NUREGs, EPRI reports, SNL reports, or Research Information Letters (RILs) will be used as appropriate. A final report will document the ultimate conclusions of this research program, and make updated recommendations on HEAF modeling to supplement or supersede the guidance currently in Appendix M of NUREG/CR-6850.

Public Engagement

In addition to the technical input from EPRI partners in the joint working group, NRC-RES has routinely solicited feedback from the public and stakeholders during the development and execution of this program, and will continue to do so. Deliverables will be published for public comment as they are completed, and public meetings will be held as necessary to guide the program direction.

1 BACKGROUND

1.1 PROJECT ORIGINS

1.1.1 OECD Operating Experience Review

An initial review of operating experience related to HEAF events, and starting point for the HEAF research project, was conducted by the Organisation for Economic Co-operation and Development (OECD) Fire Incidents Records Exchange (FIRE) project. The scope of the review was limited to events in the OECD fire incident database. Parameters of interest were the specific equipment and components involved in the HEAF event, the arcing duration, the location of the HEAF, the effects of the HEAF on systems, structures, and components (SSCs), and operator actions before, during, and after the HEAF. In total, 48 HEAF events were analyzed.

This effort indicated that a non-negligible number of reportable events resembled high energy arcing faults, and the OECD member countries were interesting in compiling international operating experience with the objectives of:

- Investigating the frequency of HEAF events
- Investigate causes of HEAF events and preventative measures
- Investigate failures of fire barriers and other fire protection features due to HEAF events

Key takeaways from this review were:

- HEAFs represent a non-negligible fraction of the events in the OECD FIRE database (11.5%). This fraction also includes large yard transformers which periodically catastrophically fail.
- The probability of damage to SSCs is significantly higher among HEAF events than other categories of events in the OECD FIRE database.
- HEAF events in high or medium-voltage electrical enclosures saw the highest relative share of safety significance.[2]

This review of international operating experience was the impetus for the Phase 1 experimental test series. In its conclusion, the review notes that the statistical sample used is small and provides the recommendation that "experiments [be performed] for obtaining comprehensive scientific fire data on the HEAF phenomena known to occur in nuclear power plants through carefully designed experiments."

This OECD operating experience review is publicly available and can be downloaded at: https://www.oecd-nea.org/nsd/docs/2013/csni-r2013-6.pdf

1.1.2 Sandia National Laboratories Literature Review

In 2009, Sandia National Laboratories (SNL) performed a literature review about arc faults occurring in electrical switching equipment. The purpose of this review is to assess the extent to which existing

[2] The referenced report uses the category "high or medium voltage electrical enclosure" to describe enclosures with a nominal system voltage of 6.9kV or higher. This is not consistent with the commonly used U.S. definitions (NEMA C84.1), which are: low voltage (<1000 V), medium voltage (1000V – 100kV), and high voltage (>100kV).

literature might support improvements in current fire probabilistic risk assessments (PRAs). This review covered domestic and international operating experience from the early 1900's up until the mid-2000's.

Key takeaways from this review were:

- The focus of most research efforts was limited to the behaviors of the initiating equipment and the initial arc flash itself.
    - Poor test execution, measurement techniques, and differences between personal safety (arc flash) and equipment functionality limit the usefulness of existing test data.
    - A disconnect between the initial HEAF event and the impact on nearby equipment is apparent.
    - There is a need to characterize the potential for ignition of secondary combustibles (target fragility), characterize fire growth and intensity if a fire ensues, and characterize the effectiveness and timing of the fire suppression efforts.
- Existing research is sharply limited in scope and has not addressed any of the key factors of interest to fire PRA in anything more than a preliminary and/or qualitative manner. Specific areas of fire PRA methodology that require additional work include:
    - initiating frequency,
    - behavior of the HEAF-initiated enduring fire, and
    - the effectiveness and timing of fire suppression.

This literature review is 10 years old, and an appreciable amount of arc-related research has since been performed. Though it is documented here for background information, it is by no means a definitive collection of relevant literature. Although a periodic, all-encompassing literature review is not an efficient use of resources, focused literature reviews for specific aspects of the project (e.g., arc modeling, thermal measurement device design, etc.) will be performed on an as-needed basis.

The findings from this effort are documented in Sandia National Laboratories Report SAND2008-4820, "High Energy Arcing Fault Fires in Switchgear Equipment, A Literature Review," dated February 2009.

The report is publicly available and can be downloaded at: https://www.osti.gov/servlets/purl/972462

1.1.3 Sandia National Laboratories Instrument Scoping Study

The Sandia National Laboratories literature review (Section 1.1.2) concluded that past experimental programs suffered from limitations with respect to the instrumentation. In order to better position the laboratories' measurement capabilities to support Phase 1 testing (Section 1.2), a limited series of scoping tests were performed at SNL.

The testing utilized SNL's National Solar Thermal Test Facility to evaluate devices' capabilities to measure thermal incident energy and SNL's Terminal Ballistic Facility to evaluate devices' capabilities to measure pressure. The purpose of the testing was to determine which measurement devices are better suited for measuring thermal and pressure effects from a HEAF that could be used to characterize the zone of influence (ZOI). The tests evaluated an array of temperature and pressure measurement devices that were selected based on their fast response and robust design to survive the short HEAF exposure. Passive and active devices were evaluated. A list of devices evaluated is presented below:

	Active	**Passive**
Pressure	Pressure Transducers	Bikini Pressure Gauge

Thermal	NANMAC E6 TC's	Temperature Lacquers
	Plate Thermometers	
	Directional Flame Thermometers	
	Infrared Temperature Sensor	
	Gardon Gauge	

In addition to the instrumentation above, surrogate target cable coupons were used for qualitative assessment of damage to cable jacket and insulation. Though the cable coupons were only used for anecdotal heat damage data in this study, future tests could use electrically monitored cable segments with sub-jacket thermocouples to evaluate the hazard magnitude or cable failure in a more rigorous manner.

Key takeaways from this study were:

- Plate thermometers instrumented with intrinsic Type K thermocouples were capable of responding adequately to the step change heat flux exposure, are rugged, and relatively inexpensive.
- Gardon gauges are highly capable of accurately measuring heat flux and were used to calibrate other flux measurement devices. However, the need for active cooling adds significant logistics to their use in HEAF testing.
- NANMAC TC's provided measurements that are very consistent with the Gardon gauge and are easier to configure during testing, however, their use requires development of a model for transient heat flux estimate, which was not part of the effort.
- Cable coupons (thermoset and thermoplastic) didn't provide any useful information on cable ignition or electrical functionality.
- Pressure transducers provided unexpectedly low-pressure measurements and Bikini gauges while capable of surviving a non-HEAF explosive test, were not suitable for HEAF tests where ejected material could compromise the device.

This instrument scoping study is publicly available and can be downloaded at:
https://www.osti.gov/servlets/purl/1204110

1.2 Phase 1 Testing

Phase 1 testing consisted of twenty-six full scale experiments conducted over a three-year period, designed to confirm the zones of influence in NUREG/CR-6850 (NRC/EPRI, 2005). Arcing faults were initiated in enclosures rated from 0.48 to 10 kilovolts (kV) by means of a copper shorting wire. Real-time electrical measurements, including voltage, current and frequency, were recorded during the experiments. Heat fluxes and incident energies were measured with plate thermometers and slug calorimeters at various locations around the electrical enclosures during the experiments. Internal enclosure pressures were measured during the experiments, and the heat release rate was measured during the post-arcing phase. The experiments were documented with normal and high-speed videography, infrared imaging and photography. The complete results of the Phase 1 testing are documented in (NEA/CSNI/R(2017)7 Report on the Testing Phase (2014-2016) of the High Energy Arcing Fault Events (HEAF) Project)." One of the key observations from this test series was that HEAF events involving aluminum resulted in more severe physical damage to equipment than those involving only copper and steel at the voltage levels tested. In two experiments where aluminum was consumed during the HEAF, measurement devices were either damaged or the maximum measuring range was exceeded. These instruments were unable to measure the actual maximum temperature and heat flux. HEAF events involving aluminum were also observed to produce an airborne conductive compound that coated the test facility, causing short circuits and unintended current paths in the exposed buswork of the test facility, located several feet away from the test equipment.

The phase 1 testing report is publicly available, and can be downloaded at: https://www.oecd-nea.org/nsd/docs/2017/csni-r2017-7.pdf

1.3 Information Notice IN 2017-04

As a result of the observations from the Phase 1 testing related to aluminum, the NRC conducted a review of operating experience. This review uncovered six events from the U.S. operating fleet where aluminum effects like those observed in testing were present. An Information Notice 2017-04, "High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components" detailing the relevant aspects of the licensee event reports and Phase 1 testing was published in August of 2017.

Information Notice 2017-04 is publicly available, and can be downloaded at: https://www.nrc.gov/docs/ML1705/ML17058A343.pdf

1.4 Generic Issue Program

The staff in the Office of Nuclear Regulatory Research (RES) proposed this potential safety concern as a generic issue (GI) in a letter dated May 6, 2016. (GI Letter (ML16126A096).) The Generic Issue Review Panel (GIRP) completed its screening evaluation for proposed Generic Issue (GI) PRE-GI-018, "High-Energy Arc Faults (HEAFs) Involving Aluminum," and concluded that the proposed issue met all seven screening criteria outlined in Management Directive (MD) 6.4, "Generic Issues Program." Therefore, the GIRP recommended that this issue continue into the Assessment Stage of the GI program. The GIRP has completed an assessment plan, issued August 23, 2018 (Assessment Plan (ML18172A185)). Though the HEAF research project will result in updated fire PRA guidance for all arcing faults, much of the HEAF research program exists to resolve PRE-GI-018 in accordance with the assessment plan.

The status of PRE-GI-018 and associated documents are publicly accessible at: https://www.nrc.gov/about-nrc/regulatory/gen-issues/dashboard.html#genericIssue/genericIssueDetails/26

1.5 EPRI/NRC Working Group

To continue its efforts to advance the state of knowledge as it relates to HEAFs, the NRC teamed up with its collaborative research partner, the Electric Power Research Institute (EPRI). Under the NRC-RES / EPRI Memorandum of Understanding (MOU), knowledge and expertise from these two organizations can be leveraged to better support the objectives of this work. The goals of this group are to develop tools, methods, and data to assess the risk from HEAFs. The working group charter can be found in Appendix A to this project plan.

2 PROJECT OVERVIEW AND SCOPE

2.1 PROJECT OBJECTIVES

The overall objective of the HEAF project is to develop data, tools, and methods to better understand and assess the risk of high energy arcing faults in nuclear power plants (NPPs). This objective will be achieved in three parts, as described by the working group charter (Appendix A):

1) Characterize the primary factors that influence the occurrence and severity of arcing fault events (arc flash, arc blast, or HEAF).

   The current zones of influence in NUREG/CR-6850 Appendix M (NRC/EPRI, 2005) and Supplement 1 (NRC/EPRI, 2010) are “one-size-fits-all” models, insensitive to the various configurations that affect the severity of an arc fault.

2) Develop tools and methods to assess the risk posed by HEAF events based on experimental data, operating experience, and engineering judgement.

   The current modeling methodologies in NUREG/CR-6850 Appendix M (NRC/EPRI, 2005) and Supplement 1 (NRC/EPRI, 2010) have a limited technical basis, and updated methods will add realism to more accurately reflect plant risk.

The following step is an objective of the NRC only, and not EPRI or the joint working group.

3) Develop an NRC screening method to bin plants of interest for further evaluation.

   The NRC is employing an enterprise risk management (ERM) approach to resolving this issue, which requires a focusing of resources to reduce risk as efficiently as possible. NRC staff will develop a screening method to identify plants where risk-reduction measures will have the greatest impact based on factors like plant fire PRA status, CCDP, change in CDF, etc. Analyzing and assessing plant risk resulting from the influence of aluminum on a HEAF in NPPs is a requirement of PRE-GI-018.

3 DELIVERABLES AND TASKS

3.1 HIGH-LEVEL OVERVIEW

The phase 2 HEAF program began shortly after phase 1 with planning exercises such as the Phenomena Identification and Ranking Table (PIRT), public meetings, and Federal Register Notices to solicit public input. These activities and the initial development of the phase 2 test matrix took place prior to the formation of the joint EPRI/NRC HEAF working group, and have since been supplemented and modified as a result of the working group activities, additional stakeholder input, and lessons learned as the research progressed. Despite significant evolution, these activities are documented in Task A for completeness.

The basic strategy for executing the remainder of the project consists of five main components:

1. Development and validation of a multi-physics model for an electrical arc source term capable of predicting environmental conditions as a function of source equipment (voltage, current, duration, conductor material) at remote locations where targets are located. (Task B)
2. A comprehensive survey of the U.S. nuclear fleet to inform equipment selection for full-scale testing and provide guidance as to the range of conditions for PRA method development. (Task C)
3. Physical testing to provide input data for model development, and subsequently, data against which to validate the model. Physical testing can also support alternative approaches to modeling. (Task D)
4. PRA method development to address hazard binning, frequency, and influence of plant design. (Task E)
5. Fragility testing to characterize the functional response of common targets to the environmental conditions caused by the HEAF. (Task F)

The multi-physics model will predict environmental conditions at the location of potential targets. These conditions can be compared to the fragility characteristics of a specific target; if the threshold criteria are exceeded, the target is assumed to fail. This strategy is referred to as a “dynamic zone of influence (ZOI),” as it is specific to the source equipment and target. The consequences of the dynamic ZOI (conditional core damage probability) and event frequency can be used to assess plant risk.

The remainder of this chapter consists of a description of the tasks and sub-tasks required for project completion.

Task A. PIRT AND TEST MATRIX DEVELOPMENT

Subtask A.1. Phenomena Identification and Ranking Table (PIRT)

Task Status: Complete.

Task Overview and Purpose

The planning for phase 2 of the HEAF project began with an international Phenomena Identification and Ranking Table (PIRT) expert elicitation exercise, held in February of 2017. The objective of the PIRT exercise was to develop an ordered list of phenomena influencing a HEAF that can be used in the development of a "roadmap" for future research and allows for an informed use of resources for research and regulatory needs.

The panelists were comprised of representatives and experts from many of the organizations/countries that participated in the Phase 1 OECD/NEA HEAF testing:

- Institute De Radioprotection et de Surete Nucleaire (IRSN), France
- Korea Institute of Nuclear Safety (KINS), Korea
- Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany
- Japan Nuclear Regulation Authority (JNRA), Japan
- Central Research Institute of Electric Power Industry (CRIEPI), Japan
- U.S. Nuclear Regulatory Commission (US NRC), United State of America

The PIRT was conducted over the course of a several weeks and facilitated by NRC staff.

A PIRT requires participants to have an understanding of the phenomenon to be evaluated, and to be aware of the relevant scientific body of knowledge. To assist the PIRT participants, a library of material relevant to HEAFs was assembled and shared several months in advance. The complete list of documents included in this library is documented in the PIRT report in sections 5.1 and 5.2. The purpose of the PIRT literature review was to provide PIRT participants with a common and comprehensive base of knowledge from which to draw their expert opinions and judgements.

The PIRT report is publicly available and can be downloaded at:
https://www.nrc.gov/docs/ML1803/ML18032A318.pdf

Assumptions

The PIRT literature review assumes that the assembled body of literature accurately reflects the state-of-the-art regarding the subject matter. To help ensure completeness, PIRT participants were asked to contribute any relevant literature to the library. The major assumption in any expert elicitation exercise is that expert opinions are a valid representation of the informed scientific communities understanding of the relevant phenomena and parameters.

Expected Results

The expected result of a PIRT is a ranked list of relevant phenomena and parameters associated with the HEAF hazard. The PIRT report also summarizes the panelist discussions, conclusions, and recommendations.

Project Flow

Input/Output	Description	Related Task(s)
Input	Phase 1 test results and draft report	
Input	The assembled body of literature distributed prior to the PIRT	
Output	PIRT report and recommendations	Subtask A.2 Subtask B.1 Subtask D.2 Task FSubtask B.1

Risks and Mitigation
There are a number of risks associated with expert elicitation exercises. One risk is that project sponsor organization become "locked in" to the results of the PIRT and fail to consider new evidence and information as it becomes available. This risk can be mitigated by third-party review of project management and periodic reassessment of project goals and status. As with the literature review, a focused, need-driven review of the PIRT conclusions would help the working group avoid this risk. Another risk is that panelists failed to consider the full range of phenomena that are important to the subject hazard of the PIRT. It is difficult or impossible to be assured that no phenomenon or parameter was missed; but stakeholder input and periodic assessment of project progress and direction can help mitigate this risk.

If the body of literature is incomplete or inaccurate, PIRT participants may produce biased judgements. This risk can be mitigated by periodically revisiting the conclusions of the PIRT when new information or literature with contrasting conclusions becomes available.

Influence on Project Execution
One of the major knowledge gaps identified in the PIRT was the lack of target fragility data for short duration, high heat flux exposures with respect to traditional thermal fires. This is documented in section 4.2 of the PIRT. This knowledge gap led to the addition of the target fragility component (Task F) to the project.

Subtask A.2. Full-Scale Test Matrix Development

Task Status: Complete, but subject to review and modification by the working group.

Task Overview and Purpose
A test matrix specifying the tests to be conducted and major parameters to be varied was developed. This test matrix forms the basis for the full-scale testing carried out in Task B. The test matrix consists of two sets of tests: those under the auspices of the NRC's GI Program, and those under the auspices of the OECD/NEA HEAF Program. The former set was identified as the minimum combination of tests required to support resolution of PRE-GI-018.

The experimental variables (voltage, current, duration, conductor material) were initially chosen as a result of the PIRT's conclusions. They have since been reviewed by NRC staff, NIST, SNL, KEMA, EPRI, and stakeholders, and are still expected to be the most influential experimental variables.

The specific test parameters (voltage, current, duration) were informed by the output of several processes. First, NRC staff conducted a review of operating experience related to HEAF. Next statistics and arcing fault current calculations were performed for sites where the information was available to support that exercise. Next, NRC staff submitted draft test plan to OECD/NEA partners for review and comment, as they are participating in complementary testing. Next, the NRC issued a draft test plan for public comment in the federal register. All comments received in response to this notice were dispositioned by the staff. Finally, the NRC held a public workshop to further discuss these parameters in April of 2018 and met with the ACRS regarding the testing methodology in August of 2018.

Assumptions

During the development of the test matrix, it was assumed that the test laboratory will be able to provide the specified voltage/current/duration levels specified. It was also assumed that the NRC would be able to procure the specified quantity of near-identical equipment.

Expected Results

This task produced a full-scale test matrix to serve as a high-level blueprint for the test program and outlined the major experimental variables to be investigated and their values. This test matrix, shown below, was documented in the test plan published for comment and will be documented in the final test report. The original test matrix has been updated to reflect the addition of the decrement curve and supplementary tests, and undergoes periodic review as the research program progresses. The test matrix is shown in the figures below:

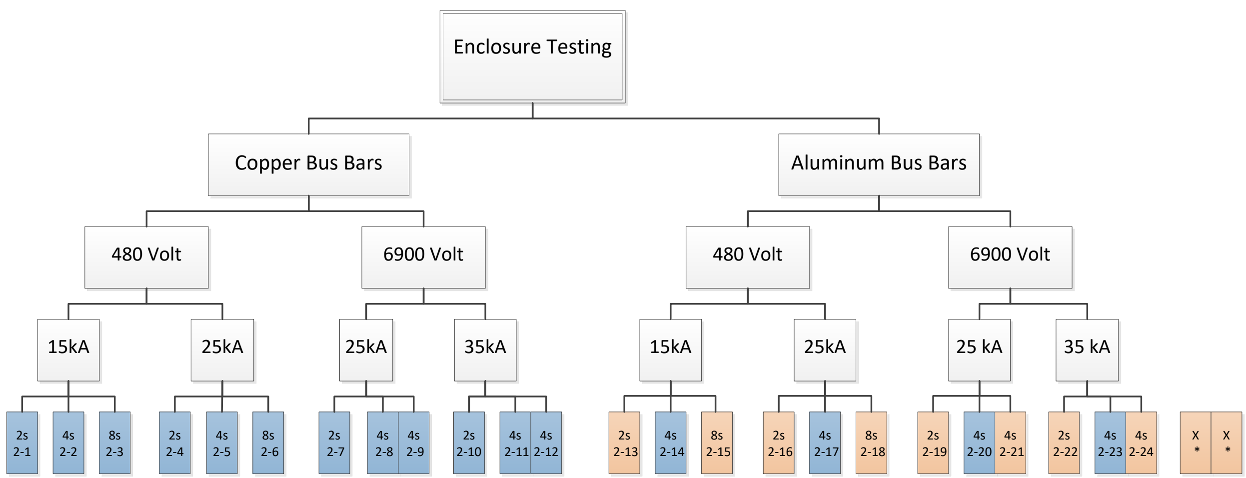


Figure 2. Test matrix illustration for electrical enclosures

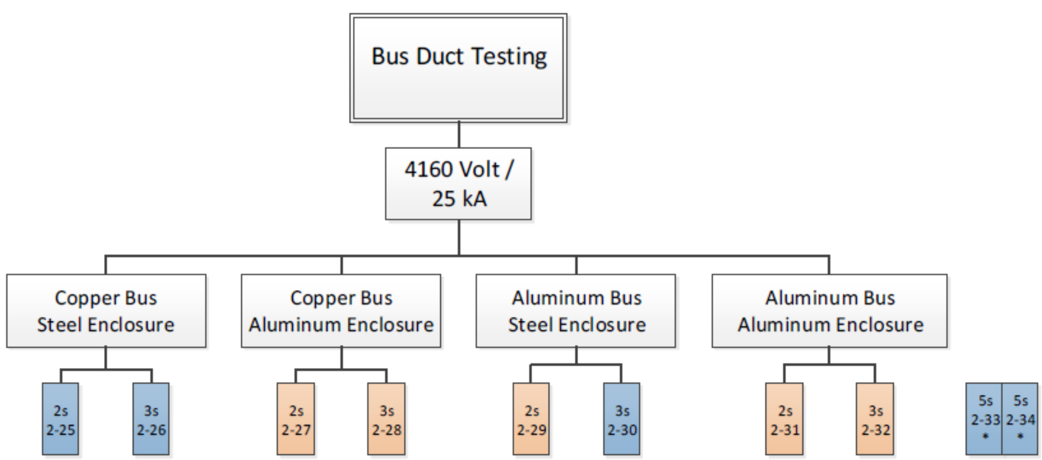


Figure 3. Test matrix illustration for medium voltage bus duct

Project Flow

Input/Output	Description	Related Task(s)
Input	Phase 1 test results	
Input	Lessons learned from Phase 1 testing	Subtask D.1
Input	PIRT report and recommendations	Subtask A.1
Input	Limited review of plant configurations	
Input	Feedback from OECD partners	
Input	April 2018 HEAF Workshop	Subtask D.3
Input	Working Group input	
Input	In-plant configurations and equipment	Task C
Output	Test matrix for full-scale testing	Subtask D.4 Subtask D.5 0 0

Risks and Mitigation

The test matrix depends on the correct identification of experimental variables that will have the greatest impact (sensitivity) on energy release. The variables selected in the development of the matrix are equipment type (enclosure/duct), design, voltage, current, duration, and material (aluminum/copper/steel). To mitigate the risk of incorrect parameter selection, the NRC relied on several processes to increase confidence in the choice of parameters: the PIRT, stakeholder interactions, review of relevant literature, and continual evaluation under the EPRI/NRC-RES working group.

The test matrix also depends on selecting the correct values for these parameters. The parameter values were initially selected after a review of several plant configurations. To mitigate the risks of a non-conforming sample, feedback on parameter values were reviewed and discussed during the 2018 workshop. The parameter values were also published in the draft test plan for public comment. Finally, the parameter values (except for the September 2018 tests, which preceded the working group formation) were reviewed by the EPRI/NRC working group. In late 2019, EPRI issued a formal survey to its members (Task C). The purpose of this survey is to understand the installation of aluminum in HEAF susceptible equipment. The results of this survey will provide the manufacturer and models of aluminum HEAF susceptible equipment such that NRC can procure equipment that is identical or comparable.

The test matrix does not include replicate tests due to time constraints and the high costs associated with testing. Without replicate tests, the working group will be unable to assess repeatability and uncertainty. If the working group suspects that the results of a particular test are atypical, an additional test can be scheduled for replicability. Modeling may also indicate whether the results of a test are atypical, and allow for targeted test replicates.

Task B. MULTI-PHYSICS MODELING

Subtask B.1. Selection of Model Input/Output Parameters

Task Status: Complete.

Task Overview and Purpose

In order to select a model, modelers must first determine what inputs will be available to the model and what outputs are needed for a particular application. In this case, any model employed will need to use standard information available to PRA practitioners and produce outputs that can be directly compared to the target fragility criteria.

The selection of output parameters began with a Phenomena Identification and Ranking Table (PIRT) exercise in 2017 (Subtask A.1), and has evolved and matured as the research program has progressed. The conclusions of the PIRT highlighted important input and output parameters for predicting damage from a HEAF:

Inputs	Outputs
Arc characteristics (Voltage, current duration)	Thermal effects (heat flux, temperature)
Conductor material (copper, aluminum)	Pressure effects
Target characteristics (fragility)	Electromagnetic effects
Enclosure properties and arrangement	Ejected material (smoke, ionized gas, conductive particulate) effects

As testing and analysis progressed, and experts from various industries and the EPRI/NRC HEAF Working Group provided input, the list of input/output parameters evolved. For example, electromagnetic spectroscopy showed no significant EMI fields outside the enclosure of origin, thus the model's ability to predict electromagnetic effects became irrelevant.

The model outputs must also match the inputs for the fragility testing in order to compare the environmental conditions to the targets' failure threshold criteria. The fragility model is discussed in detail in Task F, but the inputs that have been identified for a fragility model are heat flux and fluence.

Expected Results

This subtask will identify the available inputs and needed outputs for the selection of an appropriate modeling framework. The inputs will comport with the data available to PRA practitioners and the development of the PRA characterization, and the outputs will comport with the target fragility modeling input needs.

Assumptions

The input/output parameters identified during the PIRT remain relevant.

Project Flow

Input/Output	Description	Related Task(s)
Input	Important input/output parameters from PIRT	Subtask A.1
Input	Important parameters for PRA characterization	Task E
Input	Output parameters of the multi-physics model to ensure they match the input parameters of the target fragility model	Subtask F.1
Output	Selected inputs and outputs for multi-physics model selection	Subtask B.2

Risks and Mitigation
This task carries the same risk at the PIRT; i.e. that the identified input output parameters may not capture everything they need to. There is an additional risk that the input parameters do not match those identified in the PRA development process because they are occurring in parallel. This can be mitigated by frequent communication between the modeling and PRA development teams, making adjustments as needed.

Subtask B.2. Arc Modeling Literature Review & Model Selection

Task Status: Complete.

Task Overview and Purpose
This task reviews existing models and identifies modeling techniques that can utilize known HEAF scenario parameters as inputs and predicting the quantities of interest that are needed for evaluating target fragility.

Literature related to predictions of arc voltage, incident energy, electrode burn rate, and enclosure burn-through was reviewed and evaluated against existing data. This effort identifies the capability of existing models to be used for project needs.

The ability to predict the quantities of interest can be broken into three linked phenomena:

1) The behavior of the arc, given its major parameters (voltage, current, duration, electrode materials)
2) The behavior of the enclosure (time to breach, view factor, subsequent energy movement)
3) The transfer of thermal energy, effluent, and plasma to remote locations where targets may be located

The working group is investigating the ability of Fire Dynamics Simulator (FDS) to model aspects of the HEAF phenomenon. FDS is a large-eddy simulation code for low-speed flows, widely used for modeling smoke and heat transport from fires. Though FDS is not capable of representing an electrically consistent arc source term, assumptions and substitutions can be made to allow for a reasonable approximation.

Expected Results
This task will identify models that are suitable for use and identify the data needs for validation and/or further development. Confirmatory testing, verification, and validation will also be documented (Subtask B.6).

Assumptions
No assumptions have been identified.

Project Flow
Input/Output	Description	Related Task(s)
Input	Selected inputs and outputs for multi-physics model	Subtask B.1
Output	Need for small-scale tests to gather additional data for model development and validation	Subtask B.3 Subtask B.4

Output	Need for open-box tests to gather additional data for model development and validation	Subtask B.5
Output	Modeling approach to be developed and validated	Subtask B.6

Risks and Mitigation

1) The models may be difficult for the working group to review and evaluate due to its complexity. This risk can be alleviated by providing careful documentation comparing results to staged tests.
2) Model physics will be based on various tests. If these tests do not reflect characteristics of actual HEAF events, the default assumptions will be wrong, and that can compromise the entire model. This risk can be managed by ensuring that tests used for determining model physics replicate HEAF events to the extent possible.
3) Model physics may not accurately replicate physics that are important in actual HEAF events. This could include arc movement. Validation using tests that display this behavior this can reduce this risk (Subtask B.6).
4) The role of aluminum oxidation in the model will be difficult to implement and verify. Verification will rely on tests that can clearly discriminate between electrode materials, so managing this risk involves validation with tests that show a difference in performance based on electrode material.

Subtask B.3. Small-Scale Measurement and Instrumentation Selection

Task Status: Complete.

Task Overview and Purpose

This task consists of the selection of diagnostics and probes to image arc behavior and measure temperature, irradiance, and conductivity critical for gaining insight into arc fault hazards. The instrumentation and diagnostics were selected to address the data needs identified in **Error! Reference source not found.**. Techniques were developed on small-scale testing and then fielded during open-box testing in 2019.

Expected Results

Results include data readily usable for multi-physics model validation, including:

1) Time-resolved measurements to spectral radiation of the arc and its surrounding environment
2) Time-resolved current and voltage traces from each arc
3) Time-resolved Schlieren imaging of heat conduction from the arc and arc jet
4) High-speed videography
5) Two-dimensional IR imaging of the arc and its surrounding environment
6) Air conductivity measurements
7) Arc-generated thermal energy measurements via black calorimeters

Assumptions

1) Instrumentation used in small-scale testing can also be used for open-box field testing. The diagnostics and instrumentation are all developed on the small-scale experiments. The high-speed videography and IR imaging has been previously demonstrated in the field. Spectroscopic measurements and conductivity sensors have likewise been used on separate projects.

Project Flow

Input/Output	Description	Related Task(s)
Input	Data needed to support multi-physics model development and validation	Subtask B.2
Output	Diagnostic data (iterative)	Subtask B.3
Output	Measurement and instrumentation selection and configuration	Subtask B.4

Risks and Mitigation

1) The type of instrumentation used for small-scale experiments will determine the type and quality of data collected to develop the model. If the modeling needs evolve or change, there is a risk that the data to support model development will be missing. This risk is somewhat mitigated by the cost of the small-scale testing; these tests are relatively inexpensive and if additional data needs are identified, more experiments can be run in a short time.
2) There is a risk that measurements taken at small-scale will not accurately inform the model for predictions at full-scale. This risk is inherent to both the instrumentation as well as the experiments themselves. The incremental model development process should help mitigate this risk. After small-scale data is used for model tuning, the relevant components of the model can be compared to full-scale data before proceeding with model development.

Subtask B.4. Small-Scale Experiments

Task Status: Complete.

Task Overview and Purpose

This task consists of efforts to sustain stable arc plasmas in a laboratory setting to provide well characterized measurements for physics model validation. The tests were completed at SNL in 2019. Four electrode materials were tested: carbon, copper, aluminum, and tungsten. This task used the well-behaved arc to develop diagnostics for 2019 field testing.

Different materials and electrode tip geometries were tested to generate sustainable and steady arcs for small-scale testing. The results were made into best practices for experiments. The specific current and voltage were set by the power supply available at SNL. This produced an average voltage of 64 V or less and average currents between 90 and 300 A. Arc gap spacing was varied between 5 and 25 mm; due to the limitation in voltage and current, larger gap spacing was unable to initiate and sustain an arc. Instrumentation was used to assess the stability and repeatability of an arc of given electrode material and geometry. Arc jetting and smoke production were monitored using videography and Schlieren imaging. The effect of the smoke could be assessed through the spectroscopy, which showed contributions from both atomic and molecular emission and graybody emission. The current and voltage also assessed properties of the arc, including time-resolved behavior and the relationship between gap spacing and arc material to current.

The small-scale test plan is publicly available, and can be accessed at:
https://www.nrc.gov/docs/ML1817/ML18170A333.pdf

Expected Results

This task produced the following data:

1) Time-resolved current and voltage traces from arc initiation to arc extinction

2) Time-resolved profiles of ultraviolet and visible spectral radiation
3) Schlieren imaging of convective heat currents produced during the arc
4) Calorimeter data of temperature increase/incident thermal energy

Assumptions

No assumptions have been identified.

Project Flow

Input/Output	Description	Related Task(s)
Input	Measurement and instrumentation	Subtask B.3
Output	Instrumentation data to support multi-physics model development and validation	Subtask B.6

Risks and Mitigation

The risks include data that is non-applicable to the modeling approach and measurements that are not scalable. This risk is minimized by the relatively low cost of the small-scale tests and the quick turnaround time for completion of additional tests. The risks from scaling the experiments is minimized by developing the tests using conventional scaling approaches and comparison of small- and large-scale test results. Additionally, the open box experiments provide an "intermediate-scale" to augment the validation.

Subtask B.5. Open Box Experiments

Task Status: Complete.

Task Overview and Purpose

Like the small-scale experiments (Subtask B.4), the open-box experiments were designed to address the modeling data needs identified in Subtask B.1, but at larger scale and at conditions unattainable at small scale. This task encompasses a total of 18 tests at KEMA Power Test Laboratories (KPT) in Chalfont, PA. These tests were conducted during July, August, and September of 2019.

The electrodes were made of aluminum or copper. Three ½-inch or 1-inch diameter electrodes were installed in each box. The box was a cube with 20-inch dimensions. One side of the box was open to the environment and the electrodes entered the top of the box through insulative media.

Voltage, current, and arc duration were set by NRC in accordance with similar parameter selection for the Low-Voltage Enclosure Tests, Subtask D.5.

The instrumentation fielded at KEMA in 2019 was a direct evolution of prior arc testing from both full-scale and small-scale test series. The instrumentation detected measurands of interest including arc temperature, air conductivity, incident energy released, IR emission, and imaging of arc behavior. The testing methodology was outlined at a public meeting in July of 2019, where it was discussed, and commentary was received and used to inform the tests.

These measurements both address arc fault hazards and provide validation data for a multi-physics model. Data collected was processed internally by SNL personnel and compiled into a collaborative working space. The results are being drafted into peer reviewed journals, to engage the community of experts, gain feedback on methodologies, and provide a well-established forum to release results and trends.

The open box test plan is attached as Appendix E. The schematics for the box design and construction are available in Attachment 7.

Expected Results

This task produced the following data sets for each of the KEMA arc-in-the-box tests:

1) Dimensions for the boxes and geometry of the instrumentation in relation to the arc
2) Incident thermal energy around the enclosure
3) Infrared videography from one location
4) High speed, high dynamic range videography from two locations
5) Videography from various other locations
6) Electrical test data provided by the test laboratory
7) Spectral profiles from directly under the arc and 3” away to gauge air excitation

Three additional instruments will be used to investigate electromagnetic emission:

1) Surface conductivity from effluent deposition
2) Surface breakdown from effluent deposition
3) Electromagnetic Interference response using up to three D-DOT sensors
4) Air holdoff strength using a spark gap apparatus similar to ASTM D2477
5) Air conductivity using parallel plate sensor

Assumptions

1) The selected instrumentation measures quantities of importance for predicting target failure in fire PRA analysis.
2) The simplified geometry replicates arcs of similar magnitude as those seen in HEAF scenarios
3) The tests are run for a long enough duration to capture all important phenomena in a HEAF scenario

Project Flow

Input/Output	Description	Related Task(s)
Input	Measurement and instrumentation	Subtask B.3
Output	Instrumentation data to support multi-physics model development and validation	Subtask B.6

Risks and Mitigation

The risks surrounding open box testing are primarily associated with the atypical configuration. These tests involve uniform bus geometries, which provide greater test consistency, but can be a disadvantage when trying to evaluate parameters like arc migration. Similarly, the flow of oxygen and its impact on oxidation may atypical. These risks can be reduced by sizing and spacing conductors as similarly to plant equipment as possible, and through careful evaluation of full-scale tests to determine what parameters might be skewed in the open-box tests.

Subtask B.6. Model Development and Validation

Task Status: In progress. Scheduled completion Q4 CY2021. Draft report to be published Q1 CY2022.

Task Overview and Purpose

This task consists of the efforts focused on refining a physics-based model to characterize the emitted energy from arc faults. The mass, momentum, energy, current, and radiation transport equations will be solved in a coupled, transient manner in a multi-physics simulation to estimate the extent of hazardous environments due to HEAF events.

Benchmarking exercises will be conducted at discrete points during the exploratory development effort. Intermediate solution results will be produced prior to the completion of the model, but a full and relevant comparison to the data will not be accomplished until all the relevant physics have been implemented. Benchmarking will consist of comparison to thermal history and radiance at specific positions from the arc from test data. The initial benchmarking exercises are not expected to produce satisfactory results, since the appropriate physics will not have been implemented in the model. In anticipation of this, the exploratory development effort includes a hierarchy of radiation transport models. Analysis of the benchmarking comparison will allow the modeling effort to identify the shortcomings of the model and develop an approach to resolve them (e.g., implement more complex radiation transport models). After the final benchmarking exercise, the model is expected to produce an acceptable result through comparison to actual test data. The results of the comparison will be shared with the working group, who will determine whether the model provides an acceptable level of confidence. These benchmarks and the technical basis for the working group's choice of model will be published.

Videographic as well as spatial and temporal measurements of temperature, heat flux, and radiative flux will be used to evaluate the acceptability of the model predictions. The outputs of this task will be used in the Fragility Evaluation task (Task F) to compare the extent of the harsh environment with the critical fragility criteria. This model validation comparisons and spatial extent of harsh environments will be provided to the working group to inform ZOI development.

Expected Results

The output of the modeling task is predictions for cabinet of origin breach, given specific equipment parameters such as current, voltage, and conductor spacing. For cabinets where breach is predicted, the transient spatial temperatures, heat fluxes, and radiative fluxes will be predicted at various points from the breach.

Sandia will document the validation of the model against the experimental data, and will provide a report describing the validation methodology, the model biases, and any uncertainty statistics that can be reported. The NRC will publish this report with the modeling results.

Assumptions

The model development strategy makes a number of technical assumptions, including:

1) A simple gas species (air) plus a few additional species (e.g. copper vapor) can be used as the initial source for thermal and radiation terms, as opposed to a detailed air chemistry system.

2) Transport properties (e.g., thermal conductivity, electrical conductivity, radiation fluence, etc.) will utilize a simplified single species gas model, or simplified few-species gas mixture models.
3) The current transport equation captures the relevant energy transfer mechanisms, and resolving electromagnetic effects is not necessary (i.e. electro-magneto-statics is sufficient, and full Maxwell's equations are unnecessary.)
4) The heat flux and incident energy to typical targets will be insensitive to the "far field" fluctuations of a dynamic/chaotic arc.

Project Flow

Input/Output	Description	Related Task(s)
Input	Basic modeling approach to predict thermal effects of a HEAF	Subtask B.2
Input	Instrumentation data from the medium-voltage enclosure tests	Subtask D.4
Input	Instrumentation data from the low-voltage enclosure tests	Subtask D.5
Input	Instrumentation data from the medium-voltage bus duct tests	0
Input	Instrumentation data from the supplementary tests	0
Input	Instrumentation data from the small-scale tests	Subtask B.4
Input	Instrumentation data from the open-box tests	Subtask B.5
Output	Validated multi-physics model for predicting thermal environmental conditions as a result of a HEAF	Task G

Risks and Mitigation

1) Model development may take longer than anticipated to produce acceptable results.
2) The models under development have not been validated specifically for nuclear applications.
3) The development plan does not adequately capture some phenomena that winds up being important, or that simplifying assumptions remove a critical phenomenon from consideration.

Task C. EPRI Plant Survey

Task Status: Complete.

Task Overview and Purpose

The HEAF with Aluminum survey is intended to collect information about the presence of Aluminum in relevant electrical equipment and its potential significance for each operating plant in the US. The information will be analyzed by EPRI to:

- Provide summary, generic information about potentially susceptible locations for long duration HEAFs involving Al. No plant identifying information will be shared or published by EPRI.
- Inform EPRI's comments and recommend adjustments to future NRC-RES HEAF testing programs and plans to assure conditions tested are representative of in-situ conditions of actual plant equipment as installed and operated in the US fleet.
- Guide development of enhanced PRA modeling guidance for HEAFs to assure that the guidance covers the range of conditions in US plants and provides adequate detail to achieve realistic Fire PRA results.

The survey requested information about the location of Aluminum within HEAF-susceptible equipment. When aluminum is not present (i.e. the SSCs contain only copper) then no additional detail or input, unless explicitly specified, is necessary.

General Plant Information

- Plant/unit and general information

Electrical Equipment Information

- Information on equipment containing Al for each of the following types of equipment:
    - Medium Voltage Switchgear (SWGR)
        - Total number of Medium Voltage Switchgear
            - Number of Medium Voltage Switchgear that contains aluminum
        - Manufacturer/Model
        - Vertical vs horizontal lift circuit breakers
        - Voltage
        - Class 1E vs non-Class 1E
        - Location of aluminum
            - Main bus bars
            - Primary cable compartment bus bars (load or supply cable termination)
            - Enclosure material
            - Current limiting reactors
        - Insulated vs uninsulated bus bars
    - Low Voltage SWGR / Load Centers
        - Total number of Low Voltage Switchgear
            - Number of Low Voltage Switchgear that contains aluminum
        - Manufacturer/Model
        - Voltage
        - Class 1E vs non-Class 1E
        - Location of aluminum
            - Main bus bars
            - Runback bus bars
            - Current limiting reactors
        - Insulated vs uninsulated bus bars
    - Non-segregated Bus Ducts
        - Voltage
        - Class 1E vs non-Class 1E
        - Location of aluminum
            - Conductor
            - Enclosure
        - Insulated vs uninsulated bus bars
    - Iso-phase Bus Ducts
        - Conductor and housing material

Electrical Design Information

- Design information related to the transformer backup timed overcurrent design setpoint for offsite and unit auxiliary power transformers
    - UAT or SAT Transformer Lineup
    - Fault Clearing time given a switchgear fault given a failed (stuck) bus supply circuit breaker

Assumptions

During the US Aluminum survey, it was assumed that the stations were able to provide a majority of the information without having to do direct equipment inspections based on plant QA records (vendor manual, drawings, specifications, previous inspection work orders, nameplate, Library PM work orders, station procedures, plant modifications, experienced of maintenance and system engineers, etc.).

Expected Results

It is expected that the presence of aluminum in the US Nuclear fleet will be identified for:

- Low-voltage switchgear
- Medium-voltage switchgear
- Non-segregated bus duct
- Iso-phase bus duct
- Electrical Design Data: Fault Clearing Time

Project Flow

Input/Output	Description	Related Task(s)
Output	NRC/RES Informed Test based on Survey Results	Task D
Output	Review of the test matrix to ensure it remains valid and representative	Subtask A.2

Risks and Mitigation

There is the potential that plant QA records do not exist that can distinguish between aluminum and copper components. Mitigation was the survey request contained an Appendix entitled "*Approach for Switchgear, Load Center, Bus Duct Material Determination*" that provided a list of common source documents that may identify the material contained in switchgear and bus ducts.

Task D. FULL-SCALE TESTING

Subtask D.1. Lessons Learned from Phase 1 Testing

Task Status: Complete.

Task Overview and Purpose

Prior to designing the test plan for Phase 2, the NRC and the National Institute of Standards and Technology (NIST) reviewed the Phase 1 testing protocol, instrumentation, and results to identify testing elements which required modifications. Though the PIRT's recommendations also draw on observations from Phase 1 testing, this NRC/NIST review focused more on the logistics and execution of the experiments.

The major outcomes of this review were:

1) The elimination of the oxygen consumption calorimetry hood. The hood was a complicated instrument to transport, configure and operate. Based on the information it provided, the NRC determined that the minimal benefit did not justify the resource expenditure.

2) The addition of tungsten slug calorimeters. Several experiments in Phase 1 testing produced heat fluxes that over-ranged or destroyed the copper slug calorimeters, and instrumentation to measure those higher ranges were needed.
3) New methods of mounting and protecting instruments from damage were needed.

Expected Results

This task is expected to improve and refine the testing methodology, improve efficiencies and to minimize risks associated with testing.

Project Flow

Input/Output	Description	Related Task(s)
Input	Phase 1 test results	
Output	Instrumentation modifications and additions	Subtask D.2
Output	Lessons learned and test plan modifications	Subtask A.2 Subtask D.2 Subtask D.4 Subtask D.5 0 0

Risks and Mitigation

The risk associated with the removal of the calorimetry hood is the loss of heat release rate data and the possibility that it is a significant factor in the development of a new HEAF model. This risk is somewhat mitigated by the availability of heat release rate data from Phase 1 testing. The NRC acknowledges this risk and has determined that the benefits of proceeding without the calorimetry hood outweighs it. There are also risks associated with the use of new or novel instrumentation, like the tungsten slug calorimeters. They do not have the record of performance, nor the body of accompanying literature as more traditional instruments do. This risk was mitigated by the extensive validation efforts of measurement experts at NIST prior to testing.

Subtask D.2. Phase 2 Instrumentation Selection

Task Status: Complete, but subject to working group modification if additional testing is requested by the working group.

Task Overview and Purpose

The phenomena and parameters to be measured, as well as the instrumentation used were selected based on the output of several tasks. Prior to Phase 1 testing, the NRC contracted Sandia National Laboratories to perform a literature review and subsequent instrumentation scoping tests to evaluate measurement techniques (sections 1.1.2, 1.1.3). The phenomena to be measured were initially those that appear in other areas of fire PRA: convective and radiative heating, pressure, and products of combustion. To refine and confirm the important phenomena, the NRC hosted a PIRT expert elicitation exercise in February of 2017. Internally, NRC and NIST evaluated the data from Phase 1 testing and the instrument performance. Next, NRC staff submitted a draft test plan, which detailed the instrumentation to be used, to OECD/NEA partners for review and comment. The draft test plan was also issued for public comment with a federal register notice, and the NRC staff dispositioned all comments related to instrumentation and measurement. Finally, the NRC held a public workshop to further discuss instrumentation and measurement in April of 2018, met with the ACRS regarding the testing methodology in August of 2018 and held two public meetings in 2019.

Some of the instruments used in the phase 1 testing were preserved: the ASTM slug calorimeters and plate thermocouples were used in phase 2 as well. The pressure transducers were upgraded to a more EMI-resistant design, and the HRR hood was removed. Based on the lessons learned from phase 1 testing, various concerns that required dispositioning, and the modeling data needs outlined in Appendix B, new instrumentation was identified for phase 2 tests. The new pieces of instrumentation used in phase 2, their purpose, and associated test plans are described in each of the sections below.

- Heat Flux

  A tungsten slug calorimeter was designed, validated, and fielded by NIST to capture the high range heat flux. The Inconel plate thermocouples in phase.1 failed and vaporized under high flux conditions, and a different material was needed to withstand the environmental conditions. Documentation of the development and validation of the tungsten slug calorimeters is provided in Attachment 8.

- Electromagnetic Interference

  Based on the pressure readings from phase 1, it was apparent that electromagnetic fields were interfering with the data collection. Though the pressure transducers were upgraded to a more EMI-resistant design, a concern remained that EMI could negatively impact surrounding equipment and create a failure mechanism that had not been previously considered in HEAF models.

  To disposition this issue, electric field (D-DOT) sensors were placed at several locations around the enclosure during phase 2 low-voltage and open box testing. For all tests where D-DOT sensors were used, no EMI fields above the ambient trigger levels were detected. The working group determined that there was no need to monitor electrical field strength in subsequent tests.

- Air Conductivity

  Another potential failure mechanism of concern was the arc ejecta (smoke, ionized gas, vaporized metal) causing shorting as it moves about the room. If the conductivity of the cloud reached significant values, or if the voltage holdoff strength of air was lowered enough relative to system voltages, shorting could occur. To measure air conductivity and voltage holdoff strength, an air conductivity sensor and DC spark gap were fielded during phase 2 low-voltage and open box tests.

  Documentation of the instrumentation and the plan for their use is included in Appendix C and Appendix D. Data from these devices indicate that the conductivity of the air never decreased to the point where arcing could occur, even at low voltages, and with a large margin of safety. Therefore, the working group determined there was no need to monitor air conductivity in subsequent tests.

- Surface Conductivity

  During phase 1 testing, errant conduction paths were created in the test cell's incoming power supply after being coated with particulate from a test involving aluminum conductors. This potential failure mechanism is similar to that of air conductivity, but is related to the conductivity of the cumulative deposit, rather than the transient cloud. To measure surface conductivity, a surface conductivity sensor was fielded during phase 2 low-voltage and open box tests. Documentation of the instrumentation and the plan for their use is included in Appendix C.

- Transient Arc Temperature

An Ocean Optics HR4000 Spectrometer will be mounted to monitor the spectral radiation profile emitted from the arcing fault at a data acquisition rate of 100 Hz for the entire test duration. A UV-VIS optical fiber will collect light from the arc and disperse it by wavelength/energy using a grating and imaged onto a detector. This will provide information on how many photons of a given energy were present during the collection time. This energy is specific to the emitting species, the temperature of the emitter, and the density of the emitter. By analyzing the emission spectra produced, quantitative time-resolved measurements are produced of both the arc temperature and surrounding graybody temperature. This data can be shown as a scatter plot and correlated to time-resolved current and/or voltage. In addition, emission spectra provide species identification in the arc and the surrounding gas environment.

- Particulate Characterization

Two types of passive particle capture devices were used for phase 2 testing: carbon tape and silica aerogel. The captured particles could be subject to a number of post-test analysis techniques to quantify particle size, morphology, and oxidation state. Though particulate was characterized in the small-scale testing (Subtask B.4), these capture devices were included in the full-scale testing because they are easy and inexpensive to deploy and capturing data at full scale could reduce the risk in scaling or extrapolating from the small scale. While these devices are cheap to deploy, the analysis is time consuming and expensive; therefore, this analysis will only take place on an as-needed basis to support the working group or modeling teams at their request.

The instrumentation array for the medium-voltage enclosure tests (Subtask D.4) is shown below. This is a general configuration that places redundant measurement devices in several locations to increase the likelihood of measuring the HEAF effluent at several locations to better understand exposure gradients.

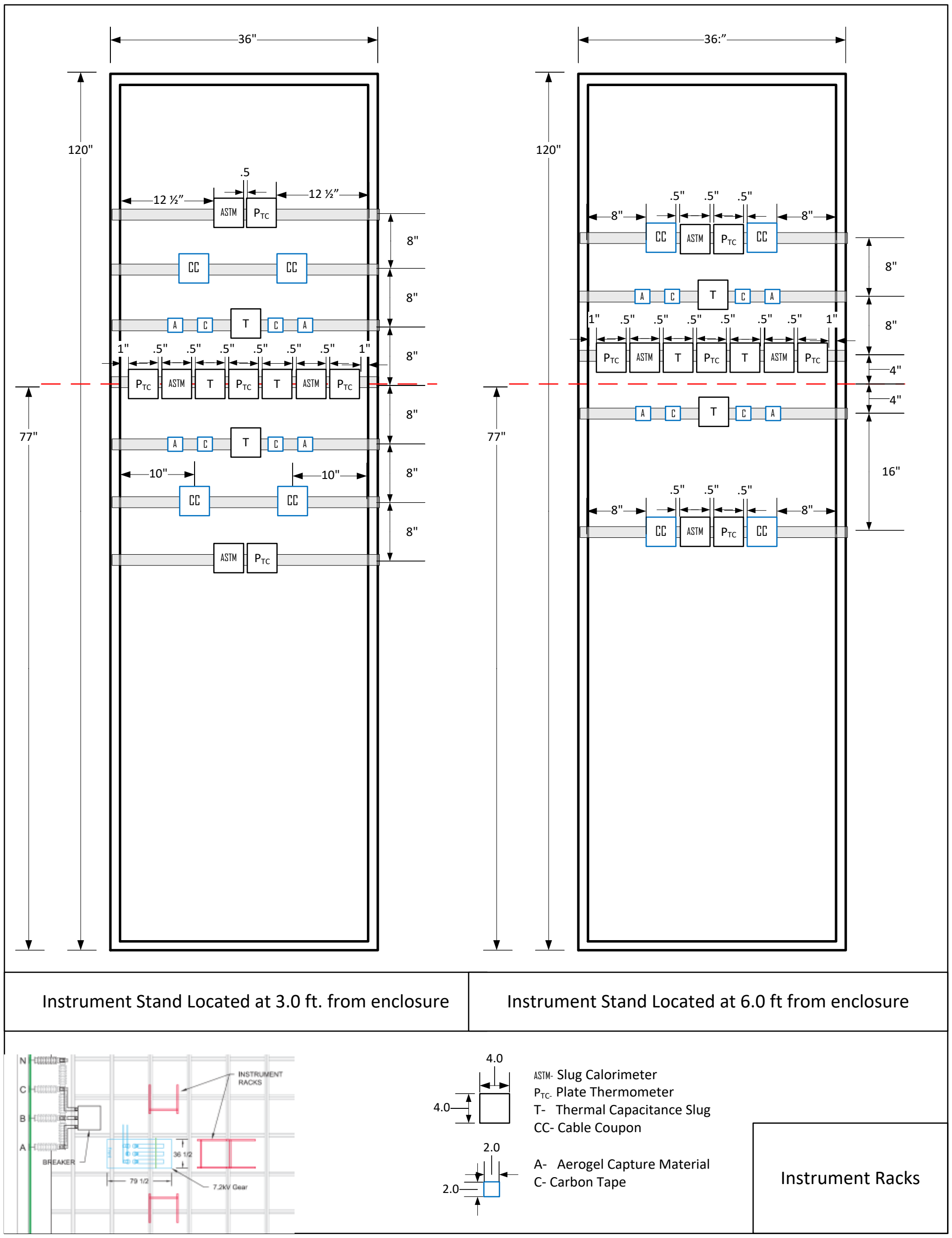
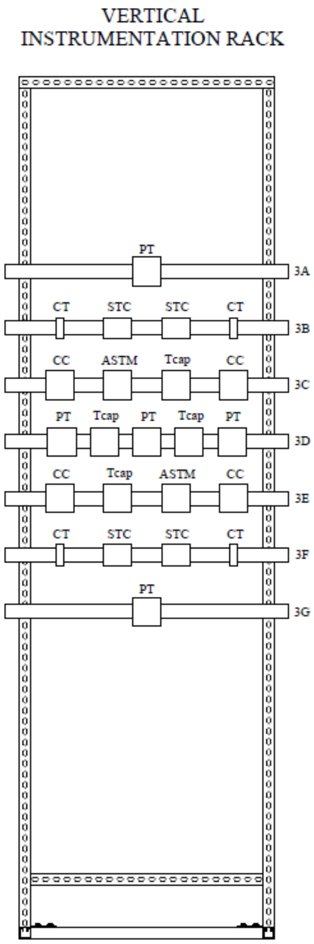
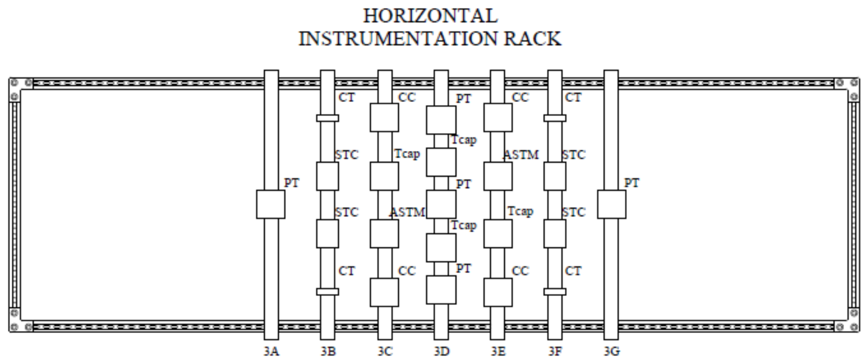


Figure 4 Vertical instrumentation rack layout.

A modified instrumentation array was used in the later series of tests (Subtask D.5 – 0) based on lessons learned from the earlier series. The modified instrumentation array is shown below.





SWGR VERTICAL RACK 1

LOCATION	SENSOR	DAQ CHANNEL
3A	PT	NIST DAQ -1
3B	CT	N/A
3B	STC	N/A
3B	STC	N/A
3B	CT	N/A
3C	CC	N/A
3C	ASTM	KEMA - A
3C	Tcap	NIST DAQ - 2
3C	CC	N/A
3D	PT	NIST DAQ - 3
3D	Tcap	NIST DAQ - 4
3D	PT	NIST DAQ - 5
3D	Tcap	NIST DAQ - 6
3D	PT	NIST DAQ - 7
3E	CC	N/A
3E	Tcap	NIST DAQ - 8
3E	ASTM	KEMA - B
3E	CC	N/A
3F	CT	N/A
3F	STC	N/A
3F	STC	N/A
3F	CT	N/A
3G	PT	NIST DAQ - 9

SWGR VERTICAL RACK 2

LOCATION	SENSOR	DAQ CHANNEL
3A	PT	NIST DAQ -10
3B	CT	N/A
3B	STC	N/A
3B	STC	N/A
3B	CT	N/A
3C	CC	N/A
3C	ASTM	KEMA - C
3C	Tcap	NIST DAQ - 11
3C	CC	N/A
3D	PT	NIST DAQ - 12
3D	Tcap	NIST DAQ - 13
3D	PT	NIST DAQ - 14
3D	Tcap	NIST DAQ - 15
3D	PT	NIST DAQ - 16
3E	CC	N/A
3E	Tcap	NIST DAQ - 17
3E	ASTM	KEMA - D
3E	CC	N/A
3F	CT	N/A
3F	STC	N/A
3F	STC	N/A
3F	CT	N/A
3G	PT	NIST DAQ - 18

SWGR VERTICAL RACK 3

LOCATION	SENSOR	DAQ CHANNEL
3A	PT	NIST DAQ -19
3B	CT	N/A
3B	STC	N/A
3B	STC	N/A
3B	CT	N/A
3C	CC	N/A
3C	ASTM	KEMA - E
3C	Tcap	NIST DAQ - 20
3C	CC	N/A
3D	PT	NIST DAQ - 21
3D	Tcap	NIST DAQ - 22
3D	PT	NIST DAQ - 23
3D	Tcap	NIST DAQ - 24
3D	PT	NIST DAQ - 25
3E	CC	N/A
3E	Tcap	NIST DAQ - 26
3E	ASTM	KEMA - F
3E	CC	N/A
3F	CT	N/A
3F	STC	N/A
3F	STC	N/A
3F	CT	N/A
3G	PT	NIST DAQ - 27

Figure 5 Updated instrumentation racks layout.

To address potential hazards that were raised during the project, and to support Sandia's multi-physics model development, the following measurements were added to the later series of tests:

1) Spectral emissions of the arc
2) Voltage hold-off strength of air in HEAF conditions
3) Surface conductivity from HEAF effluent deposition
4) Air conductivity in HEAF conditions

All of these additional measurements, as well as the instrumentation, were documented in independent test plans that were distributed and discussed within the EPRI/NRC working group. In many instances, the data collection approach was exclusionary in nature with possibility for refinement to the approach if measurements identified potentially risk significant exposures.

Expected Results

This task is expected to produce the complement of instrumentation and measurements for use in full-scale testing.

Assumptions

The selection of instrumentation assumes that they will produce reliable signals free from environmental or electromagnetic interference (to the extent possible), will have power supplies and ground connections as needed, and will be capable of transmitting data to an appropriate acquisition device or devices.

Project Flow

Input/Output	Description	Related Task(s)
Input	PIRT report and recommendations	Subtask A.1
Input	Lessons learned from Phase 1	Subtask D.1
Input	April 2018 HEAF Workshop feedback	Subtask D.3
Input	Measurements needed to support multi-physics model development and validation	Subtask B.2
Output	Measurements and instrumentation for full-scale testing	Subtask D.4 Subtask D.5 0 0

Risks and Mitigation

There are number of risks when choosing instrumentation to develop a hazard model.

1) The measurements selected may fail to capture the <u>relevant quantities</u> to support model development.

   In selecting the measurements of importance, the NRC used diverse means of soliciting input (described in the Task Overview and Purpose) to minimize the risk that important measurements or phenomena would be overlooked. Modeling needs may only become apparent when simulation capabilities advance to the full-scale benchmarking stage. As the test program evolves, the NRC can continue to mitigate this risk by soliciting stakeholder feedback and re-evaluating the data needs for the hazard modeling components of the project.

2) The instruments selected may fail to capture the measurements of interest due to <u>error or extreme conditions</u>.

   Many of lessons learned from Phase 1 were related to mitigating the risk of instrumentation failure due to extreme environmental conditions. In addition to the protective methods described in Subtask D.1, the potential for data loss is mitigated by using multiple devices and routing instrumentation wire and connections in different directions. Some data from the Phase 2 medium-voltage enclosure tests (Subtask D.4) were lost due to human error. As a result, the test facility upgraded their data acquisition system and procedures.

3) The instrument <u>placement</u> may not be conducive to capturing the full range of conditions generated by the HEAF event

   Past tests have demonstrated that HEAF events can generate highly directional thermal conditions, particularly in cases where the enclosure breach area is small. The quantity, placement, and coverage of the instrumentation devices was selected to capture the areas most likely to span the range of environmental conditions generated, but there is a risk that the arc will strike in or migrate to an unexpected location. Attempts to mitigate this risk include evaluation of past test data for the location of the enclosure breach and direction of energy flow, placing multiple test stands around the enclosure, and analysis of the magnetic forces in the enclosure to help predict energy flow. Another mitigation strategy is to move the portable instrumentation racks; if energy is observed in an unanticipated location, the racks can be relocated for future tests.

Subtask D.3. April 2018 Workshop & Equipment Selection

Task Status: Complete, but subject to modification if the working group determines additional tests are needed.

Task Overview and Purpose

The NRC organized and hosted a public workshop in April of 2018 with the following objectives:

1) Inform interested stakeholders about the status of PRE-GI-018 and related research
2) Review and resolve public comments received on the Phase 2 draft test plan
3) Solicit and review information from industry partners regarding common equipment types, configurations, and electrical operating characteristics to inform future testing
4) Provide an opportunity for public feedback on future testing

The proceedings of this workshop and key conclusions are publicly available and can be downloaded at: https://www.nrc.gov/docs/ML1921/ML19212A150.pdf

Expected Results

This workshop was expected to identify relevant equipment makes and models to be used in full-scale testing, as well as any comments on the test plan that required modification.

Assumptions

This workshop was an information-gathering exercise, and no risks were identified.

Project Flow

Input/Output	Description	Related Task(s)
Output	Equipment models and configurations	Subtask D.4 Subtask D.5 0
Output	Modifications to test plan based on public feedback	Subtask D.2 Subtask D.4 Subtask D.5 0

Risks and Mitigation

The value of the information, suggestions, and feedback gleaned from this workshop depends on the participation of subject matter experts. To ensure that all interested parties were notified, this workshop was announced on the NRC's public website and notifications were sent to parties with known interest or expertise in the HEAF research project.

Subtask D.4. Medium-Voltage Enclosure Tests – 2018

Task Status: Complete.

Task Overview and Purpose

This task consists of conducting four full-scale arcing fault tests conducted by the NRC at KEMA Power Test Laboratories (KPT) in Chalfont, PA. These tests took place in September of 2018. The position of these four tests in the overall full-scale test program is shown in the highlighted boxes on the test matrix below.

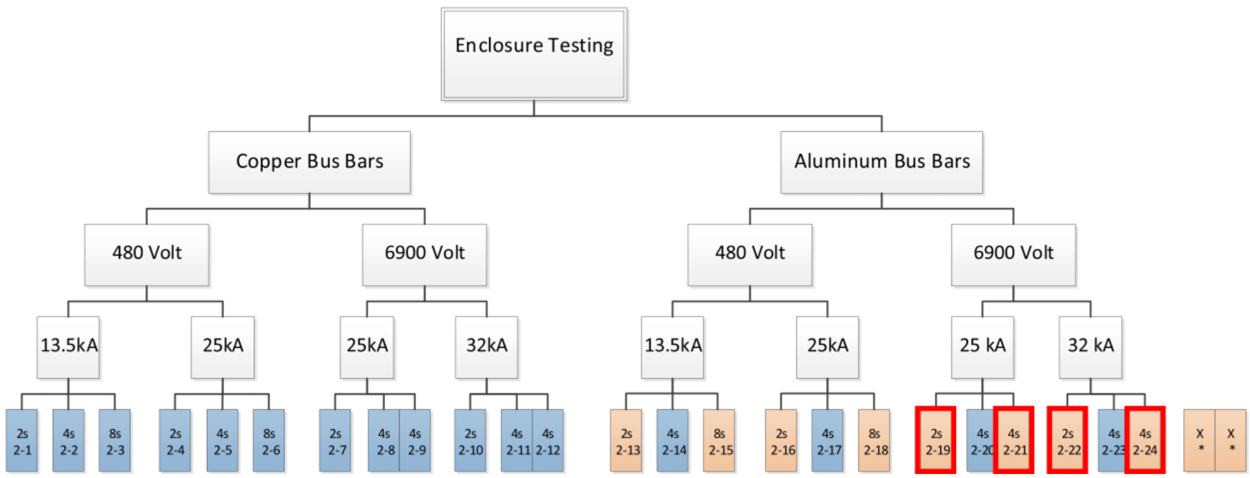


Figure 6.Test matrix illustration for electrical enclosures showing medium voltage tests performed in 2018

The test matrix and parameters therein were developed from a comprehensive review of U.S. NPP operating experience completed by the NRC. EPRI was not involved in the development of the test matrix or its parameters, and the 2018 testing predates the joint working group. EPRI's position is that their post-test review of the power flow and other parameters indicate that the 2018 tests described in this section are not prototypical of plant configurations. The four enclosures tested were General Electric Type M-36 switchgear, with aluminum buswork. This type of enclosure was selected based on stakeholder feedback during the April 2018 workshop. Though the standard is not directly applicable to these tests, the IEEE C.37.20.2 standard for arc testing on metal-enclosed switchgear was used to inform the arc initiation location and method.

Test measurement support was provided by NIST and SNL. Electrical support was provided by BSI Electric. EPRI members of the working group were present to observe these tests.

Assumptions

1) Full-scale testing closely resembles typical NPP HEAF scenarios.

   As with any laboratory testing, modifications from the as-built configuration are necessary to ensure data collection, test replicability, and satisfy various safety and logistical requirements. Within these bounds, however, the full-scale HEAF tests were designed to reflect realistic NPP configurations to the extent feasible. Equipment was procured as a result of feedback from public stakeholders. Test parameters (voltage, current, duration) were selected based on a review of U.S. operating experience and review of available plant electrical system information.

2) IEEE guidance for testing metal-enclosed switchgear is useful for informing test methodology.

   The arc location and initiation method for this test series was chosen based on IEEE C.37.20.7 Corrigendum 1 “Guide for Testing Metal-Enclosed Switchgear Rated up to 38 kV for Internal Arcing Faults”, which stipulates that the “point of initiation shall be located at the furthest accessible point from the supply within the compartment under test” and that the “fault shall be initiated between all phases in the compartment.” At the time of these tests, this standard was the most applicable guidance available; for future tests, these parameters will be informed by operating experience, survey results, and working group input.

3) Initiating the fault across all three phases of power has little or no impact on the progression of the fault. As observed in operating experience and confirmed in open-box tests, faults that start phase-to-phase or phase-to-ground progress to all three phases within milliseconds. The difference in energy release between faults that start as three-phase faults and faults that progress to three-phase faults in milliseconds is negligible.

Expected Results

This task produced the following data sets for each of the four tests:

1) Dimensions and weights for the enclosures (panels and bus bars) before and after testing
2) Incident thermal energy at 60 locations around the enclosure
3) Pressure profiles inside the enclosure at two locations
4) Qualitative data from cable coupons at 20 locations around the enclosure
5) Infrared videography from one location
6) High speed, high dynamic range videography from two locations
7) Videography from various other locations
8) Electrical test data provided by the test laboratory

Additionally, the following samples were collected, and have been selectively analyzed. Further analysis will be completed as needs are identified by the working group.

1) Aerogel particle collections located at 20 locations around the enclosure
2) Carbon tape particle collections located at 20 locations around the enclosure
3) Carbon tape samples at various locations on the floor and walls of the test cell

Project Flow

Input/Output	Description	Related Task(s)
Input	Test matrix for full-scale testing	Subtask A.2
Input	Lessons learned and test plan modifications	Subtask D.1
Input	Equipment models and configurations	Subtask D.3
Input	Modifications to test plan based on stakeholder feedback	Subtask D.3
Input	Measurement and instrumentation selection	Subtask D.2
Output	Test data and report of test	Subtask B.6 Subtask F.2 Task G

Risks and Mitigation

The expense associated with full-scale tests limits the ability to perform replicate experiments. A small sample size introduces the risk of skewed results from one or two outliers. This risk can be mitigated by careful monitoring and documentation to identify outlying results or data.

Another risk is deviation between tests that fail to isolate the experimental variables of interest. Efforts to mitigate this risk include specifying equipment that is as similar as possible, careful documentation of any configuration or material differences, and adhering to the test matrix, which specifies the experimental variables.

Other risks associated with this task include using non-representative equipment and initiating the arc at a location that is inconsistent with the location and progression of arc faults events from operating experience. The equipment selection risks are minimized by soliciting feedback from stakeholders and collaborative partners and procuring equipment that is typically used in the nuclear industry and initiating faults where operating experience indicates faults occur.

Subtask D.5. Low-Voltage Enclosure Tests – 2019

Task Status: Partially complete. No further testing will occur unless the working group determines that it is necessary.

Task Overview and Purpose

This task consists of conducting four full-scale arcing fault tests conducted by the NRC at KEMA Power Test Laboratories (KPT) in Chalfont, PA. These tests took place in August of 2019. The location of these tests within the overall test program are shown in the figure below.

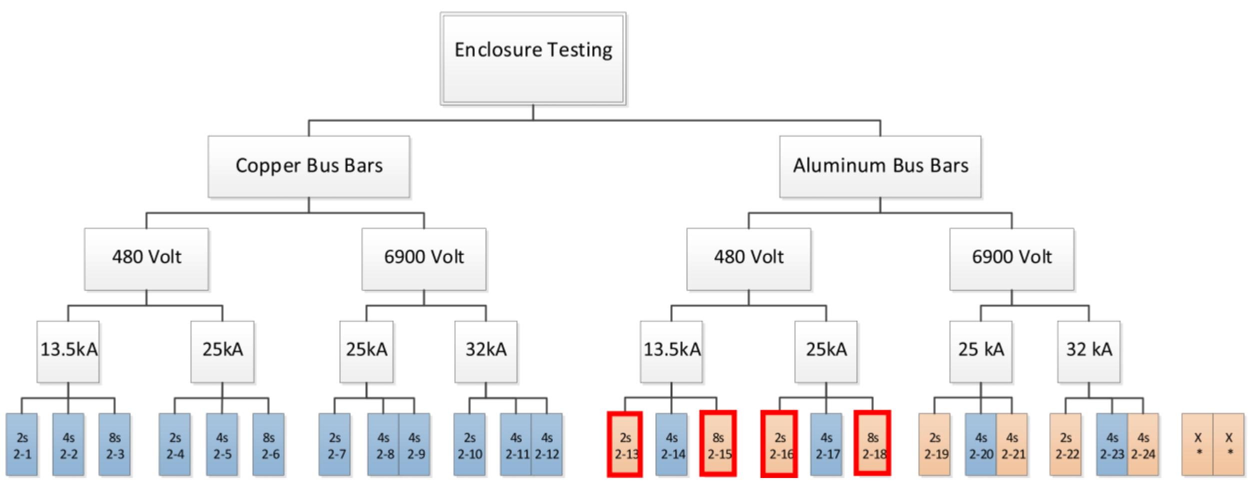


Figure 7. Test matrix illustration for electrical enclosures showing low voltage tests planned for 2019

The four enclosures tested were Westinghouse DS-416 supply breakers, with Westinghouse DS-206 load breakers. Test measurement support was provided by the NIST and SNL. Electrical support was provided by BSI Electric. EPRI members of the working group were present to observe these tests.

The specification for these tests involved initiating the arc on the main bus bars rather than at the breaker stabs, where operating experience indicates low-voltage faults are most likely to occur. There were three reasons for initiating the arc here:

1) Phase 1 testing involved low-voltage arcs initiated on the breaker stabs, and may already provide sufficient data for that configuration.
2) Aluminum is typically located in the runbacks or main bus bars, and if the arc does not migrate to the aluminum, no data about the impact of aluminum will be collected.
3) The location and orientation of the breaker stabs within the enclosure make it difficult to collect the types of data needed to support modeling.

EPRI does not agree with this specification, and prefers that the arcs be initiated on the breaker stabs to reflect operating experience as closely as possible.

As in phase 1, the low-voltage tests did not easily sustain an arc. Even when raising the voltage levels to 600V, the configuration of the low-voltage equipment prevents the arc from sustaining itself. This presented the working group with a dilemma; while this is valuable data, in that it highlights the reduced risk of a sustained low-voltage arc, it cannot rule out such an event, and provides no data on it. The working group debated this at length and did not come to any consensus. In keeping with an enterprise risk management approach, the NRC recognizes that low-voltage HEAF events represent a much lower risk than medium-voltage HEAF events and is proceeding with modeling efforts despite the possibility of insufficient low-voltage data. The NRC can perform more low-voltage tests if the working group determines the need for them.

Assumptions

1) Full-scale testing closely resembles typical NPP HEAF scenarios.

   As with any laboratory testing, modifications from the as-built configuration are necessary to ensure data collection, test replicability, and satisfy various safety and logistical requirements. Within these bounds, however, the full-scale HEAF tests were designed to reflect realistic NPP configurations to the extent practical. Equipment was selected as a result of public input as to common models across the U.S. NPP fleet. Test parameters (voltage, current, duration) were selected based on a review of U.S. operating experience and protective relay coordination design.

2) The current transformers (CTs) should remain in the enclosure. The working group concluded that the current transformers should remain in the enclosure with the secondary windings shorted so as to most closely resemble the operating condition of the enclosure. In the event that CTs interfere with a particular aspect of testing, they may be removed and the basis for removal will be documented and placed in the final report.

3) Some quantity of cabling should be restored to the enclosure. The enclosure was received with most or all of the internal cabling removed. The working group concluded that a few strands of single conductor and multiple conductor cable should be added to the wireways to most closely resemble the operating condition of the enclosure, and to collect post-mortem data on electrical continuity and jacket/insulation damage.

4) The addition of a shorting plate may be necessary to ensure a sustained arc in a predictable location. Though the addition of this plate deviates from the in-plant configuration, an arc that cannot be sustained does not provide any data. While the ability or inability of an arc to sustain itself is important data in terms of arc frequency and potential, it does not provide any data about the effects of hazard that assumes a sustained arc. The deviation from in-plant configuration will be

considered by the working group when evaluating the probability of and severity of a low-voltage arc. EPRI does not agree that testing should seek to sustain an arc, and prefers that equipment be tested as closely as possible to the in-plant configuration.

5) The protection of a portion of the main bus via physical means may be necessary to ensure arcing in a predictable location. There is a possibility that when the main bus is energized and the arc is initiated at one location, ionized gases will fill the enclosure and the arc will migrate to another section of the main bus. Protection will increase the likelihood of a sustained arc in one location and aid in the collection of data. This is purely a testing consideration related to the limitations on data collection instrument quantity and location. EPRI does not agree that modifications should be made to ensure a predictable arc location, and prefers that equipment be tested as closely as possible to the in-plant configuration. See Appendix F for more information.

Expected Results

This task produced the following data sets for each of the four tests:

1) Dimensions and weights for the enclosures (panels and bus bars) before and after testing
2) Incident thermal energy at 60 locations around the enclosure
3) Pressure profiles inside the enclosure at two locations
4) Qualitative data from cable coupons at 20 locations around the enclosure
5) Infrared videography
6) High speed, high dynamic range videography
7) Videography from various other locations
8) Electrical test data provided by the test laboratory

The following passive samples were collected:

1) Carbon tape particle collections located around the enclosure

Three additional instruments were used to measure various types of conductivity:

1) Surface conductivity from effluent deposition
2) Surface breakdown from effluent deposition
3) Electromagnetic Interference response using up to three D-DOT sensors
4) Air holdoff strength using a spark gap apparatus similar to ASTM D2477
5) Air conductivity using parallel plate sensor

D-DOT sensors were added to this test series as well as the box tests (Subtask B.5) to assess the potential impact of electromagnetic interferences (EMI) on surrounding equipment. For all tests where D-DOT sensors were used, no EMI fields above the ambient trigger levels were detected. The working group determined that there was no need to monitor electrical field strength in subsequent tests.

Project Flow

Input/Output	Description	Related Task(s)
Input	Test matrix for full-scale testing	Subtask A.2
Input	Lessons learned and test plan modifications	Subtask D.1
Input	Equipment models and configurations	Subtask D.3
Input	Modifications to test plan based on public feedback	Subtask D.3
Input	Measurement and instrumentation selection	Subtask D.2
Output	Test data and report of test	Subtask B.6 Subtask F.2 Task G

Risks and Mitigation

The largest risk inherent to low-voltage testing, and one that occurred during testing, is the possibility that the enclosure configuration coupled with the lower voltages will be insufficient to maintain an arc. If the arc cannot be maintained for the specified duration, the data required to inform the models will be lacking. A number of steps were taken at the time of testing to try to mitigate this risk, including the addition of a shorting plate and physical bus protection to minimize arc migration. Nevertheless, videographic data demonstrates the arc experienced a great deal of instability and migration if it could be sustained at all. As a result, only two of the four available enclosures were tested.

Another mitigation strategy used during testing was daily, pre-planned working group phone calls to discuss any unexpected results and determine an appropriate path forward. The shorting plate and bus protection strategies were agreed to by working group consensus during these daily communications.

Task E. PRA Scenario Development

Task Status: In progress. Scheduled completion Q1 CY2022. Draft report to be published Q2 CY2022.

Task Overview

This task consists of the documentation of relevant HEAF experience, experimental results, and the development of updated methodology for the modeling the risk associated with HEAFs in nuclear power plants (NPPs). The current methodology, as documented in NUREG/CR-6850, prescribes a one size fits all bounding ZOI for all HEAFs. Using the information developed in other tasks (arcing fault modeling and code validation from Sandia (Task B) and experimental testing by NRC-RES (Task D)) the granularity of the methodology is expected to expand in order to increase realism. The report will include chapters on:

- Background: A brief historical review of domestic and international HEAF events. Additionally, this chapter highlights a number of insights gained from a detailed review of U.S. NPP HEAF events as recorded in the EPRI Fire Events Database (FEDB).
- U.S. NPP operating experience: This chapter consolidates pertinent insights and aspects of events with respect to U.S. NPP HEAF operating experience.
- HEAF fire ignition frequency and non-suppression rates: This chapter provides updated HEAF ignition frequencies and manual non-suppression rates based upon experience in the EPRI FEDB.
- Risk modeling of HEAF scenarios: This chapter describes a revised methodology for modeling HEAFs in fire PRAs using the information documented in earlier chapters. This methodology allows for a more detailed approach to the modeling of a HEAF event considering the electrical distribution system (EDS), possible fault locations within an ignition source, the arcing material, and possible arcing fault durations.
- Examples applications: This chapter reviews the application of the methodology through the use of several examples.

Task Purpose

Provide a more realistic HEAF methodology than what is currently documented in NUREG/CR-6850, NUREG/CR-6850 Supplement 1, and related publications. This methodology is expected to provide more granularity over the current methodology.

Assumptions

Primary assumptions will be carried over from the arcing fault modeling and code validation from Sandia and experimental testing by NRC-RES.

Expected Results

This task will produce an EPRI/NRC joint technical report that reviews the available operating experience (OPEX), arc energy modeling, experimental evidence and the development of the revised HEAF methodology. The methodology presents a simplified generic electrical distribution system (EDS) and divides the plant into generic fault zones (see Figure 8). These fault zones were developed based on ignition source type and expectation of similar durations, characteristics, and ZOIs. It is expected that this method is used by fire PRA analysts to estimate the risk associated with HEAFs at NPPs. The event progression in each fault zone is organized in an event tree.

The conceptual event tree for an arcing fault in the first switchgear downstream of the Auxiliary Transformer (Zone 2) is presented in Figure 9. The event tree also captures insights from OPEX, such as the location of the fault in switchgear and load centers – as shown in Figure 9 the location of HEAF is most commonly seen in the supply cabinets rather than the load cabinets or bus bars.

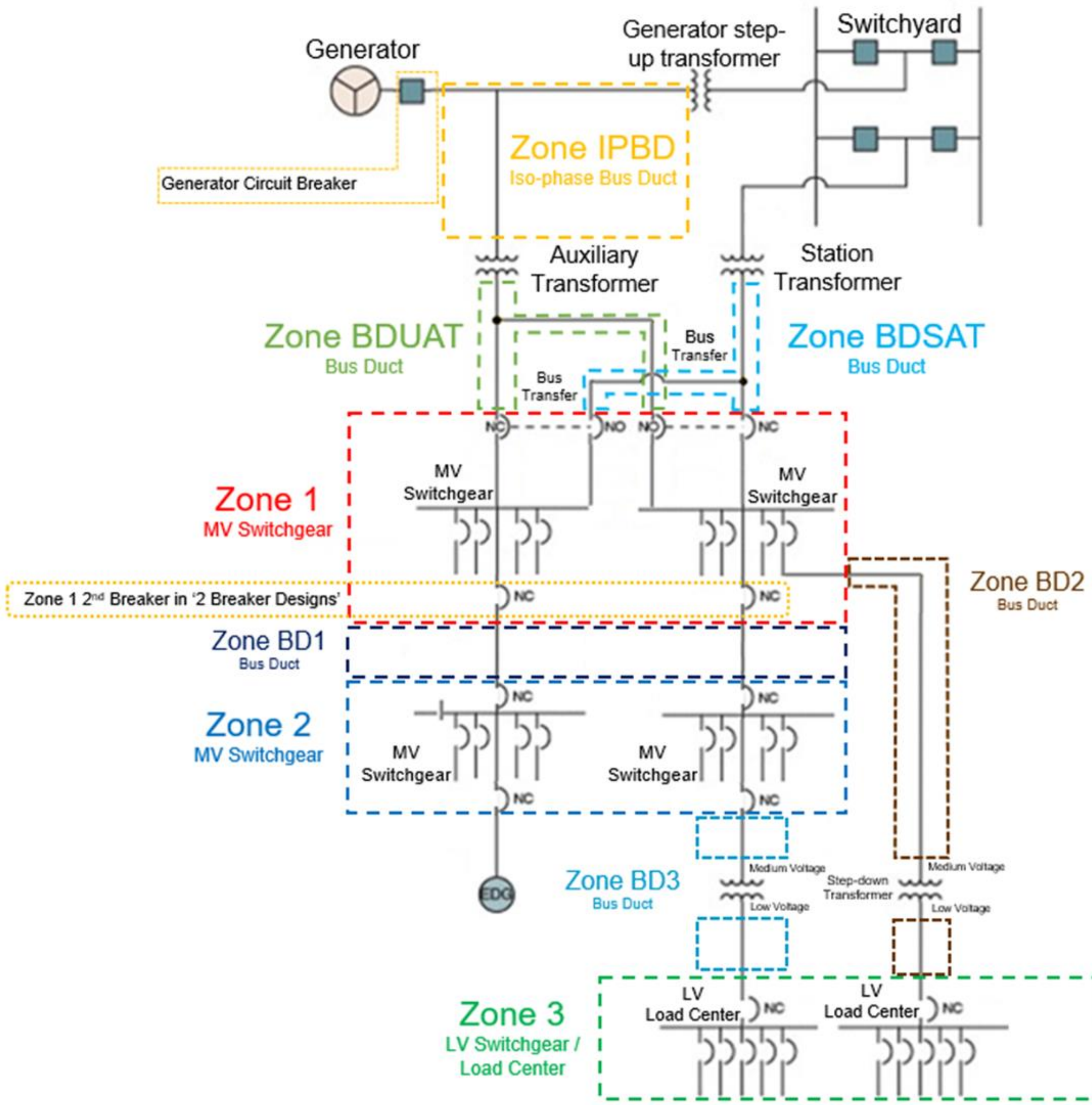


Figure 8 Fault zones for generic plant electrical distribution system configuration.

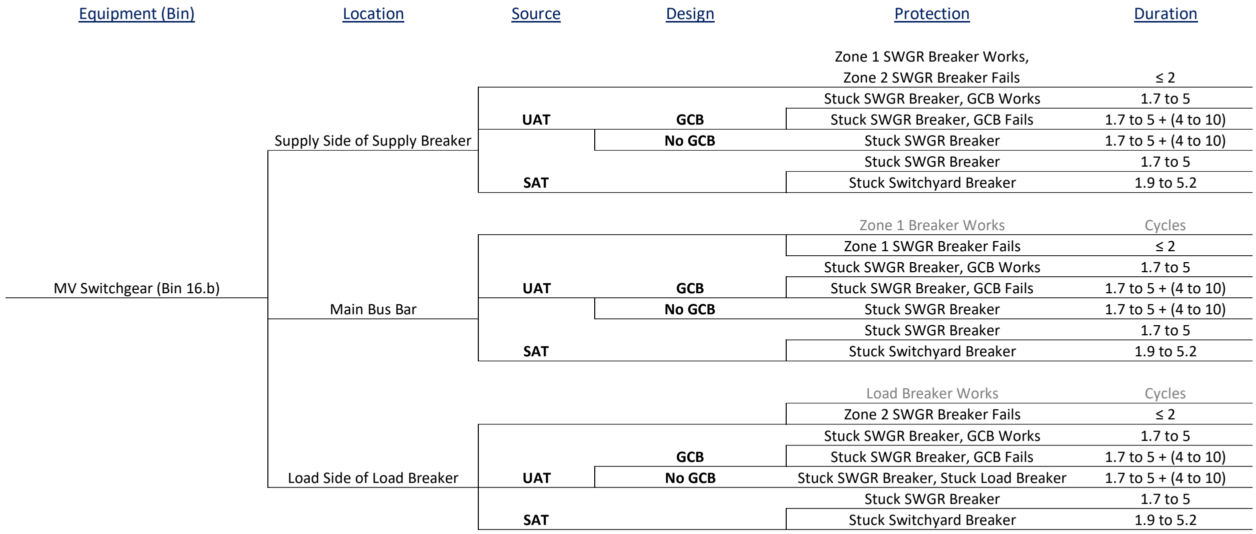


Figure 9 Zone 2 event tree.

Project Flow

Input/Output	Description	Related Task(s)
Input	OpEx review performed by EPRI and WG for fault duration, location, impact of plant protection scheme	
Input	Hazard results from the arc fault modeling performed by SNL	
Input	Experimental tests performed by NRC	
Output	Matrix of the tests and simulation configuration/runs necessary to develop ZOI. This Model Matrix is intended for use by the testing and code development team as an input for the test matrix and simulation runs.	Task G
Output	Joint EPRI/NRC technical report for the modeling of risk in fire PRAs for HEAFs	

Deliverables: A joint EPRI/NRC technical report of relevant HEAF OPEX and revised HEAF methodology.

Task F. TARGET FRAGILITY TESTING

Subtask F.1. High Flux Ignition Literature Review & Modeling Methodology

Task Status: Complete.

Task Overview and Purpose

This task consists of reviewing existing literature for high flux ignition criteria and determining an appropriate modeling approach for evaluating target fragility. This review focused largely on the high flux ignition work of Martin et al. (Attachment 6), supplemented with more recent data from SNL's Solar Test Facility. The proposed modeling approach predicts failure as a function of heat flux, fluence, and target properties.

Expected Results

The relevant literature and proposed modeling approach will be documented in a report together with the results of Subtask F.2 and Subtask F.3. Specifically, this task will establish the target fundamental failure criteria—the criteria (e.g., temperature/energy limits, component ignition) for which a target (e.g., cables, electrical cabinets, etc.) exposed to a HEAF would fail. It will also establish the failure model to be evaluated in confirmatory testing and used in the updated HEAF model.

Assumptions

The proposed model assumes that cable ignition is an appropriate surrogate for electrical failure, based on data from past NRC cable fire research programs (NUREG/CR-6931, Cable Response to Live Fire). The model also assumes that the target conductor is isothermal, and effects like pyrolysis and thermal losses can be ignored. These assumptions will be validated during confirmatory testing, where cables will be monitored for ignition and electrical failure. It is also assumed that the base model can be extended to cables in conduits, or in bundles through the confirmatory testing in Subtask F.3.

Another assumption, which is documented in the target fragility test plan and will be included in the final report, is that cable jacket compromise due to HEAF ejecta is bounded by the ignition mechanism. This assumption is supported by test data, which shows rapid cooling of the ejecta as distance from the HEAF increases and little more than surface damage to targets struck by ejecta.

Project Flow

Input/Output	Description	Related Task(s)
Input	Identified need for fragility modeling from PIRT	Subtask A.1
Input	Output parameters of the multi-physics model to ensure they match the input parameters of the proposed model (flux and fluence)	Subtask B.1
Output	Fundamental target failure criteria	Subtask F.2 Subtask F.3
Output	Basic modeling approach for predicting target failure in high heat flux conditions.	Subtask F.2 Subtask F.3

Risks and Mitigation

Subtask F.2. Working Group Target and Test Strategy Selection

Task Status: Complete, but subject to working group modification as needed based on results of testing.

Task Overview and Purpose

Subtask F.1 proposes the fundamental model to be validated and extended but does not specify the types of targets to be tested, or the range of test parameters. This task requires that the Working Group review the test approach and specify the types of targets to be tested and the range of the experimental values.

This task also requires that the working group agree on a strategy for extending the base model to conduits and electric raceway fire barrier systems.

Expected Results

Five specific PRAs were analyzed and a list of targets was compiled (Appendix B). Though cables represent the majority of the targets, the remaining targets need to be considered for screening or testing.

This task will produce the information needed to complete the test matrix for the confirmatory testing specified in Subtask F.3. The Working Group will select cable jacket materials, jacket thicknesses, heat flux magnitude, exposure durations, and exposure shape. This test matrix will be documented in a written report, along with the results of Subtask F.1 and Subtask F.3.

Assumptions

This task assumes that a selection of cable targets can serve as a representative sample for the generic application of the proposed model. This assumption is consistent with other areas of fire PRA, where a wide variety of generic cable targets are binned by important properties (e.g. thermoset vs. thermoplastic.)

Project Flow

Input/Output	Description	Related Task(s)
Input	Fundamental target failure criteria	Subtask F.1 Subtask B.6
Input	Basic modeling approach for predicting target failure in high heat flux conditions.	Subtask F.1 Subtask B.6
Input	Full-scale test data to inform solar tower flux ranges	Subtask D.4
Output	Representative targets for confirmatory testing	Subtask F.3
Output	Representative parameter ranges for confirmatory testing	Subtask F.3

Risks and Mitigation

There is a risk that Sandia's Solar Test Facility will be unable to accommodate the test parameter ranges (heat flux, in particular) specified by the Working Group. This risk is minimal, as test data from full-scale 2018 tests (Subtask D.4) measured maximum incident heat fluxes between 50 kW/m^2 and 7.5 MW/m^2 and the Solar Tower Facility can support the bulk of this range (up to 6 MW/m^2).

Subtask F.3. Fragility Model Validation & Confirmatory Testing

Task Status: In progress. Scheduled completion Q4 CY2021. Draft report to be published Q4 CY2021.

Task Overview and Purpose

This task consists of physical testing to address two main sources of uncertainty in the target fragility approach: the cable ignition model for exposed cables, and the effect that shielding (e.g., conduit, enclosed/solid bottom cable trays, bundling) has on the target. The cable ignition model is the basis of the fragility evaluation plan, so validation of the model through confirmatory testing is essential. Once this has been addressed, sensitivity tests can be conducted evaluated the effect of shielding on ignition.

These experiments will be performed at the Solar Furnace at the National Solar Thermal Test Facility at SNL in Albuquerque, New Mexico. The Solar Furnace concentrates sunlight to generate intense thermal environments reaching 6 MW/m^2 on a spot roughly ~5 cm. The cables will be monitored for ignition with visual observation and sub-jacket thermocouples.

Expected Results

This task is expected to produce test results that demonstrate the validity of the failure model proposed in Subtask F.1, and provide a basis for extending the model to cables in conduits and bundles. This model will be capable of predicting cable failure based on HEAF conditions and cable properties and can be used directly in the updated HEAF model (Task G). The test results, validation process, and complete model will be documented in a written report along with the results of Subtask F.1 and Subtask F.2.

Assumptions

This task assumes that the heat flux and fluence conditions in the Solar Test Facility are comparable to those experienced during a HEAF. This assumption is coupled with the assumption from Subtask F.1 that ejecta-induced failure is bounded by thermally-induced cable ignition.

Project Flow

Input/Output	Description	Related Task(s)
Input	Fundamental target failure criteria	Subtask F.1 Subtask B.6
Input	Basic modeling approach for predicting target failure in high heat flux conditions.	Subtask F.1 Subtask B.6
Input	Representative targets for confirmatory testing	Subtask F.2 Subtask F.3
Input	Representative parameter ranges for confirmatory testing	Subtask F.2 Subtask F.3
Output	Validated target failure models for HEAF exposures, as a function of HEAF conditions (predicted by multi-physics model) and target properties.	Task G

Risks and Mitigation

The risk that the confirmatory testing will invalidate the proposed model is minimal, as previous work has demonstrated its applicability for single air dropped cables or cables located in a tray with an open ladder bottom. There is a more substantial risk that the confirmatory testing will be unable to extend the base model to cables in conduits or bundles. This risk can be mitigated through the use of expert judgment or alternate modeling approaches.

Task G. UPDATED HEAF MODEL

Task Status: Incomplete. Scheduled completion Q1 CY2022. Draft report to be published in Q2 CY2022.

Task Overview and Purpose

This task consists of delivering an advanced HEAF hazard model that will aid in conducting fire PRA. The updated model will provide a zone of influence (ZOI) that is more realistic and representative for plant scenarios. This task represents the consolidated deliverable for the cumulative work outlined in this plan and described in the Working Group charter. The information gained from the thorough review of operating experience and literature, revisions to PRA methods (Task E), hazard damage estimate (Task B), and target fragility evaluation (Task F) are used to develop an overall updated and consolidated modeling approach.

Expected Results

This task is expected to provide an updated HEAF model. The model output is a zone of influence (ZOI) estimate for HEAF scenarios. This model will use scenario specific parameters that are known to influence the severity of the HEAF hazard. The level of detail is unknown at this time but could range from an analytical calculation to simple lookup table(s). The updated HEAF model ZOI estimates are used in the PRA evaluation to estimate plant fire risk.

Assumptions

This task assumes that the updated PRA methodology develops scenarios that are representative of plant configurations, the HEAF physics model(s) can accurately characterize the hazard source term and transport, and the fragility of targets important to plant risk can be determined.

Project Flow

Input/Output	Description	Related Task(s)
Input	Operational experience and literature knowledge	
Input	PRA scenarios	Task E
Input	Plant configuration	Task C
Input	HEAF physics model (source, transport)	Task B
Input	Target fragility estimates	Task F
Output	Zone of influence	

Risks and Mitigation

One risk associated with this task is its high dependency on other tasks. This risk can be reduced by focusing resources on the subtasks that are complex and exhibit a largest uncertainty for completion. Given this, the highest focus of resources should be placed on the HEAF physics modeling (Task B), followed by ensuring adequacy of PRA scenario development and assumptions.

4 SCHEDULE

A detailed project schedule is attached as a Gantt chart in an Excel worksheet.

A simplified schedule of major milestones is listed here:

Task A. PIRT and Test Matrix Development: Complete
- Subtask A.1. Phenomena Identification and Ranking Table (PIRT): Complete
- Subtask A.2. Full-Scale Test Matrix Development: Complete

Task B. Multi-Physics Modeling: Scheduled completion Q4 CY2021.
- Subtask B.1. Selection of Model Input/Output Parameters: Complete
- Subtask B.2. Arc Modeling Literature Review & Model Selection: Complete
- Subtask B.3. Small-Scale Measurement and Instrumentation Selection: Complete
- Subtask B.4. Small-Scale Experiments: Complete
- Subtask B.5. Open Box Experiments: Complete
- Subtask B.6. Model Development and Validation: Scheduled completion Q4 CY2021.

Draft document to be published Q1 CY2022.

Task C. EPRI Plant Survey: Complete

Task D. Full-Scale Testing: Complete
- Subtask D.1. Lessons Learned from Phase 1 Testing: Complete
- Subtask D.2. Phase 2 Instrumentation Selection: Complete
- Subtask D.3. April 2018 Workshop & Equipment Selection: Complete
- Subtask D.4. Medium-Voltage Enclosure Tests – 2018: Complete
- Subtask D.5. Low-Voltage Enclosure Tests – 2019: Partially complete

Data report to be published Q4 CY2021.

Task E. PRA Scenario Development: Scheduled completion Q1 CY2022.

Draft document to be published Q2 CY2022.

Task F. Target Fragility Testing: Complete
- Subtask F.1. High Flux Ignition Literature Review & Modeling Methodology: Complete
- Subtask F.2. Working Group Target and Test Strategy Selection: Complete
- Subtask F.3. Fragility Model Validation & Confirmatory Testing: Complete

Data report complete and published: https://www.nrc.gov/docs/ML2125/ML21259A256.pdf

Draft methodology report to be published in Q1 CY2022.

Task G. Updated HEAF Model: Scheduled completion Q1 CY2022.

Draft document to be published Q2 CY2022.

Appendix A. WORKING GROUP CHARTER

Mission Statement

To advance the state of knowledge and improve understanding of risk from electrical arcing fault hazards in nuclear power plants (NPPs).

Goal Statements

- Characterize the primary factors that influence the occurrence and severity of arcing fault events (arc flash, arc blast, or HEAF).
- Develop tools and methods to assess the risk posed by arcing fault events based on experimental data, operating experience, and engineering judgement.
- Analyze the plant impact of and quantify the change in risk from arcing fault events involving copper and aluminum.

Team Members

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Deliverables

1. Representative probabilistic risk assessment (PRA) frequencies and binning for electrical arc faults, including factors such as:
    - Arc flash, arc blast, or HEAF scenario definitions
    - Damage to external targets vs. confined to electrical component of origin
    - Component type and application
2. A technical model for the spectrum of arcing fault events based on experimental data, operating experience, and engineering judgement that:
    - includes the technical bases for representative damage models
    - accurately predicts the risk
    - is properly correlated with event frequencies and consequences
    - accounts for influential plant features

3. Representative pilot plant risk analysis. The pilot plant analysis should:
    - Represent the hazard across the fleet. The contribution of arcing fault events to plant risk is expected to vary, and may require plant engagement to understand which plants have aluminum in SSCs of interest (location, configuration, amount, etc.).
    - Seek industry stakeholder participation to evaluate the risk impact of the updated arcing fault model for aluminum and associated frequency.
4. Updated guidance to parse and more accurately characterize the risk of arcing fault events in fire PRAs. The updated methodologies and guidance should be published per the standard industry or NRC practices.
5. Periodic communications to keep stakeholders apprised of Working Group activities and progress.

Appendix B. List of Targets for Fragility Modeling

- Cables (thermoset, thermoplastic, armored) in raceways
    - Raceways
        - Cable trays
            - No coves (ladder)
            - Covers (solid bottom or solid top and bottom
        - Conduits
        - Cable bus ducts or cable risers
        - Junction boxes
    - Air drop cables (thermoset, thermoplastic, armored)
- ERFBS (fire wrap)
- Bus ducts
- Switchgear (across the aisle from the HEAF source)
- Load centers
- Transformers (well-sealed or vented)
- MCCs (may be in-line and beside HEAF source or may be across the aisle).
- Other electrical cabinets, inverters, wall mounted cabinets, distribution panels
    - well-sealed or vented
    - Sensitive Electronics
- Air/Instrument lines
- MG sets

Appendix C. CONDUCTIVITY MEASUREMENT

Problem Statement:

High energy arcing fault (HEAF) testing has identified that surface deposition of HEAF effluent resulted in unacceptable insulation resistance between uninsulated and non-enclosed power conductors. This observation questions the impact of HEAF effluent the functionality of nuclear power plant electrical equipment. The impact of HEAF effluent on the performance of equipment important for safety is desired to ensure adequate understanding of the hazard.

Standards:

ASTM D 257, Standard test methods for D-C resistance or conductance of insulating materials
IEC/TS 60695-5-3, Corrosion damage effects of fire effluent – Leakage-current and metal-loss test method

Objectives:

Measure surface conductivity from HEAF effluent deposition
Measure surface breakdown from HEAF effluent deposition
Measure air conductivity

Requirements/Task(s):

Task 1 – prepare experimental equipment and ship to KEMA
Task 2 – finalize sensor placement
Task 3 – collect data during HEAF test
Task 4 – analyze data and document measurement
Task 5 – evaluate data for potential use in Fire PRA

Experimental Approach

Several approaches will be deployed for measurement of electrical conductivity of HEAF effluent. These measurements will include passive measurements which will provide information on pre- and post-test conductivity and active measurements that will provide temporal information.

Surface conductivity will be measured using two different devices. The first uses interdigitated circuit cards. Leakage current between two conducting elements occurs due to the presence of a conducting medium between the elements. These cards are installed within the test cell in both vertical and horizontal orientations. As HEAF effluent is deposited on the circuit cards the conductivity between the circuit paths change. Pre- and post-test measurements will allow for a determination of the change in conductivity and the effects of orientation (vertical or horizontal) and distance from test object. The interdigitated circuits will be printed on a high temperature polyimide (quarts?) square with 1-inch dimensions. This size will allow for the use of existing mounting hardware. Initial locations to place circuit cards include KEMA test cell wall and select locations beyond within 8-12 feet of test object. The devices are targeted to be elevated 4-6 feet above ground. Geometrically the samples will be in a location where the HEAF effluent is expected to be directed. In addition to providing surface conductivity measurements, the interdigitated circuit cards will allow for surface breakdown tests. These tests are destructive in nature but will involve increasing the voltage potential between the two circuit traces until current avalanche conditions are achieved. The voltage at avalanche will be indicative of the surface breakdown strength (V/m). The surface breakdown tests will be performed after surface conductivity measurements are made. In addition, particle capture near interdigitated circuit cards will allow for post-test gravimetric measurement of deposition.

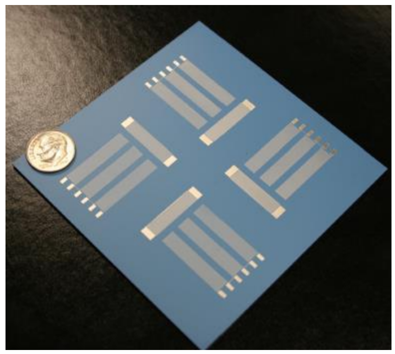

Figure 10 Photo illustrating interdigitated circuit card.

The second surface conductivity measurement uses a Trek 152-1 surface resistivity measurement probe. HEAF effluent that is deposited on a flat insulating surface will be measured. Pre-test measurements on a clean substrate will be compared to post-test measurements. Measurement points will be located at specific points within the test cell, including KEMA test cell wall, floor, and intermediate locations between the test object and facility walls. Vertical and horizontal surface measurements will be made.

Surface resistivity calculation is based on a 10V supply, 1μA current, and a geometry factors (ln R_2/R_1).

$$\rho_s = R_s \frac{2\pi}{ln\left(\frac{R_2}{R_1}\right)}$$

ρs, surface resistivity
R_s, surface resistance [ohms]
R_1, radius of inner conductor [mm]
R_2, radius of outer conductor [mm]

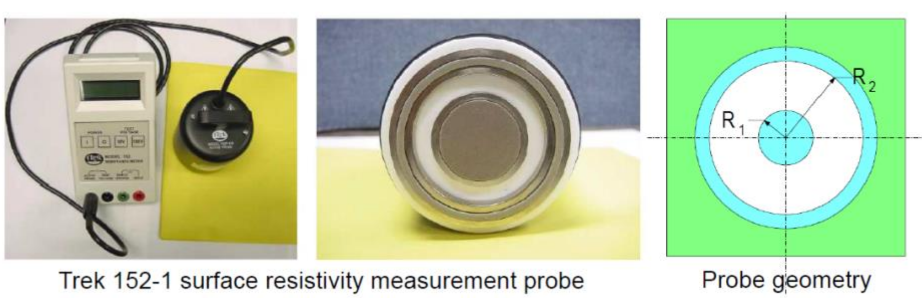

Figure 11 Surface resistivity probe.

The last conductivity measurement will use a conductivity sensor designed specifically for pulsed power research. The sensor measures free charge and is fully enclosed with a perforated screen design to eliminate Electromagnetic Interference (EMI). The sensor geometry is shown in Figure 3.

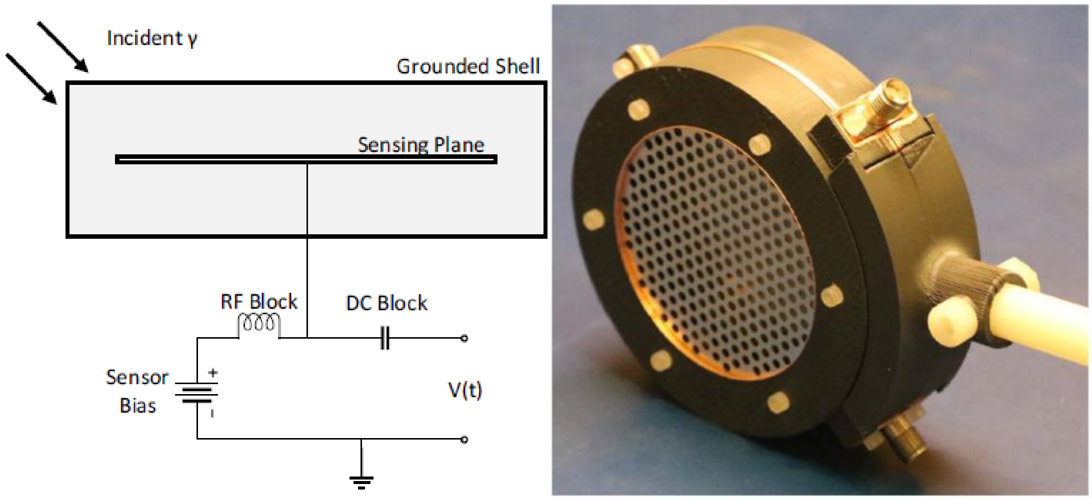

Figure 12 Air conductivity sensor geometry.

The sensor is formed from a hollow grounded cylinder with a suspended metal disk. A sensor bias is applied to the disk through a radio frequency (RF) block. As conductive particulate enters the chamber, the time change of resistance is measured as a voltage change through a DC block. Up to three of these devices will be placed at accompanying locations of other conductivity measurements. The grounded shell and use of coaxial cable to fiber link will ensure EMI reduction. The use of these sensors in pulse power applications (similar environment to HEAF testing from an electrical interference perspective) have shown successful results.

Post Experimental Action

After the testing campaign, the data obtained shall be made available to working group. The working group will evaluate the measurements against failure criteria of NPP equipment and components. If the WG determines that equipment could be vulnerable to conductive failure modes, then additional work, which could include subsequent testing will be performed to better characterize the hazard and develop appropriate methods to apply hazard in fire PRA.

Appendix D. VOLTAGE HOLDOFF MEASUREMENT

Problem Statement:

The voltage holdoff strength of air is dependent on gas density, temperature, and composition. During a high energy arcing fault (HEAF), high temperatures and metal particulate will reduce the holdoff strength of air. The HEAF may result in environmental conditions where the holdoff strength is not sufficient to maintain insulation between electrical power conductors.

Standards:

ASTM D2477 Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Insulated Gases at Commercial Power Frequencies.

Objectives:

Measure the air breakdown strength during HEAF test
Confirm analytical models for copper and aluminum

Requirements/Task(s):

Task 1 – prepare experimental equipment and ship to KEMA
Task 2 – collect data during HEAF test
Task 3 – analyze data to determine if failure criteria is exceeded
Task 4 – adjust testing approach (open vs. box or location) based on results
Task 5 – use data to evaluate analytical model for breakdown strength of high temperature, metal composed gas
Task 6- Confirmation of sphere to sphere ability to conform to standard plate to sphere (small scale test confirmation)

Experimental Approach:

The general approach outlined in ASTM D2477 will be followed with several modifications. These modifications include:

A sphere-to-sphere arrangement will be used instead of a plate – sphere. The sphere-to-sphere geometry ensures uniform field while minimizing the air flow and deposition effects of the plate geometry. A microsecond ramp will be used instead of a steady or stepped ramp. The limited duration of a HEAF event limits the applicability of the steady or stepped approach. A microsecond ramp will support multiple breakdown voltage measurements during a single HEAF tests.

The probes will be illuminated with ultraviolet (UV) to provide initiation electrons. This ensures an accurate ramped microsecond measurement approach. Use of UV during microsecond ramp testing has shown consistent results when compared to the much slower stepped approach.

The spherical probes will be arranged with a 1-centimeter gap. A HiLo surge test generator (“the generator”) will be used to provide a capacitive discharge circuit. The generator will provide up to 24kV potential with a 10kV/μs ramp rate. The repetitive ramp approach will allow for many measurements prior to, during, and after the HEAF test. Current viewing transformers, voltage monitor, and temperature monitor will be used and connected to oscilloscopes via fiber optic links. Particle capture devices will also be deployed near the units to understand metal vapor concentration. Spectroscopy (UV, visible, and near infra-red) will be used to estimate the volume percentage of metals in the arcs and as a function of distance.

Two units will be utilized during initial trials. The iterative nature of the testing allows for some adjustments to be made as the tests progress. Initially, the units will be placed at an elevation of 4-6 ft. above the ground and 8-12 feet from the test object. The exact floor location will be dependent on the equipment being tested and the expected (or observed for follow-on tests) locations for the HEAF ejecta / cloud emissions. Initial tests will employ an open box configuration. That is, the spherical probes are in open air and not impeded by any enclosure. Subsequent tests may use a closed, but vented box configuration if the results exceed the failure criteria (see below). If the results do not exceed the failure criteria, deployment of two adjacent units (one open air, and one closed/vented) should be performed to better understand ventilation impacts.

Post Experimental Action:

Following each experiment, the data will be analyzed and evaluated against the failure criteria of 1kV/cm. If failure criterion is exceeded, subsequent tests should use a closed/vented unit.

After the testing campaign, the data obtained shall be used to evaluate the analytical results. Figure 1 below shows breakdown strength for air and air/metal compositions at ambient and an elevated temperature. The model will be run for the measured temperatures from the testing and the results of the model will be compared to the test measurements.

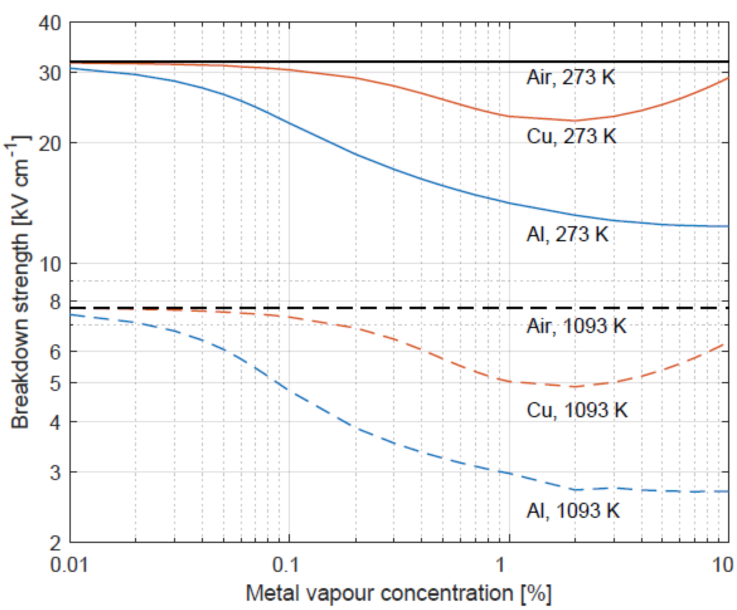

Figure 13 Breakdown strength for air/metal compositions for two different temperatures.

The data and analytical evaluation will be provided to the working group for resolution of HEAF initiated secondary arc-over.

Appendix E. OPEN BOX TEST PLAN

Problem Statement:

The arc that is formed during a high energy arc fault needs to be characterized to define the source term of energy emitted during these events. A model is being created to enable the HEAF Working Group to determine the extent of damaging environments generated by the HEAFs. The open box tests will allow the arc to be visible to diagnostic instrumentation to record parameters needed for the model and is validation for use in full scale predictions. Additionally, data, theoretical models, and much small-scale experiments for arcs exist for DC arcs. In order for AC arcs to be successfully predicted, direct correlations between parameters for DC and AC tests will allow translation of the physics and equations to the AC arcs experienced at nuclear power plants. If the source term for the model is incorrect, then the modeling efforts will not be accurate.

Standards:

IEEE 1584-2018 IEEE Guide for Performing Arc-Flash Hazard Calculations
NFPA 70E-2015 Standard for Electrical Safety in the Workplace

Objectives:

Observe and record behavior of arc with high speed videography
Measure spectral emissions from arc
Confirm analytical models for copper and aluminum

Requirements/Task(s):

Task 1 – prepare experimental equipment and ship to KEMA
Task 2 – collect data during HEAF test
Task 3 – analyze data to tune arc model characterizing emissions and arc temperature
Task 4 – adjust arc model based on results
Task 5 – use data to evaluate analytical model for arc source term

Experimental Approach:

The general approach outlined in IEEE 1584 will be followed with several modifications. These modifications include:

AC circuit configuration with three electrodes.

An open box configuration consisting of a 5-sided box, as show in Figure 1, will be used for the series of four tests. The tests will be conducted either in an adjacent test cell or in the main test cell, depending on the cadence of testing at the facility. Two main parameters will be varied in the tests – the current and the conductor material. Two tests will be conducted with aluminum conductors and two tests will be performed with copper conductors. The size of the conductors will vary according to the current used of the respective tests. Two tests will be performed at the currents similar to the DC arc fault tests being conducted separately in Detroit Michigan and sponsored by EPRI. These two tests will assist directly with translating the difference in energy emitted between the constant current DC tests and the alternating current AC tests which have time variant current value that passes through zero twice with each cycle. The test plan specifications for the four open box tests are show in Table 1.

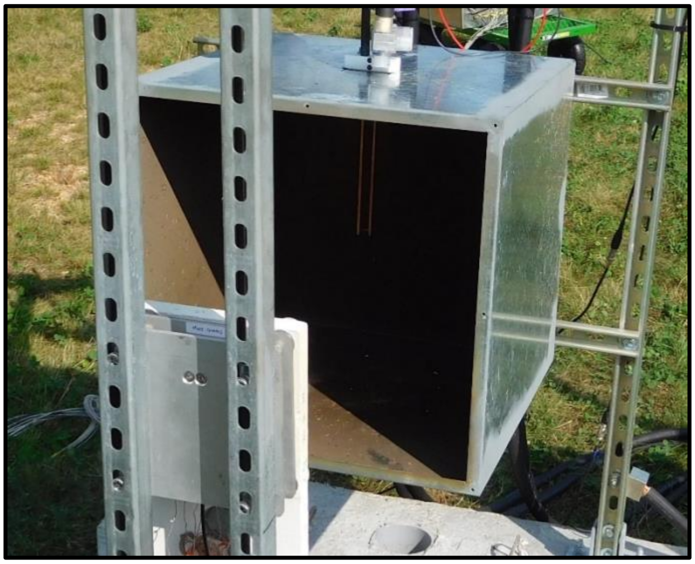

Figure 14 Open box arc enclosure.

Test Number	Current (Amps)	Voltage (Vac)	Conductor Material	Conductor Dimensions	Gap Between Conductors	Duration
OB01	1,000	1000	Copper	½" dia. X 24" long	3	2 seconds
OB02	15,000	1000	Copper	1" dia. X 24" long	3	2 seconds
OB03	15,000	1000	Copper	1" dia. X 24" long	3	4 seconds
OB04	30,000	1000	Copper	1" dia. X 24" long	3	2 seconds
OB05	1,000	1000	Aluminum	½" dia. X 24" long	3	2 seconds
OB06	15,000	1000	Aluminum	1" dia. X 24" long	3	2 seconds
OB07	15,000	1000	Aluminum	1" dia. X 24" long	3	4 seconds
OB08	30,000	1000	Aluminum	1" dia. X 24" long	3	2 seconds
Contingency Tests						
OB09	5,000	1000	Copper	½" dia. X 24" long	3	2 seconds
OB10	5,000	1000	Aluminum	½" dia. X 24" long	3	2 seconds

Table 1: Open Box Test Plan

The open box measures 20 inches each side, forming a cube. With ½ inch and 1 inch conductors and a gap spacing of 3 inches the total width of the conductor set will be 7.5 and 9 inches, which is narrow enough in width to have a sufficient gap spacing with the box side walls. The box is constructed out of galvanized sheet steel 26 gauge (0.551 mm) thick. The top of the box has slots installed to allow the conductors to pass into the box and the gaps distance between conductors to be set. Each test will have three conductors (one for each phase) oriented in the vertical position.

Parameters to be Measured:

Measurements of arc size, temperature, behavior, spectral emission, and smoke generation will be made during each test. Two primary technologies will be used to capture these measurements.

High Speed Videography

One or more video cameras will provide high-speed quantitative and qualitative imaging of the arcing fault in the open box. Data fusion products will be used to visualize instrumentation data (current and voltage) and imaging measurements. All imaging will be time-synchronized to the start of the arcing event. Fusion of the short-wave high-speed infrared imager with the high-resolution high-speed visible imager will provide quantitative temperature data in the overlaid images. A color legend will show the calibrated temperature range with uncertainties.

Optical Emission Spectroscopy

An Ocean Optics HR4000 Spectrometer will be mounted to monitor the spectral radiation profile emitted from the arcing fault at a data acquisition rate of 100 Hz for the entire test duration. A UV-VIS optical fiber will collect light from the arc and disperse it by wavelength/energy using a grating and imaged onto a detector. This will provide information on how many photons of a given energy were present during the collection time. This energy is specific to the emitting species, the temperature of the emitter, and the density of the emitter. By analyzing the emission spectra produced, quantitative time-resolved measurements are produced of both the arc temperature and surrounding graybody temperature. This data can be shown as a scatter plot and correlated to time-resolved current and/or voltage. In addition, emission spectra provide species identification in the arc and the surrounding gas environment.

Post Experimental Action

After the testing campaign, the data obtained shall be used to evaluate the analytical results. The model will be run for the measured temperatures from the testing and the results of the model will be compared to the test measurements.

The data and analytical evaluation will be provided to the working group for resolution of HEAF initiated secondary arc-over.

Appendix F. ARC MIGRATION MANAGEMENT

Problem Statement:

During the inspection of the electrical enclosure, it was noted that there may be a possibility for arc migration to the adjacent vertical run of aluminum bus bars during the arcing event. This migration could occur due to the hot ionized gasses which are created during the arcing event and because the adjacent bus bars will also be energized through the supply breaker and are in closure proximity to the incoming power source, resulting in a lower bus impedance (Figure 1). While the vertical bus bars are identical in either section, migration to the vertical buses associated with the supply breaker (incoming power) side poses a logistical problem for the testing and placement of instrumentation. The goal of the instrumentation placement is to capture the most probable location which the bulk of the energy will escape the electrical enclosure. Testing two vertical sections adds realism to the testing configuration as compared to a single vertical section without adding the complexity and cost of a complete switchgear lineup. If the arc migrates to the adjacent energized bus bars there is the potential, the arc ejecta could be missed and the objective of the testing (to characterize the hazard) be lost.

Figure 15 Buswork in Westinghouse DS-Series enclosure.

Experimental Approach:

To prevent this from occurring several of the working group members (Phone call held on 8/23/2019, Nick Melly, Marko Randelovic, Gabe Taylor, Ken Fleischer, Ken Miller) agreed that the best course of action was to isolate the adjacent bus bars to minimize the probability the arc will migrate during the test. The benefit of this isolation is that it will allow placement of the instrumentation test racks in the most probable locations where we can expect hot gasses to escape or breach the enclosure. Additionally, it will allow for the instrumentation to evaluate a single arc location without adding into the experiment a potential unknown parameter which could affect the results. The identified potential for arc migration is dependent on the electrical enclosure configuration and cannot be easily predicted. The current arc initiation location is in line with the IEEE guide for testing metal enclosed switchgear and is placed farthest from the incoming power supply within the cabinet.

This change to the electrical enclosure is being made from a testing logistics standpoint and will require a physical change to the procured equipment. BSI (contractor to the NRC) has constructed an isolation compartment out of red board material (GPO-3) which should reduce the likelihood of arc migration to the adjacent bus bars (Figure 2).

Figure 16 Top of vertical bus as procured (left) with isolation box (right).

Standards:

IEEE C37.20.7-2007 - IEEE Guide for Testing Metal-Enclosed Switchgear Rated Up to 38 kV for Internal Arcing Faults

Objectives:

Measure thermal impact from HEAF

Requirements/Task(s):

Task 1 – BSI to prepare isolation apparatus and ship to KEMA
Task 2 – Conduct low voltage test at 480 V, 13.5 kV, 2s with apparatus in place
Task 3 – Inspect enclosure and bus work for potential migration indications
Task 4 – Alter isolation channel as needed OR revisit testing assumptions with working group

Appendix G. OPTIONAL TESTING

This appendix consists of the tasks for the full-scale modeling of medium-voltage bus ducts and supplementary tests. During the low-voltage tests conducted in 2019, NRC management made the decision to suspend full-scale testing until the working group identified a specific need for testing. These tasks are included here for completeness, but there are currently no plans to conduct these tests.

Medium-Voltage Bus Duct Tests

Task Status: Incomplete. Not scheduled.

Task Overview and Purpose

This task consists of conducting five full-scale arcing fault tests conducted by the NRC at KEMA Power Test Laboratories (KPT) in Chalfont, PA. These tests were scheduled to take place in September 2019 but have been postponed pending resolution of stakeholder concerns. The location of these tests within the overall test program is shown in the matrix below.

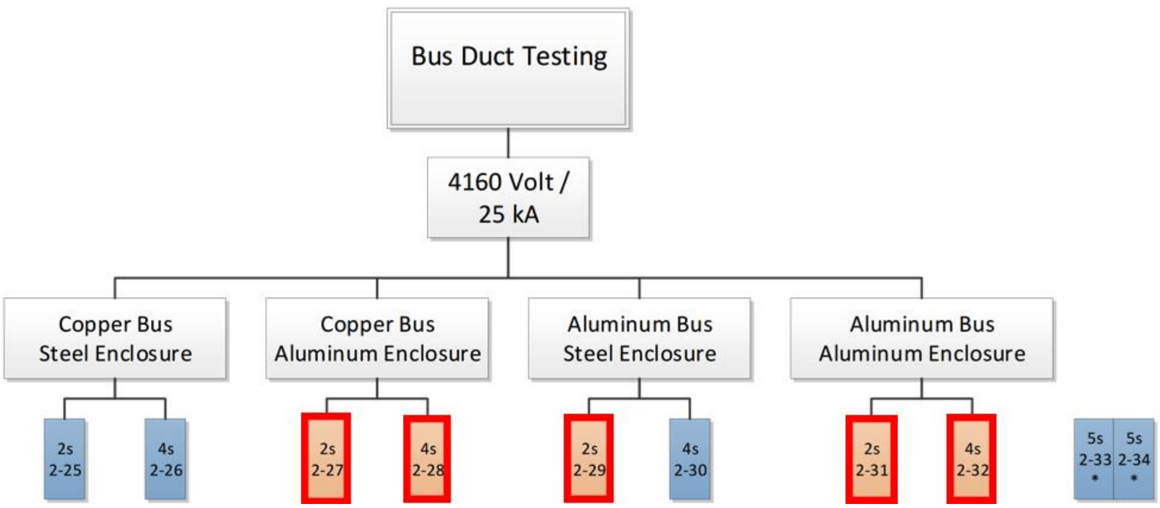

Figure 17. Test matrix illustration for Bus Ducts showing tests planned for 2019, but postponed.

Test measurement support will be provided by the NIST and SNL. Electrical support will be provided by BSI Electric.

Assumptions

1) Full-scale testing closely resembles typical NPP HEAF scenarios involving a non-segregated phase bus duct. As with any laboratory testing, modifications from the as-built configuration are necessary to ensure data collection, test replicability, and satisfy various safety and logistical requirements. Within these bounds, however, the full-scale HEAF tests were designed to reflect realistic NPP configurations to the extent feasible. Equipment was procured based on public input and a design specification developed under the EPRI/NRC working group. Test parameters (voltage, current, duration) were selected based on a review of U.S. operating experience and review of available plant electrical system information.

2) The arc can be stabilized within the duct at a location where measurements can be taken. Magnetic forces are likely to push the arc in the direction of power flow and if unimpeded, may push the arc off the ends of the bus bars. In order to capture energy release with stationary instruments, the arc must be stabilized in a particular location.

3) The majority of the escaping energy will be directed downward. This assumption is in keeping with the current NUREG/CR-6850 methodology and review of operational events. Most of the energy release from the bus is assumed to be directed downward in a conical pattern. This assumption will dictate the placement of the measurement racks and the placement of the duct. The proposed arrangement is shown in the figure below:

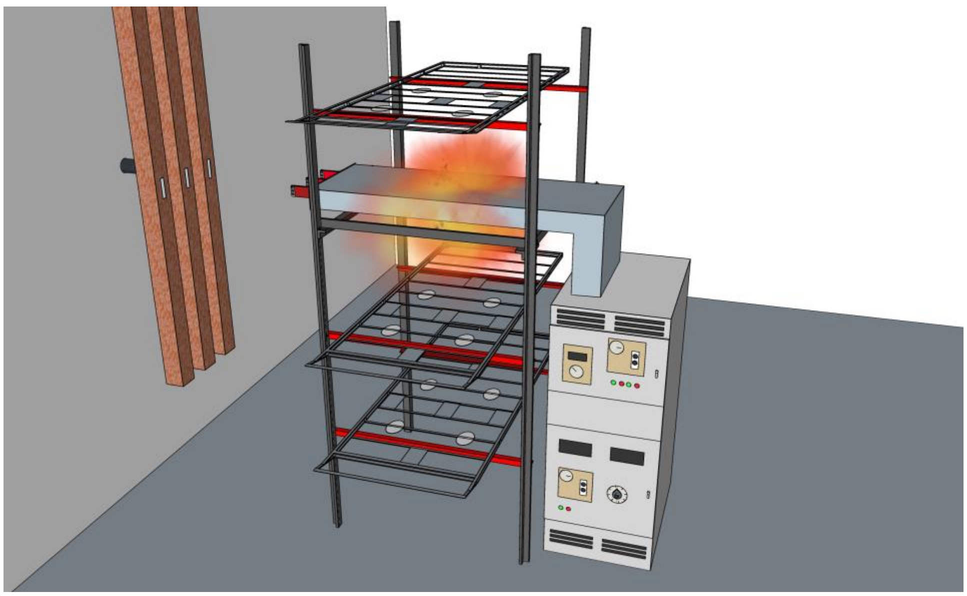

Figure 18 Preliminary test configuration for bus duct testing.

Expected Results

This task is expected to produce the following data sets for each of the five tests:

1) Dimensions and weights for the enclosures (panels and bus bars) before and after testing
2) Incident thermal energy at 60 locations around the enclosure
3) Pressure profiles inside the enclosure
4) Qualitative data from cable coupons at 20 locations around the enclosure
5) Infrared videography from one location
6) High speed, high dynamic range videography from two locations
7) Videography from various other locations
8) Electrical test data provided by the test laboratory

The following passive samples will be collected:

1) Carbon tape particle collections located around the enclosure

Three additional instruments will be used to measure various types of conductivity:

1) Surface conductivity from effluent deposition
2) Surface breakdown from effluent deposition

3) Air holdoff strength using a spark gap apparatus similar to ASTM D2477
4) Air conductivity using parallel plate sensor

Project Flow

Input/Output	Description	Related Task(s)
Input	Test matrix for full-scale testing	Subtask A.2
Input	Lessons learned and test plan modifications	Subtask D.1
Input	Equipment models and configurations	Subtask D.3
Input	Modifications to test plan based on public feedback	Subtask D.3
Input	Measurement and instrumentation selection	Subtask D.2
Output	Test data and report of test	Subtask B.6 Subtask F.2 Task G

Risks and Mitigation

1) There is a risk that energy and arc ejecta may hit the floor and rebound, hitting the back surfaces of the instrumentation racks and creating misleading measurements. Compared to in plant configurations, this experimental variation may not reflect the actual hazard. This risk can be mitigated by protecting the rear surfaces of the instrumentation racks and leaving sufficient space between the lowest rack and the floor to reduce the possibility of rebounding heat and ejecta.
2) There is a risk that the escaping energy is directed upward rather than downward. This risk is being mitigated by placing an instrumentation rack above the duct in addition to the placement of two racks below it. Additional mitigation strategies to increase the likelihood of energy being directed downward are under discussion with the working group, such as notching the bus bar insulation on their bottom surfaces and using bus to grounded enclosure shorting wire connections to initiate the arc test.
3) The arc may move during the test. It may arc at one location for a while then flashover at another location and start arcing there, causing inconsistent measurements. Using a short section of bus helps to limit the possibilities of arcing locations, especially where the instruments would fail to capture the intended data. Keeping the bus bars insulated except where the arc is to be initiated will also help prevent the arc from re-striking in other locations.

Supplementary Tests

Task Status: Incomplete. Not scheduled.

Task Overview and Purpose

This task consists of full-scale experiments to investigate two phenomena of interest identified by EPRI:

1) The behavior of a generator-fed HEAF

Data from the EPRI/NRC working groups review of operating experience demonstrated that the longest credible HEAF durations are likely to occur in generator-fed faults in unit-connected designs. [EPRI 3002015992, Nuclear Station Electrical Distribution Systems and High-Energy Arcing Fault Events. https://www.epri.com/research/products/000000003002015992] The behavior of a HEAF fed by a generator coasting down has not been measured and is expected to differ in energy output from a HEAF being fed by a constant-voltage power supply.

2) The behavior of a switchgear in the supply configuration

The full-scale tests performed prior to 2019 involved a mixtures of test configurations. Approximately 55 percent were testing in a supply configuration, while the other configurations (45 percent) used a “load” configuration. The working group operating experience review indicates that the majority of HEAF events occurred in enclosures in the “supply” configuration. The behavior of a HEAF may differ across these two configurations, and experimental data are lacking.

Two tests will investigate the effect of generator coast-down (one aluminum and one copper), and two tests will investigate the effect of the supply configuration (one aluminum and one copper). There is the possibility to perform two additional tests if additional data is needed.

Expected Results

This task will produce the following data sets for each of the four tests:

1) Dimensions and weights for the enclosures (panels and bus bars) before and after testing
2) Incident thermal energy at 60 locations around the enclosure
3) Pressure profiles inside the enclosure
4) Qualitative data from cable coupons at 20 locations around the enclosure
5) Infrared videography
6) High speed, high dynamic range videography
7) Videography from various other locations
8) Electrical test data provided by the test laboratory

The following passive samples will be collected:

1) Carbon tape particle collections located around the enclosure

Three additional instruments will be used to measure various types of conductivity:

1) Surface conductivity from effluent deposition
2) Surface breakdown from effluent deposition
3) Air holdoff strength using a spark gap apparatus similar to ASTM D2477
4) Air conductivity using parallel plate sensor

Assumptions

When the NRC committed to these tests, it was assumed that the KEMA Power Test Laboratory can perform the generator coast-down tests. The KEMA short-circuit generators are designed to maintain near constant current for arc testing and they have not performed a test of this nature. Their generators also have thermal limits and calculating the heat-up of this type of test requires an engineering review. KEMA has been contracted to perform this review, and the results are pending.

Project Flow

Input/Output	Description	Related Task(s)
Input	Public meeting and stakeholder feedback	
Input	Working group operating experience review	
Input	Test matrix for full-scale testing	Subtask A.2
Output	Test data and report of test	Subtask B.6 Subtask F.2 Task G

Risks and Mitigation

In the event that KEMA cannot perform these tests as specified, the working group will have to develop an alternative approach to evaluating the long duration coast down events. Alternatively, the working group may choose to have to rely on theoretical models or expert judgment to inform the hazard model for this configuration.