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NUREG-2218

An International Phenomena Identification and Ranking Table (PIRT) Expert Elicitation Exercise for High Energy Arcing Faults (HEAFs)

Office of Nuclear Regulatory Research

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ABSTRACT

This report documents the results of a phenomena identification and ranking table (PIRT) exercise performed for nuclear power plant (NPP) high energy arc fault (HEAF) analysis applications conducted on behalf of the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research.

The PIRT exercise was performed via a facilitated expert elicitation process. In this case, the expert panel comprised six international HEAF experts. The panel was facilitated by NRC staff. The objective of a PIRT exercise is to identify key phenomena associated with the intended application and to then rank the current state of knowledge relative to each identified phenomenon. The expert panel was presented with a series of specific HEAF scenarios, each of which is based on the types of scenarios typically considered in NPP applications. Each scenario includes a figure of merit (i.e., a specific goal to be achieved in analyzing the scenario using HEAF analysis or modeling tools). Given each scenario, the panel identified phenomena that are of potential interest to an assessment based on the figure of merit. The identified phenomena are then ranked relative to their importance in predicting the figure of merit. Each phenomenon is then further ranked for the existing state of knowledge and the adequacy of existing modeling tools to predict that phenomenon.

The PIRT panel covered three HEAF scenarios and identified a number of areas potentially in need of further analysis and model development. This report discusses the results in detail.

FOREWORD

Analysis of the most recent international nuclear power plant (NPP) fire event data identifies an increase in the number of high energy arc fault (HEAF) events. The international HEAF operational experience illustrates that significant damage can occur during a HEAF event. In the interest of safe nuclear operations, it is imperative that engineers, operators, and probabilistic risk assessment (PRA) practitioners understand the risk potential of a HEAF and protect safety systems from its effects.

This report documents the work of an international group of nuclear fire safety experts from five countries participating in a structured, facilitated expert elicitation. The experts evaluated three different HEAF scenarios encountered in NPPs. By following the NRC's well-established phenomena identification and ranking table (PIRT) process, expert insights are gained into important areas of HEAF phenomena. These include answers to questions such as:

- How well do we think we understand the phenomena?
- What are their importance and potential for NPP damage?
- Where are the gaps in our state of knowledge?

The results of the PIRT identify and rank important:

- Level 1 phenomena such as target characterization, arc characterization, and arc mitigation.

- Level 2 phenomena such as internal and external ensuing fires, pressure effects, and electrical configuration effects.

- Level 3 phenomena including internal and external cabinet enclosure effects, effects of fire detection and suppression, and room configuration.

These rankings can then be used as a technical compass to help guide and inform future testing and research endeavors.

This report builds upon previous Organization for Economic Cooperation and Development/ Nuclear Energy Agency and NRC HEAF work. This research continues to advance our understanding of this complex phenomenon and its impact on safety. I hope this work will ultimately be used to make a positive contribution to NPP fire safety.

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June 2, 2017
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TABLE OF CONTENTS

LIST OF TABLES

EXECUTIVE SUMMARY

Background

This report documents the results of an international phenomena identification and ranking table (PIRT) expert elicitation exercise performed for high energy arcing fault (HEAF) hazards. This PIRT exercise was conducted on behalf of the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) and facilitated by RES staff.

Objectives

The objective of this PIRT exercise is to develop an ordered list of phenomena involved in a HEAF event. This list will be ordered by priority; the more important a phenomena is judged to be and the poorer its state of knowledge is judged to be, the higher its priority. This information can be used in the development of a "roadmap" for future research and allows for an informed focusing of resources for research and regulatory entities.

Approach

The expert panel was presented with a series of specific HEAF scenarios, each based on the types of scenarios typically encountered in nuclear power plant (NPP) applications. For each scenario, a specific figure of merit was defined; that is, a specific goal to be achieved in analyzing the scenario. The panel identifies all those related phenomena that are of potential interest to an assessment of the scenario via probabilistic risk assessment (PRA) tools and methods. The phenomena are then ranked relative to their importance in predicting the figure of merit. Each phenomenon is then further ranked for the existing state of knowledge with respect to the ability of existing tools and methods to predict that phenomena, the underlying base of knowledge associated with the phenomena, and the potential for developing new data to support improvements to the existing tools.

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

Results

As a result of the process, "level one" phenomena were identified. The level one phenomena are those that were ranked with high importance and low state of knowledge. These would nominally represent potential research priorities. The level one phenomena identified by the panel included the following:

- Electrical arc characterization: thermal and magnetic effects of the arc, arc ejecta (smoke, ionized gas, conductive particulate), arc location, and migration.

- Pressure effects: mechanical shock, projectile impact, and degradation of the compartment pressure boundary.

- Arc mitigation: the use of HEAF-resistant equipment, thermal insulation, or "HEAF shields" to minimize damage incurred as a result of a HEAF.

- Target characterization: establishing the sensitivity of target equipment to various failure mechanisms, and associated damage criteria.

- Internal ensuing fire: the likelihood, impact, and phenomenology of an enclosure fire ignited by a HEAF event.

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Lastly, the author wishes to thank the NRC staff members who supported the development and execution of the PIRT exercise─Mr. Theron Brown, Ms. Tammie Rivera, Mr. Mark Henry Salley, Mr. David Stroup, Mr. Gabriel Taylor, and Mr. Joseph Zabel.

ABBREVIATIONS AND ACRONYMS

CNSC	Canadian Nuclear Safety Commission (Canada).
CRIEPI	Central Research Institute of Electric Power Industry (Japan).
CSN	Consejo de Seguridad Nuclear (Spain).
DID	Defense in Depth.
ERFBS	Electrical Raceway Fire Barrier System(s).
EMI	Electromagnetic Interference.
EPRI	Electric Power Research Institute.
FAQ	Frequently Asked Questions (Reactor Oversight Program).
GDC	General Design Criteria (10 CFR Part 50 Appendix A).
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany).
HEAF	High Energy Arcing Fault.
HRR	Heat Release Rate.
IAGE	Integrity and Aging (Task Group).
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France).
KINS	Korea Institute of Nuclear Safety (S Korea).
LER	Licensee Event Report.
NEA	Nuclear Energy Agency.
NPP	Nuclear Power Plant.
OECD	Organisation for Economic Co-operation and Development.
PIRT	Phenomena Identification and Ranking Table.
PRA	Probabilistic Risk Analysis.
RES	Office of Nuclear Regulatory Research.
S/NRA/R	Regulatory Standard and Research Development, Secretariat of Nuclear Regulation Authority (Japan).
SSC(s)	Systems, Structures, and Components.
STUK	Säteilyturvakeskus (Finland).
ZOI	Zone of Influence

1 INTRODUCTION

1.1 Background

Switchgear, load centers, and bus bars/ducts (440 V and above) are subject to a unique failure mode and, as a result, unique fire characteristics. In particular, these types of high-energy electrical devices are subject to high-energy arcing faults (HEAFs). This fault mode leads to the rapid release of electrical energy in the form of heat, vaporized copper, and mechanical force. Faults of this type are also commonly referred to as high energy, energetic, or explosive electrical equipment faults or fires. Similar failure modes can occur in large oil-filled transformers. [1]

The arcing or energetic fault scenario in these electrical devices consists of two distinct phases, each with its own damage characteristics and detection/suppression response and effectiveness. The first phase is a rapid release of energy in the form of heat, light, and pressure. This energetic first phase is due to the high current arcs between electrical conductors. The second phase consists of ensuing fire(s) that may involve the electrical device itself as well as any external exposed combustibles such as overhead exposed cable trays or nearby panels that may be ignited during the energetic phase. This second phase is treated similar to other postulated fires within the zone of influence. [1]

International operating experience documents a significant number of HEAFs that have occurred worldwide in operating nuclear power plant (NPP) facilities. An Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA) report from June 2013 documents 48 such instances in 10 member countries [2]. This number represents about 10 percent of the fire events reported through the OECD/NEA Fire Incidents Records Exchange (FIRE) program.

Appendix A to 10 CFR Part 50 [3] lists the General Design Criteria (GDC) or minimum requirements for the principal design of a water-cooled NPP. Two criteria are particularly applicable to HEAFs: criterion 3 and criterion 17. Criterion 3 requires that structures, systems, and components (SSCs) important to safety be designed to minimize the probability and effect of fires and explosions. Criterion 17 requires that the onsite electric power supplies have sufficient independence, redundancy, and testability to perform their safety functions assuming a single failure. The “defense in depth” (DID) approach to NPP design and operation requires multiple independent and redundant layers of defense so that no single layer, no matter how robust, is exclusively relied upon. The DID strategy, as it applies to HEAFs, consists of:

1. Prevention – Maintenance practices designed to eliminate the underlying causes of faults (loose connections, degraded insulation, foreign materials, etc.).[4]

2. Mitigation – Selective coordination to limit the duration and magnitude of the fault as well as design and location of plant SSCs such that a HEAF, should it occur, does as little damage as possible to nearby equipment and does not endanger the functionality of redundant equipment.

3. Safe shutdown – Ensuring the ability of the plant to safely shut down and maintain the reactor in a safe state in the event of a HEAF.

HEAF events have, in many cases, presented extra challenges to the safe shutdown of a reactor. The electrical disturbance responsible for the HEAF can cause loss of essential electrical power, and the physical damage and products of combustion can present significant challenges to the

operators and fire brigade members responding to the emergency.[5][6][7] HEAFs can present one of the more risk-significant and challenging fire scenarios that an NPP will face.

In 2008, the U.S. Nuclear Regulatory Commission (NRC) contracted with Sandia National Laboratories to perform a literature review on HEAFs. The review [8] concluded that the focus of research had primarily been limited to the behaviors of the initiating equipment and the initial arc flash in the context of personnel safety. More research was necessary to evaluate the HEAF phenomenon in the context of damage to adjacent equipment.

Two methods are available to model the effects of a HEAF [9]. The first is described in NUREG/CR-6850, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 2: Detailed Methodology, Appendix M for Chapter 11, High Energy Arcing Faults" [1]. This method stipulates the following assumptions:

1. The faulting device is destroyed.
2. Adjacent cubicles in the same cabinet bank will trip open.
3. Unprotected cables that enter the panel in an air-drop configuration are destroyed.
4. The first unprotected cable tray within 1.5 m of the top of the cabinet will ignite.
5. Vulnerable equipment within 0.9 m horizontally of the front or rear doors will be destroyed.

This method is subject to an unknown degree of uncertainty because it was derived from one single well-documented HEAF event that occurred at the San Onofre Nuclear Generating Station, Unit 3, on February 3, 2001 [10]. The second method can be found in "Fire Probabilistic Risk Assessment Methods Enhancements Supplement 1 to NUREG/CR-6850 and EPRI 1011989" section 7 bus duct (counting) guidance for high energy arcing faults (FAQ 07-0035) [11]. This method stipulates the following assumptions for HEAFs occurring in bus ducts:

1. Molten material will be ejected from the bottom of the bus duct and spread downwards in the shape of a right circular cone whose sides are at an angle of 15 degrees from the vertical axis.

2. The cone will expand to a maximum diameter of 20 feet (37 feet below the point of origin) beyond which point molten material will fall straight down in a cylindrical shape of 20-foot diameter.

3. Molten material will be ejected outwards from the fault point in the shape of a sphere with a 1.5-foot radius.

4. Exposed combustible material within these zones will ignite.

In an effort to confirm these modeling methods described in NUREG/CR-6850 and to better characterize HEAFs, an OECD/NEA working group conducted an experimental program between 2014 and 2016, hereafter referred to as "phase one." Led by the NRC, this phase consisted of 26 full-scale HEAF experiments conducted at KEMA Powertest LLC's Chalfont facility. This test program was largely exploratory; the test equipment was whatever participant countries could donate, and various measurement techniques were evaluated. The results of the phase one testing suggest that the current modeling methodology may, in some cases, be nonconservative, especially where aluminum components are involved. The full results of this experimental campaign are documented in an NEA/CSNI report issued in 2017 [12].

In August 2016, the Regulatory Standard and Development Department Secretariat on Nuclear Regulation Authority (S/NRA/R) and the NRC jointly published an International Report titled

NUREG/IA-0470 Volume 1, "Nuclear Regulatory Authority Experimental Program to Characterize and Understand High Energy Arcing Fault (HEAF) Phenomena" [13]. The focus of this report was to better understand the seismic-induced HEAF that occurred in 6.9 kV switchgear at the Onagawa NPP during the March 11, 2011, Great Eastern Earthquake in Japan. The research focused on simulating the HEAF that occurred and recording data such as temperature, heat flux, and heat-release rates (HRR) from ensuing fires. The report was also one of the first to identify high thermal energy released when aluminum electrical components are involved.

The phase one testing and joint S/NRA/R NRC report demonstrated the need for additional, more focused testing to further refine HEAF modeling methodology. Given the complexity of a HEAF event and related phenomena, the Office of Nuclear Regulatory Research held a Phenomena Identification Ranking Table (PIRT) exercise in February 2017 to aid in the process of planning future testing.

1.2 Objectives

The objective of this PIRT exercise is to develop an ordered list of phenomena involved in a HEAF event. This list will be ordered by priority; the more important a phenomena is judged to be, and the poorer its state of knowledge is judged to be, the higher its priority. This information can be used in the development of a "roadmap" for future research and will allow for an informed focusing of resources for research and regulatory entities.

1.3 Scope

The scope of the PIRT exercise defines the bounds of:

1. The scenarios to be analyzed.
2. The figures of merit to be achieved.
3. The phenomena's state of knowledge.

A well-defined scope will ensure that the scenarios are relevant to the intended application and that the group's analysis does not stray into tangents and hypotheticals.

The scope of this PIRT exercise is:

1. A high-energy electric arc fault event.
2. Occurring in a nuclear power generating station.
3. In low voltage (less than 600V) or medium voltage (between 600V and 15 kV) equipment or circuits.
4. NOT in the switchyard or electrical transmission/distribution network and equipment

Although an arc fault in the switchyard may result in a loss of offsite power, it is phenomenologically separate from other HEAF scenarios because:

1. It is not confined in a compartment.
2. It is not located near safety-related equipment.
3. High voltages (greater than 15kV) are common.

For these reasons, arc faults occurring on the switchyard side of the main generator and beyond are outside of the project scope.

1.4 Report Organization

Section 2 of this report discusses the PIRT process used, the preparation of the PIRT panelists, the instructions and ranking definitions given to the panelists, and a description of three HEAF scenarios.

Section 3 is a summary of the “level 1” phenomena in each of the three scenarios—those phenomena that rank highly for importance and poorly for state of knowledge. These are, in essence, the primary candidates for future research activity.

Section 4 synthesizes the panelists’ rankings, comments, and discussions into a series of recommendations for future research.

Appendices A-C contain the formatted output of the PIRT, with each panelist’s anonymized rankings.

2 OVERVIEW OF THE PIRT PROCESS APPLIED

2.1 Background

A phenomena identification and ranking table (PIRT) is a structured expert elicitation process. It is a methodical, tested process for compiling expert opinions, assessing the state of knowledge, and identifying research priorities on a particular topic. The U.S. Nuclear Regulatory Commission (NRC) has sponsored or performed a number of PIRT exercises. Two recent PIRTs that were performed by the NRC's Fire Research Branch were NUREG/CR-6978, "A Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire Modeling Applications," [14] and NUREG/CR-7150 Volume 1, "Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure." [15]

2.2 Selection of Panelists

This PIRT exercise was a follow-up to phase one testing and a prerequisite to future phase two testing. For this reason, each country/agency that participated in the phase one testing was invited to send one representative to sit on the panel. At their discretion, each country/agency was also invited to send technical experts—non-voting representatives who could advise the panelist, but whose input would not be recorded.

An invitation was extended to the following countries/organizations:

- CNSC (Canada)
- KINS (S Korea)
- GRS (Germany)
- IRSN (France)
- STUK (Finland)
- CRIEPI (Japan)
- NRA (Japan)
- CSN (Spain)
- NRC (United States)
- EPRI (United States)

Of these 10 agencies, the following sent representatives:

- KINS (S Korea) – Mr. Sangkyu Lee
- GRS (Germany) – Dr. Marina Röwekamp
- IRSN (France) – Dr. Sylvain Suard
- CRIEPI (Japan) – Dr. Koji Shirai
- NRA (Japan) – Dr. Hajime Kabashima
- NRC (United States) – Mr. Nicholas Melly

2.3 Panelist Preparation

None of the PIRT panelists had participated in a PIRT before. To maximize what could be accomplished during the week of the PIRT, the panelists were provided with a variety of preparation and orientation materials.

2.3.1 Knowledge Base

Several months in advance of the PIRT, panelists were given access to an online file store containing relevant literature on high energy arcing faults. In addition to those materials provided, panelists were asked to contribute any other material of which they were aware. This knowledge store is essentially the equivalent of a literature review for this exercise. These materials include both nuclear and non-nuclear studies, and a list of these materials are given in the references section of this report (section 5.2).

The objective of providing these materials was to calibrate the panelists for their evaluation of phenomena state of knowledge. To draw a conclusion about whether a phenomenon has been adequately characterized, some knowledge of the current literature is required.

2.3.2 Orientation Materials

In addition to access to the online knowledge base, panelists were provided with periodic orientation materials. These materials largely dealt with the PIRT process itself to familiarize panelists with the steps involved. These orientation materials also included worked example scenarios and logistical information.

2.4 The PIRT Process Applied

2.4.1 Scenario Development

The scenarios to be analyzed were developed so that they span the plausible range of HEAF events while still staying within the scope of the PIRT. The development of these scenarios was guided by documented operating experience and common NPP configurations. The scenarios are mainly focused on the HEAF source equipment. The panelists were instructed to consider the targets only in a generic manner. In reality, each target is unique and will respond differently to the environmental conditions caused by a HEAF; however, the behavior of specific targets is a voluminous subject and outside the scope of the PIRT. Therefore, when considering the damage states of a target in the scenarios, panelists listed phenomena that are applicable to any generic target of a similar equipment class.

Each scenario is accompanied by a “figure of merit” (i.e., a goal to be achieved through analysis of the scenario). In other PIRTs, the figure of merit is often the prediction of a specific quantity, such as ceiling jet temperature or pressure rise. In the case of this PIRT, where all possible mechanisms of failure are being considered, the figure of merit for each scenario is simply the determination of the extent of damage to the targets. This broad figure of merit allowed panelists to consider any and all phenomena.

2.4.2 Steps in the PIRT Process

The PIRT process follows a series of formal steps, each of which is outlined here.

2.4.2.1 Presentation of the HEAF Scenario

The first step is the presentation of a HEAF scenario, which includes a description of the pre-defined elements and characteristics of the scenario as well as the specific objectives and goals of our analysis. Section 2.5 details the three scenarios used in this PIRT.

2.4.2.2 Phenomena Identification

The next step is for the panel to identify all phenomena relevant to the scenario and the analysis goals. A phenomenon is loosely defined as "something that is observed to happen." In the context of this PIRT, a phenomenon is something that has, or might have, a model associated with it. A phenomenon may include one or more sub-phenomena, which are grouped accordingly.

As an example, an external ensuing fire that occurs as a result of a HEAF is a phenomenon. It is a physical occurrence that PRA practitioners need to model. This phenomena can be broken down into sub-phenomena, each with its own sub-model. Examples of sub-phenomena for an external ensuing fire are ignition, fire development, and smoke generation.

2.4.2.3 Parameter Identification

In concert with the identification of phenomena, panelists were also asked to identify key parameters associated with the phenomenon. If phenomena can be thought of as events to be modeled, parameters are the inputs to those models. These are quantities that can be measured and reported with standard units. Each phenomenon or sub-phenomenon may encompass multiple key parameters.

Continuing the example above, some relevant parameters for the sub-phenomena of an external ensuing fire are heat release rate, fire growth rate, and time to peak heat release rate.

The process components outlined here and in in section 2.4.2.2 are almost like a "brainstorming session" in that the group will need to think of all phenomena and parameters that might have an impact on the scenario objective. Even phenomena or parameters that are likely to have a minor impact on the objective should be identified; their relative importance will be decided by the group in the next stage.

2.4.2.4 Phenomena Importance Ranking

In the next step, the panel ranks each identified phenomenon for its importance to the figure of merit. If the group can achieve consensus in their ranking through discussion, it lends extra credibility to the ranking, but consensus is not required. Each panel member is entitled to their opinion, and it is recorded as it is received. This stage of the PIRT requires that the panel members be familiar with the available experimental evidence to provide well-informed opinions about what factors influence the characteristics of HEAF events and their relative importance.

Section 2.4.3 describes the possible rankings for phenomena importance and their definitions.

2.4.2.5 State of Knowledge Ranking

In the next step, the panel assessed the state of knowledge for each phenomenon. This includes the current body of knowledge regarding a particular phenomenon as well as the ability to acquire information regarding that phenomenon. If new measurement techniques or equipment are required to increase the state of knowledge regarding a particular phenomenon, this should be reflected in the output of the PIRT.

Section 2.4.3 describes the possible rankings for phenomena state of knowledge and their definitions.

2.4.2.6 Parameter Importance and State of Knowledge Ranking

In addition to ranking the identified phenomena, panelists were asked to identify and rank key parameters for each of the phenomena where applicable. The ranking of a parameter is *relative to its parent phenomenon*. A phenomenon may be ranked as unimportant, but its child parameters may be highly important to characterizing that phenomenon. This process was applied even to the lowly ranked phenomena for reasons of extensibility—while this panel may deem a phenomenon unimportant to the overall analysis, future research may contradict such a judgment.

Section 2.4.4 describes the possible rankings for parameter importance and state of knowledge and their definitions.

2.4.3 Phenomena Ranking Definitions

It is important that PIRT participants have consistent and well-defined criteria to rank the phenomena and their states of knowledge. For simplicity and consistency, a low, medium, high scale was used. One category ranked the importance of the phenomenon, and three categories ranked the current state of knowledge regarding that phenomenon.

It is also important to remember that these rankings are expert opinions. Empirical evidence may or may not be available to support these rankings, but the expert should try to justify the ranking as much as possible. A ranking of “high” indicates that the given phenomenon is very important to predicting the figure of merit. Without knowledge of the phenomenon, an accurate prediction would not be possible. A ranking of “medium” indicates a phenomenon that has some appreciable impact on predicting the figure of merit but is not particularly important. Without knowledge of this phenomenon, a rough estimate would still be possible. A ranking of “low” indicates that the expert does not believe the phenomenon is important to predicting the figure of merit and that modeling this phenomenon is not necessary. An additional category of “uncertain” is available that indicates the expert believes a phenomenon has an impact on predicting the figure of merit but is unable to assess the magnitude of that impact.

The following phenomena importance ranking definitions were used throughout the PIRT:

Table 2-1 Phenomena Importance Ranking Definitions

Descriptor	Definition
High (H)	First order of importance to the figure of merit of interest.
Medium (M)	Secondary order of importance to the figure of merit of interest.
Low (L)	Negligible importance to figure of merit of interest. Not necessary to model this phenomenon for this application.
Uncertain (U)	Potentially important. Importance should be explored through sensitivity study and/or discovery experiments and the PIRT revised accordingly.

Model adequacy rankings answer the question “How well does the current HEAF modeling methodology estimate the phenomenon?”

The following model adequacy ranking definitions were used throughout the PIRT:

Table 2-2 Phenomena State of Knowledge Model Adequacy Ranking Definitions

Descriptor	Definition
High (H)	At least one mature physics-based or correlation-based model is available that is believed to adequately represent the phenomenon over the full parameter space of the applications.
Medium (M)	Significant discovery activities have been completed. At least one candidate model form or correlation form has emerged that is believed to nominally capture the phenomenon over some portion of the application parameter space.
Low (L)	No significant discovery activities have occurred and model form is still unknown or speculative.

Data adequacy descriptors answer the question "How good is the data that would be used as model input, or to validate a potential model?" For example, the distance between a target and the source equipment is data that is readily available, very precise, and easy to vary for experimentation. Data regarding electromagnetic interference caused by a HEAF might be less available or of lower fidelity. It is important to differentiate between the adequacy of data and the adequacy of the model. There is no "uncertain" category; if a panelist is not aware of pertinent data, the adequacy of the data was considered to be "low."

The following data adequacy descriptors were used throughout the PIRT:

Table 2-3 Phenomena State of Knowledge Data Adequacy Ranking Definitions

Descriptor	Definition
High (H)	A highly reliable assessment can be made based on existing knowledge. Data needed are readily available.
Medium (M)	Data are available but are not ideal due to questions of fidelity. Moderately reliable assessments of models can be made based on existing knowledge.
Low (L)	Assessments cannot be made with even moderate reliability based on existing knowledge.

The last ranking category is the ability to gather new data for a particular phenomenon. These descriptors answer the question "How easy would it be to get the data we need if we don't already have it?" This category can help prioritize the collection of data in future experiments if some data are known to be easier to collect than others.

The following data adequacy descriptors for the potential to develop new data were used throughout the PIRT:

Table 2-4 Phenomena State of Knowledge Availability of New Data Ranking Definitions

Descriptor	Definition
High (H)	Data needed are readily obtainable based on existing experimental capabilities.
Medium (M)	Data would be obtainable but would require moderate, readily attainable extensions to existing capabilities.
Low (L)	Data are not readily obtainable and/or would require significant development of new capabilities.

Panelists were not required to rank a phenomenon if they choose not to. If a panelist decided that he/she did not want to rank a phenomenon either for importance or state of knowledge, a ranking of "X" was entered.

2.4.4 Parameter Ranking Definitions

The following parameter importance and ranking definitions were used throughout the PIRT:

Table 2-5 Parameter Importance Ranking Definitions

Descriptor	Definition
High (H)	First order of importance in characterizing the parent phenomenon.
Medium (M)	Secondary order of importance in characterizing the parent phenomenon.
Low (L)	Negligible importance in characterizing the parent phenomenon.
Uncertain (U)	Potentially important. Importance should be explored through sensitivity study and/or discovery experiments and the PIRT revised accordingly.

Unlike phenomena, a single category was used to rank the state of knowledge for the identified parameters. The following parameter state of knowledge ranking definitions were used throughout the PIRT:

Table 2-6 Parameter State of Knowledge Ranking Definitions

Descriptor	Definition
High (H)	The parameter's influence on its parent phenomenon is well characterized, and the parameter is easily measured.
Medium (M)	The parameter's influence on its parent phenomenon is known but not well characterized, and measurement of the parameter is possible.
Low (L)	The parameter's influence on its parent phenomenon is unknown, and measurement of the parameter is difficult or impossible.

2.4.5 Country-Specific Concerns and Input

Although the PIRT focused on the physical phenomenology of HEAF events and the general scientific state of knowledge, concerns specific to the panelists' represented country or organization inevitably arose. Some panelists stated that several phenomena were not relevant for their applications and chose a ranking of "Unknown" or no ranking at all. Other panelists noted

that even the HEAF scenarios, as general as they were, would be an improbable or impossible configuration in their countries' facilities; therefore, their consideration of such scenarios was based less on experience and more on expert judgment, and this is reflected in their rankings.

The associated cost was another concern, especially when considering the ability to obtain new data. For many phenomena, the only way to obtain the necessary data would be to run full-scale experiments that are costly and time consuming. Although the state-of-knowledge rankings are supposed to reflect the scientific community's technical abilities, practical considerations like time and money are inevitably factored in.

2.4.6 Panelist Feedback

During the PIRT, panelists raised three procedural issues that are worth documenting here with the intent that future PIRTs can improve upon the process and that readers understand what was done and why.

The first issue discussed was whether it was a judicious use of time to rank key parameters for phenomena that had already been ranked of "low" importance. Establishing the key parameters for a phenomenon that will likely not be investigated seems, on the surface, to be impractical. The reason for doing so is that the panelists were working from the base of knowledge that existed at the time when the PIRT was held. As the state of knowledge improves, phenomena previously thought to be insignificant may be reconsidered, and having their key parameters ranked puts future readers at an advantage.

The second issue was the difficulty in assessing the ability to obtain new data for the state-of-knowledge rankings. Where the state of a model was judged to be poor or nonexistent, panelists were unable to reliably assess what data would need to be obtained or the ease of obtaining it. In cases like this, panelists were asked to rely on their judgment in assessing this state-of-knowledge category.

Lastly, it was noted during the PIRT exercise that a very large number of phenomena were being ranked "highly important" compared to those phenomena being ranked of "medium" or "low" importance. This is the result of an inevitable selection bias; when the panelists were asked to list all phenomena that could be of importance in predicting the figure of merit, the only phenomena they listed were those that could conceivably have an appreciable impact. In other words, the list of phenomena that the panelists needed to rank had already been preselected for some level of importance. This results in the median importance value being relatively high, with discrepancies between panelists being the largest source of variation.

2.5 Summary Scenario Descriptions

2.5.1 HEAF Scenario 1

2.5.1.1 Scenario Description

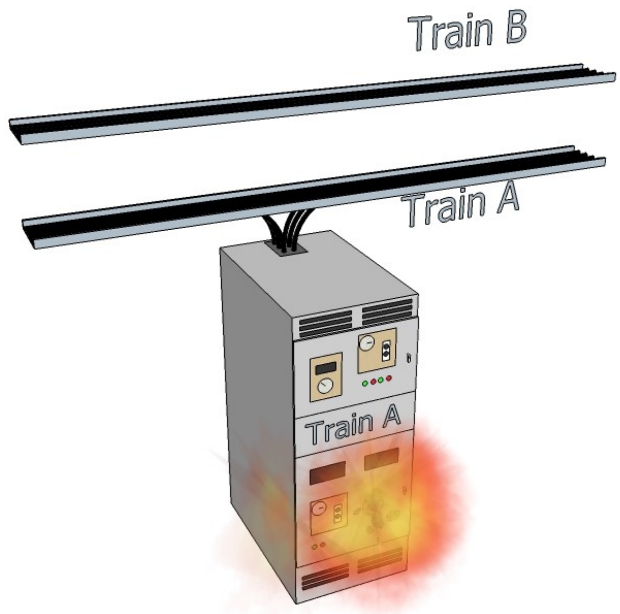

Figure 2-1 Scenario 1 – HEAF in a “Train A” Switchgear with “Train B” Cables Overhead

A high energy arcing fault occurs in a low/medium voltage switchgear that supplies power to “Train A” systems. The cables from an overhead cable tray enter the cabinet from the top (air-drop configuration). A cable tray carrying cables that supply power to redundant “Train B” systems is located near the “Train A” switchgear and cable tray.

2.5.1.2 Figure of Merit

Determining the extent of damage to the cables in the “Train B” cable tray.

2.5.2 HEAF Scenario 2

2.5.2.1 Scenario Description

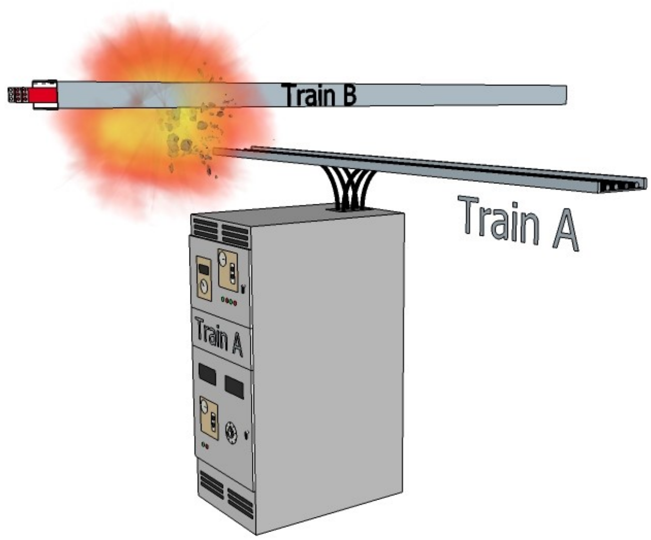

Figure 2-2 Scenario 2 – HEAF in a "Train B" Bus Duct above a "Train A" Switchgear

A high energy arcing fault occurs in a non-segregated bus duct supplying power to "Train B" systems. A switchgear supplying power to redundant "Train A" systems is located nearby.

2.5.2.2 Figure of Merit

Determining the extent of damage to the switchgear.

2.5.3 HEAF Scenario 3

2.5.3.1 Scenario Description

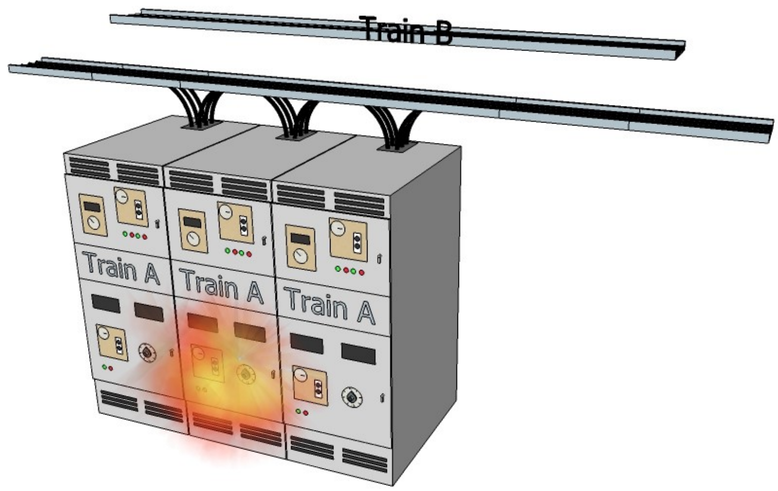

Figure 2-3 Scenario 3 – HEAF in a "Train A" Switchgear in a Bank with "Train B" Cables Overhead

A high energy arcing fault occurs in a low/medium voltage switchgear supplying power to "Train A" systems in a bank of similar switchgears. The cables from an overhead cable tray enter the cabinets from the top (air-drop configuration). A cable tray carrying cables that supply power to "Train B" systems is located nearby.

2.5.3.2 Figure of Merit

Determining the extent of damage to the adjacent switchgears and the cables in "Train B" cable tray.

3 SUMMARY OF LEVEL 1 PHENOMENA

3.1 Ranking Methodology

The method used to convert the panelists' rankings into an ordered, prioritized list is as follows:

First, each ranking was given a corresponding numerical score as shown in Table 3-1.

Table 3-1 Numerical Equivalents for Ranking Values

Ranking	Value
Low (L)	1
Low-Medium (L-M)	2
Medium (M)	3
Medium-High (M-H)	4
High (H)	5
Unknown (U)	No value
Not Applicable (N/A)	No value
Decline to Answer (X)	No value

Second, the average of all the values in a phenomenon (including its sub-phenomena) was taken for both importance and state of knowledge. An example using tables A7 and A19 (pressure effects for scenario 1) is illustrated below tables 3-2 – 3-5.

Table 3-2 Importance Rankings for Pressure Effects, Scenario 1

Phenomenon Description	Importance Ranking					
	P1	P2	P3	P4	P5	P6
7. Pressure Effects						
A. Projectile/missile damage	L	H	M	H	H	L
B. Pressure wave	L	H	M	H	H	M

The corresponding numerical values are assigned, and an arithmetic average is calculated.

Table 3-3 Numerical Equivalent of Table 3-2

Phenomenon Description	Importance Ranking						Table Average
	P1	P2	P3	P4	P5	P6	
7. Pressure Effects							
A. Projectile/missile damage	1	5	3	5	5	1	3.5
B. Pressure wave	1	5	3	5	5	3	

Table 3-4 State of Knowledge for Pressure Effects, Scenario 1

Phenomenon Description	State of Knowledge Ranking		
	Model Adequacy	Data Availability	Ability to Collect New Data
7. Pressure Effects			
A. Projectile/missile damage	M	L-M	L
B. Pressure wave	H	H	N/A

The corresponding numerical values are assigned, and an arithmetic average is calculated.

Table 3-5 Numerical Equivalent of Table 3-4

Phenomenon Description	State of Knowledge Ranking			Table Average
	Model Adequacy	Data Availability	Ability to Collect New Data	
7. Pressure Effects				
A. Projectile/missile damage	3	2	1	3.2
B. Pressure wave	5	5	N/A	

Lastly, a rank was assigned using the following simple relationship:

$$Rank = \frac{Importance_{avg}}{State\ of\ Knowledge_{avg}}$$

In the case of the example above, this would be:

$$Rank = \frac{3.5}{3.2} = 1.09$$

This process was applied to each phenomenon, and a summary of their rankings across all three scenarios sorted by average rank in descending order is shown in Table 3-6.

Table 3-6 Summary of Phenomena Rankings for All Scenarios

Phenomenon	Scenario 1 Rank	Scenario 2 Rank	Scenario 3 Rank	Average Rank
Level 1 Phenomena				
Target Characterization	1.53	1.61	1.53/1.56	1.56
Arc Characterization	1.33	1.27	2.00	1.53
Arc Mitigation	1.75	1.19	1.23	1.39
Cabinet Lineup Effects			1.29	1.29
Level 2 Phenomena				
Internal Ensuing Fire	1.63	0.31	1.54	1.16
External Ensuing Fire	1.27	0.82	1.32	1.14
Pressure Effects	1.09	0.40	1.67	1.05
Electrical Configuration Effects	1.00	1.00	1.00	1.00
Level 3 Phenomena				
External Cabinet Enclosure Effects	0.80	1.04	0.76	0.87
Internal Cabinet (Bus Duct) Configuration Effects	0.91	0.72	0.93	0.85
Suppression Effects	0.80	0.40	0.67	0.62
Room Configuration	0.79	0.43	0.65	0.62
Fire Detection	0.50	0.40	0.26	0.39

As is evident from Table 3-6, the list of phenomena was split into three equal-sized groups: level 1, level 2, and level 3. It is important to note that this grouping conveys no information about the absolute priority of any phenomenon, only its priority relative to the others. Level 1 phenomena are those that present the highest research priority, whereas level 3 phenomena are those that present the lowest research priority.

3.2 Discussion of Level 1 Phenomena

For the level 1 phenomena listed in Table 3-6, the highlights of the panelists' discussions are included in this section.

3.2.1 Target Characterization

During the PIRT, panelists considered the targets in a generic sense; that is, they ranked phenomena associated with any generic piece of equipment of a similar class. The panel's opinion is that, unsurprisingly, the properties of the target will have a first order impact on the damage that it sustains.

This phenomenon was broken down into three main sub-phenomena:

A) Characterization of target damage criteria
B) Target arrangement effects
C) Target sensitivity to damage

Sub-phenomena (A) refers to the ability to assign some type of damage threshold to the target at hand such as maximum temperature, maximum heat flux, maximum pressure, etc. The panelists noted that threshold damage criteria exist for fire scenarios, where the fire is expected to follow

some assigned growth pattern. No such criteria exists for a HEAF exposure, and any ability to predict whether a target is damaged is moot without them.

Sub-phenomena (B) refers to the target's position and orientation relative to the HEAF source. This item was not so easy to consider as it represents a departure from the currently employed "zone of influence" (ZOI) method and the standard method of analysis; here, the distance from the source equipment is being considered as a variable in calculating target damage rather than a binary in/out of ZOI.

Sub-phenomenon (C) refers to a target's susceptibility to damage from a number of items: heat, pressure, smoke, conductive particulate, and others. Different classes of equipment are likely to respond differently to each of these hazards although it may be impractical to characterize the sensitivity and damage criteria of each potential target that would represent the most realistic treatment of the scenario. Sub-phenomena (A) and (C) are linked but not identical. Susceptibility to various modes of damage is an important factor in establishing meaningful damage threshold criteria, but the knowledge of a target's physical response is different from the knowledge of its functional response.

Characterization of the target in scenario 2 is similar to that of scenario 1. The higher ranking of this phenomenon in scenario 2 is partially due to simpler source equipment. With a bus duct that is unlikely to experience an ensuing fire, the properties of the target receive more weight.

Scenario 3 featured two targets for panelists to consider: the enclosures adjacent to the source enclosure and an overhead cable tray. Each target was considered separately, but they are combined here for the purposes of discussion. As with scenarios 1 and 2, the panelists ranked the phenomenology of each target in a generic sense; that is, their rankings apply to any piece of equipment of a similar class. The panelists' ranking of the phenomena, sub-phenomena, and parameters for both targets are similar. "Orientation effects" was not considered for the enclosure targets because the position and orientation are fixed by the scenario definition. There was slightly more uncertainty about the response of an electrical enclosure to a HEAF than a cable tray due to their relative complexity. Panelists noted that enclosure sensitivity to certain failure mechanisms would be a function of enclosure type and contents; considering this type of target in a generic sense is a rough approximation.

3.2.2 Arc Characterization

Characterization of the arc is essentially the characterization of the source term. Within this phenomenon, the highly ranked items were characterizing the arc's electrical properties (voltage, current, duration, etc.); arc breeching of the enclosure; arc ejecta; and the thermal effects of the arc.

The state of knowledge regarding the characteristics of the arc is mixed. Models and data exist for the electrical properties of the arc, although some important properties such as duration have external dependencies that cannot be accounted for. The panel is not aware of any models for the breeching of the enclosure or arc ejecta. These two areas are critically important: a breeched enclosure presents a far greater hazard to adjacent equipment, and arc ejecta (smoke, conductive particulate, ionized gas) may be a significant failure mechanism for target equipment.

In scenario 2 as in scenario 1, characterization of the arc is highly ranked. One topic of discussion among the panelists was whether, and in what ways, an arc occurring in a bus duct differs from an arc occurring in an electrical enclosure. The current guidance in NUREG/CR-6850 [1][11] lays out

separate methods for evaluation of the ZOI in bus ducts and electrical enclosures due largely to what has been observed in operating experience and the expected arrangement of the bus duct relative to potential targets. This approach, while practical, says little about the underlying phenomena involved, and the panel wondered whether a single model could accurately describe an arc in both types of equipment. Also, as in scenario 1, the highly ranked sub-phenomena were the electrical characterization of the arc (voltage, current, duration); the thermal effects of the arc; arc breeching of the enclosure; and arc ejecta.

3.2.3 Arc Mitigation

Arc mitigation refers to the intentional shielding of targets from potential arc source equipment. Within this phenomenon, discussions were focused around "HEAF shields," which have no formal definition; electrical raceway fire barrier systems (ERFBS); and fire-retardant cable coatings. The presence of a barrier between the HEAF source and target equipment should moderate the incident thermal energy, pressure front, and arc ejecta effects.

The reasons for low state of knowledge rankings are myriad. Because no formal or industry-standard definition exists for a "HEAF shield," no performance criteria or qualifications exist. The panel is not aware that any test campaign has evaluated the impact of such a shield, and no operating experience is available to quantify its performance. The panel is unanimous in their opinion that the performance of ERFBS and fire-retardant cable coatings is reasonably understood under fire conditions but not under HEAF conditions. Panelists raised the possibility that the pressure wave from the HEAF could damage an ERFBS and render it ineffective. In addition, the effects of a high heat, short-duration exposure of a HEAF event on these shields is not well understood. The typical assumptions that apply to fire exposures do not apply here; there is no growth phase, the velocity of hot gases is much higher, and the constituents of the hot gases are different. Any analytical model to predict the effects of a HEAF on a shield would require analyses of heat and mass transfer as well as solid mechanics, and no such tool has been applied to the evaluation of HEAF shields.

3.2.4 Cabinet Lineup Effects

Only scenario 3 featured a cabinet lineup, so only one data point was available for the calculation of this phenomenon's average rank.

The discussions on cabinet lineup effects were focused on what properties were unique to banks of enclosures and how they might affect the results of a HEAF event. These include how the cabinets are situated next to one another; what separations are between them (none, single wall, double wall, air gap); the presence of penetrations or false floor between cabinets; and the position of the HEAF source within the bank. Some of these properties, such as cabinet separation, are closely linked to target phenomena like shielding and orientation. However, the panel's consensus was that cabinet lineup effects should be treated as its own category because banks of cabinets do not respond as if they are several closely spaced but discrete targets. Mechanical coupling of the enclosures and shared penetrations often occurs.

3.3 <u>Additional Discussions</u>

This section captures some of the important points of the panelists' discussion that do not directly pertain to level 1 phenomena but are worth noting nonetheless.

3.3.1 External Duct Housing Configuration

The importance of the external duct housing configuration is attributed to its structural design including the thickness, material, and penetrations/access points. Test data from the OECD/NEA program provides direct evidence for the significant impact of the duct housing material; in test 26, several inches of aluminum housing were oxidized creating a fireball that melted equipment over 20 feet away. Although the configuration of the external duct housing encompasses a number of things, the driver behind its ranking is the possible presence of aluminum in the housing.

3.3.2 Internal Ensuing Fire

The source equipment identified in scenario 1 was a generic electrical enclosure, and the associated target was a redundant cable tray passing over the enclosure. The panelists identified the occurrence of an ensuing fire in the source enclosure as being of first-order importance in predicting the damage to the cable tray. Although a HEAF would likely produce temperature far in excess of any ensuing fire, the extended duration of an ensuing fire poses a secondary threat to adjacent equipment.

The highly ranked sub-phenomena discussed included ignition, characterization of the fire source, and development of the fire. These are all critical phenomena in predicting the behavior and effects of a standard cabinet fire.

The state of knowledge regarding internal fires reflects this missing link. The lowest ranked phenomenon was fire ignition, and the panelists are unsure how to predict or model ignition in a HEAF scenario.

3.3.3 Pressure Effects

Panel discussions on pressure effects were centered on two failure mechanisms: a pressure wave and a projectile. In the former, a wave of pressure disturbance propagates through the medium (air) imparting mechanical energy to targets; in the latter, the pressure wave accelerates a solid object, which subsequently imparts mechanical energy to a target upon impact. The term "shock wave," which implies supersonic propagation, is not used here. Pressure measurements during phase one experiments were unreliable and noisy, and propagation speed was not measured.

Cabinets in a lineup may be particularly sensitive to a pressure wave depending on their configuration. Where sensitive electronic equipment is present, being in the same bank as a HEAF may be sufficient to cause damage even where no thermal insult is incurred. For the enclosures immediately adjacent to the source cabinet, the construction of the separating walls becomes important. Operating experience and test results clearly document the ability of a HEAF to open or dislodge enclosure doors and bow or deform enclosure walls. The panel theorized that this type of mechanical shock could raise the possibility of a secondary HEAF in an adjacent cabinet.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Practical Considerations for PRA Practitioners

The phenomena identification and ranking table (PIRT) was useful in identifying the phenomena that are most influential in predicting the impact of a high energy arcing fault (HEAF); however, certain practical considerations must be taken into account when analyzing the data for the formulation of a test plan.

Ultimately, the goal of the HEAF research program is to refine and improve the methodology by which probabilistic risk assessment (PRA) practitioners estimate the risk of a postulated HEAF event. The input to any such model or methodology must be available to the practitioner. It would be unproductive to study the impact of microscale or stochastic phenomena knowing that it cannot be incorporated into the applicable guidance.

4.2 Characterizing Target Damage

One of the consistently highly ranked phenomena was the characterization of the target equipment and its susceptibility to various types of damage. This phenomenon fundamentally differs from the others in that it is not a property of the HEAF or source equipment. Even if a HEAF can be modeled with perfect accuracy, the ability to convert that data into a damage state for a given target is critical in assessing risk.

Although thermal damage appears to be the greatest threat both in experimental observations and PIRT responses, HEAF events fall outside the range of applicability for classical fire models. The temperature of the arc column can be in excess of 15,000 °C, which is unmatched even by rocket fuel or thermite. HEAF events also do not have growth or decay phases; the energy is released suddenly and intensely before the event terminates just as suddenly. With this type of energy release, the thermal inertia of targets must be taken into account—a simple temperature threshold for damage does not adequately describe the target vulnerability.

Any future research program should focus on modeling the HEAF and on modeling the damage to targets as a function of the environmental conditions created by the HEAF. In scenario 3, the difference in response of the two targets (cable tray and enclosure) was discussed, which raised the possibility that a one-size-fits-all zone of influence approach may not be sufficient. Different classes of target equipment may need to be considered separately.

Though thermal conditions were a focal point during phase one testing, the PIRT suggests that pressure effects and the effects of conductive particulate on electronic equipment should be considered as well.

4.3 Arc Mitigation

The multi-tiered approach to safety advocated by “defense in depth” (DID) strategies applies to HEAF as well as any phenomenon. Operating plants have placed a heavy emphasis on the “prevention” aspect of DID with selective coordination designed to limit the duration of an arc fault to a few cycles—not enough to cause significant external damage. These protective schemes are often effective in limiting the damage from arc faults, but a non-trivial number of these arc faults are accompanied by the failure of an upstream breaker resulting in event durations that have exceeded 10 seconds. The frequency of these events, coupled with the catastrophic damage they can cause, demand more than a single element of DID.

If a HEAF cannot be prevented, the next logical step is to mitigate the damage it can cause. This can be done in a number of ways, but the panel discussions were focused around enclosing the source equipment (e.g., “arc resistant” cabinets[1]); protecting the target equipment (ERFBS, cable coatings); or placing barriers between the two. The pros and cons of each option were discussed.

Enclosures designed to contain the blast of a HEAF represent a costly solution to this problem. The panel deemed the replacement of electrical enclosures susceptible to HEAF with such enclosures beyond the realm of feasibility; however, their use in new construction was seen as slightly more reasonable.

Target protection is used extensively in fire protection but, where HEAFs are concerned, questions abound. Little data is available regarding the ability of classical fire protection methods (ERFBS, cable coatings) to withstand the impact of a HEAF. Target protection may be an effective method of HEAF mitigation, but further study is needed.

The last method—a physical barrier separating the source and target equipment (or “HEAF shield”)—strikes a good balance between cost and efficacy in theory. Some operating facilities have already installed some form of HEAF shield. Because no formal or industry-standard definition for such a barrier is available, no performance criteria or qualifications exist. The panel is not aware of any test campaign that has evaluated the impact of such a shield, and no operating experience is available to quantify its performance. This is an area that requires further study and should be considered in future research test plans.

4.4 Internal Ensuing Fire

Internal ensuing fires show up as high-priority items in both scenarios where the source equipment is an electrical enclosure (as opposed to a bus duct, which was assumed not to be able to support a significant sustained internal fire.) Based on operating experience and test evidence, internal ensuing fires are the most likely secondary hazard in a HEAF scenario.

The U.S. Nuclear Regulatory Commission and others have performed a significant amount of work in an attempt to quantify the behavior of a fire in an electrical enclosure [16][17]. What has not been quantified is the link between a HEAF and the advent of a fire. Specifically, the following two questions arose during the PIRT:

a) What is the likelihood of an internal fire pursuant to a HEAF?

b) Can the HEAF simply be modeled as a very energetic ignition event or does it impact the development of the fire through pre-heating and other phenomena?

Item (a) is not just a question of frequency—it should be the goal of future research to determine what conditions must be present for a sustained internal ensuing fire. From phase one testing, a rough pattern has emerged: arcs with durations of less than two seconds did not cause internal ensuing fires likely due to the linear relationship between arc duration and total energy. More tests are needed to establish whether arc energy (and by extension, arc duration) is the primary criteria for predicting ensuing fires and other conditions that are necessary or favorable for an ensuing fire.

[1] The term “arc-resistant” is a misnomer and generally refers to a cabinet designed to route hot gases and flames away from service personnel in the event of an arc. It is not designed to prevent or extinguish arcs.

Item (b) is critical for a PRA analysis of the ensuing fire and could implicate the need for a fundamentally different method of analysis. The typical fire models used for electrical enclosure fires assume a growth phase that lasts for several minutes, steady burning at peak heat release rate for several more minutes, and then a decay phase. If a HEAF is sufficiently energetic, it may heat and simultaneously ignite all cabinet internals, skipping the growth phase entirely. This type of behavior was observed several times during phase one testing. In addition to skipping a growth phase, the instantaneous ignition of cabinet internals may lead to shorter duration, higher intensity fires than would typically be expected. A sensitivity study on plant response to this alternate fire growth curve is in order. Future research should focus on the impact of a HEAF on the growth and development of an ensuing fire as compared to a standard electrical enclosure fire.

4.5 <u>Arc Characterization</u>

Characterization of the arc is essentially characterization of the "source term"—the driver behind any resultant damage, analogous to the heat release rate term in a fire model. The electrical properties of the arc including voltage, current, and duration determine the amount of energy released into the environment of interest. It is important to distinguish between the electrical properties of the equipment in which the arc occurs and the electrical properties of the arc itself. Although the former is known to a high degree of accuracy, the latter is subject to some uncertainty.

One area that was discussed at length was the location of the arc and whether it was predictable. The arc location is an important parameter for predicting the flow path of the plasma and ionized gas, if and where the arc will migrate, and whether the arc is likely to breech the enclosure. Unfortunately, past test data is not helpful in this regard as the arc was initiated in a predetermined location with the use of shorting wire as described in the IEEE standard for testing switchgear internal arcing faults.[18] Determining whether the location of an arc is predictable, random, or stochastic should be a focus of future experimental work.

Arc ejecta, which includes the smoke, ionized gas, and conductive particulate expelled by the arc, were also discussed. Ionized gas and conductive particulate may present a failure mechanism for nearby equipment that has previously not been considered. During phase one testing, conductive particulate from the arc caused shorting in laboratory equipment several meters away from the test enclosure. Panelists noted the importance of quantifying this ejecta but also that it would be difficult or impossible to separate the ejecta into its constituents. Future research should focus on establishing the properties of the ejecta (thermal conductivity, electrical conductivity, mean particle size) and its potential impact on target equipment.

4.6 <u>Pressure Effects</u>

After thermal effects, the panel ranked pressure effects as the greatest hazard to surrounding systems, structures, and components. The mechanical energy imparted by a pressure wave or projectile has the potential to disable equipment, trip breakers, cause secondary arcs, damage pressure boundaries (fire doors and dampers), and change the ventilation properties of the source enclosure.

Pressure measurements during phase one testing are difficult to analyze, and the impact of pressure effects is mostly anecdotal. From the test report:

> "Due to the EMI generated by the large currents, voltages, and arc activity, the pressure signals are noisy. The EMI tends to be most severe during large changes in current,

> voltage, and arc activity, and these are the same periods where large changes are expected in enclosure pressure. For this reason, it is difficult to determine whether the transducer signal peaks are actually pressure peaks.[12]

Despite the difficulty in obtaining reliable pressure measurements, some qualitative data are available. In numerous tests, cabinet access doors were blown open, cabinet internals were violently dislodged, and enclosure walls were deformed. An LER [19] and inspection report [20] from a 2017 HEAF event at Turkey Point document the deformation of a fire door due to pressure increase, which raises the concern of an ensuing fire unbounded by the normal compartmentation scheme.

The lack of high-quality pressure measurements factored into the low state of knowledge rankings for pressure-related phenomena. Future test programs would benefit from a better method of pressure measurement free from EMI, both inside and outside the enclosure.

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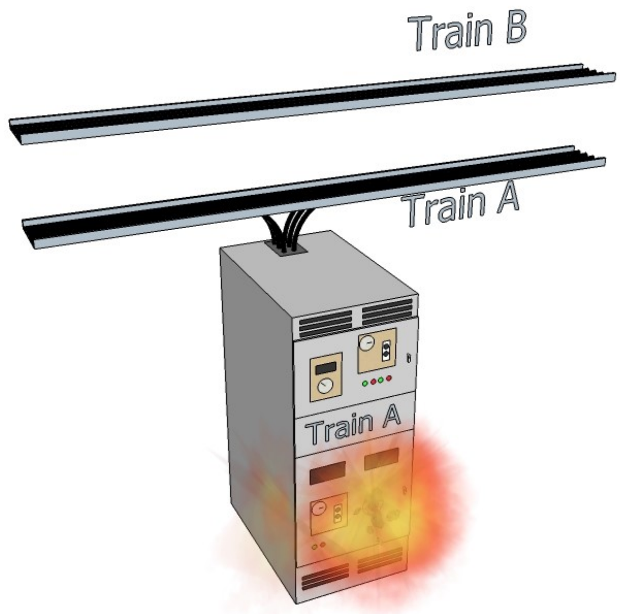
APPENDIX A PIRT HEAF SCENARIO 1

A.1 HEAF Scenario 1

A.1.1 Scenario Description



A high energy arcing fault occurs in a low/medium voltage switchgear that supplies power to "Train A" systems. The cables from an overhead cable tray enter the cabinet from the top (air-drop configuration). A cable tray carrying cables that supply power to redundant "Train B" systems is located near the "Train A" switchgear and cable tray.

A.1.2 Figure of Merit

Determining the extent of damage to the cables in the "Train B" cable tray.

A.2 List of Identified Phenomena

Phenomenon 1: Electrical Configuration Effects

A. Power supply characterization
B. Electrical protection coordination[2]

[2] Electrical protection coordination refers to the coordination and configuration of upstream breakers with the objective of minimizing the duration of an electrical fault

Phenomenon 2: Internal Cabinet Configuration Effects

A. Cabinet compartmentation
B. Breaker configuration
C. Cabinet combustible loading
D. Cabinet bus bar configuration

Phenomenon 3: External Cabinet Enclosure Configuration Effects

A. Cabinet ventilation
B. Cabinet structural design
C. Cabinet penetrations

Phenomenon 4: Arc Characterization

A. Arc electrical characterization
B. Arc migration
C. Arc breeching of enclosure
D. Thermal effects of the arc
E. Magnetic effects of the arc[3]
F. Electromagnetic interference
G. Arc ejecta

Phenomenon 5: Fire Detection[4]

A. Presence of fire detection
B. Characterizing the detection system

Phenomenon 6: Fire Suppression

A. Presence of fire suppression
B. Characterizing the suppression system

Phenomenon 7: Pressure Effects

A. Projectile/missile damage
B. Pressure wave

[3] Magnetic effects refers to the applied forces on ferrous materials by a magnetic field that can induce bending and deformation, as opposed to the interference that it may cause. Interference is addressed separately.
[4] Fire detection was assumed not to automatically trigger fire suppression. Fire suppression is considered as a separate phenomenon.

Phenomenon 8: Internal Ensuring Fire[5]

A. Fire ignition
B. Characterization of the fire source
C. Fire development
D. Smoke generation
E. Altered ventilation effects[6]

Phenomenon 9: External Ensuing Fire

A. Fire ignition
B. Characterization of the fire source
C. Fire development
D. Smoke generation

Phenomenon 10: Room Configuration Effects

A. Room integrity[7]
B. Room arrangement
C. Room ventilation

Phenomenon 11: Arc Mitigation

A. Intentional shielding
B. Electrical raceway fire barrier system effects[8]
C. Fire-retardant coating effects[9]

Phenomenon 12: Generic Cable Tray (Target) Characterization

A. Characterizing target damage criteria
B. Target arrangement effects
C. Target sensitivity to damage

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[5] Internal ensuing fire refers to a sustained fire that occurs inside the source cabinet.
[6] Altered ventilation effects refers to the manner in which changes to the cabinet's structure and integrity as a result of the HEAF impact the ventilation paths for an internal ensuing fire.
[7] Room integrity refers to the pressure boundary of the room in which the HEAF occurs, and how its response to the increased pressure will impact target damage. For example, consider whether blowing open a fire door or damper will affect target damage.
[8] Electrical raceway fire barrier systems refers to a wrap or enclosure that is installed around electrical cable trays with the intent of mitigating fire damage.
[9] Fire-retardant coating refers to a permanently installed coating or spray that is applied directly to the cables in a cable tray.

A.3 Phenomena Importance Rankings

Table A-1 Importance Ranking for Scenario 1, Electrical Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
1. Electrical Configuration Effects							
A. Power supply characterization	H	H	H	H	H	H	
B. Electrical protection coordination	H	H	H	H	H	H	

Table A-2 Importance Ranking for Scenario 1, Internal Cabinet Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
2. Internal Cabinet Configuration Effects							
A. Cabinet compartmentation	M	M	H	M	M	L	
B. Breaker configuration	L/M	H	M	M	M	H	P1 notes that whether the HEAF occurs on the primary or secondary side of the breaker affects the importance.
C. Cabinet combustible loading	H	H	M	H	H	H	
D. Cabinet bus bar configuration	M	H	M	H	M	H	

Table A-3 Importance Ranking for Scenario 1, External Cabinet Enclosure Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
3. External Cabinet Enclosure Configuration Effects							
A. Cabinet ventilation	M	H	H	M	H	H	
B. Cabinet structural design	L	H	H	M	M	M	
C. Cabinet penetrations	M	H	H	H	M	H	

Table A-4 Importance Ranking for Scenario 1, Arc Characterization

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
4. Arc Characterization							
A. Arc electrical characterization	H	H	H	H	H	H	
B. Arc migration	M	M	H	M	M	M	
C. Arc breeching of enclosure	H	H	H	H	M	H	
D. Thermal effects of the arc	H	H	H	H	H	H	
E. Magnetic effects of the arc	L	L	L	M	U	L	
F. Electromagnetic interference	L	L	L	M	U	L	
G. Arc ejecta	H	M	H	H	H	L	

Table A-5 Importance Ranking for Scenario 1, Fire Detection

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
5. Fire Detection							
A. Presence of fire detection	H	L	H	L	H	L	
B. Characterizing fire detection system	M	L	M	L	M	L	

Table A-6 Importance Ranking for Scenario 1, Fire Suppression

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
6. Fire Suppression							
A. Presence of fire suppression	H	L	H	M	H	L	
B. Fire suppression effects	H	H	H	M	H	H	

Table A-7 Importance Ranking for Scenario 1, Pressure Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
7. Pressure Effects							
C. Projectile/missile damage	L	H	M	H	H	L	
D. Pressure wave	L	H	M	H	H	M	

Table A-8 Importance Ranking for Scenario 1, Internal Ensuing Fire

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
8. Internal Ensuing Fire							
A. Fire ignition	H	H	H	H	H	H	
B. Characterization of the fire source	H	H	H	H	H	H	
C. Fire development	H	H	H	H	H	H	
D. Smoke generation	L	M	M	M	M	M	
E. Altered ventilation effects	M	H	H	M	H	H	

Table A-9 Importance Ranking for Scenario 1, External Ensuing Fire

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
9. External Ensuing Fire							
A. Fire ignition	H	H	H	H	H	H	
B. Characterization of the fire source	H	H	H	H	H	H	
C. Fire development	H	H	H	H	H	H	
D. Smoke generation	L	L	M	H	M	L	

Table A-10 Importance Ranking for Scenario 1, Room Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
10. Room Configuration Effects							
A. Room integrity	L	H	M	L	M	X	
B. Room arrangement	M	H	M	M	M	H	
C. Room ventilation	M	H	M	M	M	H	

Table A-11 Importance Ranking for Scenario 1, Arc Mitigation

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
11. Arc Mitigation							
A. Intentional shielding	M	M	H	H	H	H	
B. Electrical raceway fire barrier system	H	L	H	H	H	H	
C. Fire-retardant coating	M	M	H	M	H	H	

Table A-12 Importance Ranking for Scenario 1, Generic Cable Tray (Target) Characterization

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
12. Generic Cable Tray (Target) Characterization							
A. Characterizing target damage criteria	H	H	H	H	H	H	
B. Target arrangement effects	H	H	H	M	H	H	
C. Target sensitivity to damage	H	H	H	H	H	H	

A.4 Phenomena State of Knowledge Rankings

Table A-13 State of Knowledge Ranking for Scenario 1, Electrical Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
7. Electrical Configuration Effects				
A. Power supply characterization	H	H	N/A	
B. Electrical protection coordination	H	H	N/A	

Table A-14 State of Knowledge Ranking for Scenario 1, Internal Cabinet Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
8. Internal Cabinet Configuration Effects				
A. Cabinet compartmentation	H	H	N/A	
B. Breaker configuration	M-H	M	H	
C. Cabinet combustible loading	M-H	M	M	P1 notes that this phenomena is not as well known for older facilities.
D. Cabinet bus bar configuration	H	H	N/A	

Table A-15 State of Knowledge Ranking for Scenario 1, External Cabinet Enclosure Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
9. External Cabinet Enclosure Configuration Effects				
A. Cabinet ventilation	H	H	N/A	
B. Cabinet structural design	H	H	N/A	
C. Cabinet penetrations	H	H	N/A	

Table A-16 State of Knowledge Ranking for Scenario 1, Arc Characterization

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
10. Arc Characterization				
A. Arc electrical characterization	L-M	L/H	L-M	Panelists note that while some elements of the arc are easy to predict, others, like arc location and duration, are not.
B. Arc migration	M	L-M	U	
C. Arc breeching of enclosure	L	L	L	
D. Thermal effects of the arc	M-H	M	H	
E. Magnetic effects of the arc	L-M	L-M	M-H	
F. Electromagnetic interference	L-M	L-M	M-H	
G. Arc ejecta	L	L	L	

Table A-17 State of Knowledge Ranking for Scenario 1, Fire Detection

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
11. Fire Detection				
A. Presence of fire detection	H	H	N/A	
B. Characterizing fire detection system	H	H	N/A	

Table A-18 State of Knowledge Ranking for Scenario 1, Fire Suppression

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
12. Fire Suppression				
A. Presence of fire suppression	H	H	N/A	
B. Fire suppression effects	H	H	N/A	

Table A-19 State of Knowledge Ranking for Scenario 1, Pressure Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
13. Pressure Effects				
A. Projectile/missile damage	M	L-M	L	
B. Pressure wave	H	H	N/A	

Table A-20 State of Knowledge Ranking for Scenario 1, Internal Ensuing Fire

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
14. Internal Ensuing Fire				
A. Fire ignition	L	L	L	
B. Characterization of the fire source	H	M	M-H	
C. Fire development	M	M	M	
D. Smoke generation	M	L-M	M-H	
E. Altered ventilation effects	M	M	L-M	

Table A-21 State of Knowledge Ranking for Scenario 1, External Ensuing Fire

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
15. External Ensuing Fire				
A. Fire ignition	L/H	L/H	M	Panelists note that good models exists for fire spreading to an external source, but models are poor for HEAF-induced ignition.
B. Characterization of the fire source	H	H	N/A	
C. Fire development	M	M	H	
D. Smoke generation	M	M	H	

Table A-22 State of Knowledge Ranking for Scenario 1, Room Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
16. Room Configuration Effects				
A. Room integrity	M	M	M-H	
B. Room arrangement	H	H	N/A	
C. Room ventilation	H	H	N/A	

Table A-23 State of Knowledge Ranking for Scenario 1, Arc Mitigation

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
17. Arc Mitigation				
A. Intentional shielding	L	L-M	H	
B. Electrical raceway fire barrier system	L/H	L/H	H	Panelists note that the behavior of ERFBS is known for fire scenarios, but not for HEAF scenarios.
C. Fire-retardant coating	L/H	L/H	H	Panelists note that the behavior of fire-retardant coatings is known for fire scenarios, but not for HEAF.

Table A-24 State of Knowledge Ranking for Scenario 1, Generic Cable Tray (Target) Characterization

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
18. Generic Cable Tray (Target) Characterization				
A. Characterizing target damage criteria	M	M	H	
B. Target arrangement effects	M	M	H	
C. Target sensitivity to damage	L-M	L-M	M	

A.5 Phenomena Key Parameters Ranking

Table A-25 Key Parameters Ranking for Scenario 1, Electrical Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
1A. Power Supply Characterization								
1. Line Voltage	H	H	H	H	H	H	H	
2. Rated Current	H	H	M	H	M	M	H	
3. Short Circuit Current	H	H	H	H	H	M	H	
4. Frequency	L	H	L	L	L	L	H	
5. Grounded/Ungrounded	M	H	M	L	L	L	H	
6. Number of Phases	U	U	L	L	L	U	H	
7. MVA Available	H	H	H	H	H	H	H	

Table A-26 Key Parameters Ranking for Scenario 1, Internal Cabinet Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
2A. Cabinet Compartmentation								
1. Volume	M	H	H	M	H	L	H	
2. Internal Barriers	M	M	M	M	M	M	M-H	
2B. Breaker Configuration								
3. Arc Extinguishing Mechanism	L/M	L	L	L	L	L	H	
4. Total Breaker Combustible Load	L/M	H	M	H	H	H	H	
5. Extinguishing Medium	L/M	L	M	L	M	L	H	
6. Breaker Connection Material	L/M	M	M	H	H	H	H	
2C. Cabinet Combustible Loading								
7. Mass	H	H	M	H	H	M	M	
8. Bundle Tightness	M	U	L	M	M	H	M	
9. Thermoset/Thermoplastic	H	H	M	H	M	H	H	
10. Cables Jacketed/Unjacketed	M	H	H	H	M	H	H	
11. Combustion Properties	H	H	M	H	H	H	M	
2D. Cabinet Bus Bar Configuration								
12. Bus Bar Spacing	L	H	M	H	H	H	H	
13. Bus Bar Material	H	H	H	H	H	H	H	
14. Number of Bus Bars per Phase	M	M	L	M	M	M	H	
15. Bus Bar Insulation	L	H	L	M	M	M	H	
16. Bus Bar Orientation	L	M	M	M	M	L	H	
17. Bus Bar Cross-Sectional Area	L	M	L	M	L	L	H	
18. Bus Bar Mounting/Supports	L	L	M	L	L	M	H	

Table A-27 Key Parameters Ranking for Scenario 1, External Cabinet Enclosure Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
3A. Cabinet Ventilation								
1. Active/Passive Ventilation	L	U	M	H	H	L	H	
2. Ventilation Opening Area	H	H	H	H	H	M	H	
3. Ventilation Deflection	L	U	M	M	M	L	M-H	
4. Ventilation Opening Location	L	H	H	M	H	M	H	
5. Presence of Active Louvres	L	U	L	U	U	L	H	
3B. Cabinet Structural Design								
6. Wall Material	M	M	M	H	L	L	H	
7. Wall Thickness	M	M	L	H	M	M	H	
8. Door Latch Type	X	M	M	M	M	M	H	
9. Door Gasketing	X	M	L	M	M	L	H	
10. Wall Fastening (Welded, bolted, riveted)	M	M	L	M	M	M	H	
11. Single/Double Wall	X	U	L	M	M	L	H	
3C. Cabinet Penetrations								
12. Location of Penetrations	L	H	H	H	M	M	H	
13. Penetration Sealing	H	M	H	H	M	H	H	
14. Penetration Type (Compression, conduit, raceway)	L	M	M	M	M	M	H	
15. Viewing Ports/Mechanical Openings	U	U	M	H	M	M	H	

Table A-28 Key Parameters Ranking for Scenario 1, Arc Characterization

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
4A. Arc Electrical Characterization								
1. Arc Voltage	H	H	H	H	H	H	L-M	
2. Arc Current (Asymmetric)	L	M	H	H	L	H	H	
3. Arc Current (RMS)	H	U	H	H	H	M	H	
4. Arc Energy	H	H	H	H	H	H	M	
5. Arc Duration	H	H	H	H	H	H	M	
6. Arc Location	H	H	H	M	H	H	L	
4B. Arc Migration								
7. Arc Migration Speed	H	M	H	H	H	L	H	
8. Type (Ionized Gas/Magnetic Field)	U	H	M	H	H	L	L	
4D. Thermal Effects of the Arc								
9. Arc Heat Flux	H	H	H	H	M	H	M	
10. Bus Bar Melting	H	M	M	H	M	M	M(H)	P5 notes familiarity with a validated model for bus bar melting. The remaining panelists ranked the SOK as medium, but high pending verification of the model.
11. Oxidation of Adjacent Materials	H	H	H	H	M	H	L	
4G. Arc Ejecta								
12. Ionized Gas	L	H	H	H	H	H	L	
13. Smoke	L	L	L	L	M	L	L	
14. Conductive Particulate	H	U	M	H	M	H	L	

Table A-29 Key Parameters Ranking for Scenario 1, Fire Detection

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
5A. Presence of Fire Detection								
1. Detector Location	H	H	H	M	H	H	H	
5B. Detection Characteristics								
2. Detector Type (Heat/smoke/optical)	H	L	M	M	M	L	H	

Table A-30 Key Parameters Ranking for Scenario 1, Fire Suppression

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
6A. Presence of Fire Suppression								
1. Internal/External to Cabinet	H	H	H	M	M	H	H	
2. Proximity	H	H	H	M	M	L	H	
6B. Characterizing the Suppression System								
3. Actuation (Manual/Automatic)	M	U	H	M	M	M	H	
4. Survivability	H	H	H	M	X	X	L	
5. Suppression Type	M	L	H	L	M	M	H	

Table A-31 Key Parameters Ranking for Scenario 1, Pressure Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
7B. Pressure Wave								
1. Magnitude	H	H	M	H	H	H	M-H	
2. Propagation	H	M	M	H	H	H	M	

Table A-32 Key Parameters Ranking for Scenario 1, Internal Ensuing Fire

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
8A. Fire Ignition								
1. Internal Cabinet Temperature	M	H	H	H	H	H	L	
8B. Characterization of Fire Source								
2. Heat Release Rate	H	H	H	H	H	H	M-H	
3. Heat Release Rate per unit Area	M	L	H	M	H	L	M	
8C. Fire Development								
4. Time to Peak	M	U	H	M	H	M	M-H	
5. Fire Growth Rate	M	H	H	H	H	H	M-H	
8E. Altered Ventilation Effects								
6. Altered Internal Vent Properties	M	H	H	H	H	M	M	
7. Altered Enclosure Vent Properties	M	H	H	H	H	H	M	

Table A-33 Key Parameters Ranking for Scenario 1, External Ensuing Fire

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
9B. Characterization of Fire Source								
1. Heat Release Rate	H	H	H	H	H	H	H	
2. Heat Release Rate per unit Area	M	L	H	M	H	L	H	
3. Fire Geometry	L	M	M	H	H	H	H	
9C. Fire Development								
4. Time to Peak	H	L	H	M	H	M	H	
5. Fire Growth Rate	H	H	H	H	H	H	H	

Table A-34 Key Parameters Ranking for Scenario 1, Room Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
10A. Room Integrity								
1. Fire Dampers	M	U	M	H	H	X	L	
2. Penetrations	M	U	M	H	H	X	L	
10B. Room Arrangement								
3. Dimensions	M	U	M	H	H	H	H	
4. Contents	M	U	L	H	H	L	H	
5. Construction Material	M	U	L	M	M	L	H	
6. Location of Source within Room	L	L	H	M	M	H	H	
10C. Room Ventilation								
7. Type (Active/Passive)	H	M	L	H	H	M	H	

Table A-35 Key Parameters Ranking for Scenario 1, Arc Mitigation

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
11A. Intentional Shielding								
1. Thickness	H	M	M	H	H	H	H	
2. Material	H	H	H	H	H	H	H	
11B. Electrical Raceway Fire Barrier System								
3. Rating	M	H	M	U	H	M	H	
11C. Fire-Retardant Coating Effects								
4. Thickness	H	U	H	H	H	H	M	
5. Material	M	M	H	H	H	H	H	
6. Age	L	U	M	U	H	H	H	

Table A-36 Key Parameters Ranking for Scenario 1, Generic Cable Tray (Target) Characterization

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
12A. Target Damage								
1. Damage Criteria	L	H	H	H	H	H	L/H	Panelists note that damage criteria, critical heat flux, and critical temperature are known for fire scenarios, but not HEAF scenarios.
2. Critical Heat Flux	H	H	H	H	H	H	L/H	
3. Critical Temperature	H	H	H	H	H	H	L/H	
4. Exposure Time	H	H	H	H	H	H	M	
12B. Target Arrangement Effects								
5. Distance to HEAF Source	H	H	H	H	H	H	H	
6. Orientation Relative to HEAF Source	H	H	H	H	H	H	H	
12C. Target Sensitivity								
7. Sensitivity to Shock	L	U	M	M	M	L	M	
8. Sensitivity to Heat	H	M	H	H	H	H	H	
9. Sensitivity to EMI/RFI	L	L	M	L	U	L	M	
10. Sensitivity to Light	L	L	L	L	L	L	M	
11. Sensitivity to Ionized Gas	L	M	M	L	H	M	M	
12. Sensitivity to Conductive Particulate	L	L	M	L	L	l	M	
13. Sensitivity to Smoke	L	L	L	L	L	L	M	

A.6 Scenario 1 Phenomena Calculated Rank Values and Grouping

Phenomenon	Importance	State of Knowledge	Rank	Grouping
Arc Mitigation (11)	4.2	2.4	1.75	Level 1
Internal Ensuing Fire (8)	4.4	2.7	1.63	Level 1
Target Characterization (12)	4.9	3.2	1.53	Level 1
Arc Characterization (4)	3.6	2.7	1.33	Level 1
External Ensuing Fire (9)	4.3	3.4	1.27	Level 2
Pressure Effects (7)	3.5	3.2	1.09	Level 2
Electrical Configuration Effects (1)	5	5	1.00	Level 2
Internal Cabinet Configuration Effects (2)	3.8	4.2	0.91	Level 2
External Cabinet Enclosure Effects (3)	4	5	0.80	Level 3
Suppression Effects (6)	4	5	0.80	Level 3
Room Configuration (10)	3.4	4.3	0.79	Level 3
Fire Detection (5)	2.5	5	0.50	Level 3

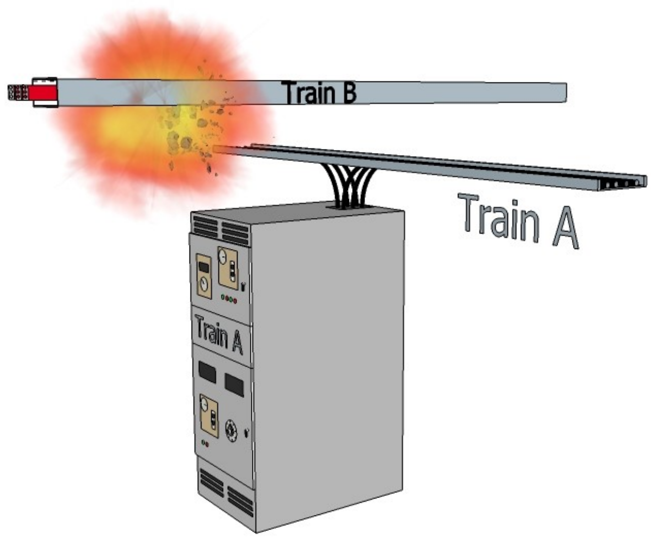
33rd percentile for Rank: 0.87

66th percentile for Rank: 1.28

APPENDIX B PIRT HEAF SCENARIO 2

B.1 HEAF Scenario 2

B.1.1 Scenario Description



A high energy arcing fault occurs in a non-segregated bus duct supplying power to “Train B” systems. A switchgear supplying power to redundant “Train A” systems is located nearby.

B.1.2 Figure of Merit

Determining the extent of damage to the switchgear.

B.2 List of Identified Phenomena

Phenomenon 1: Electrical Configuration Effects

A. Power supply characterization
B. Electrical protection coordination[10]

Phenomenon 2: Internal Bus Duct Configuration Effects

A. Duct compartmentation
B. Duct combustible loading

[10] Electrical protection coordination refers to the coordination and configuration of upstream breakers with the objective of minimizing the duration of an electrical fault

C. Duct bus bar configuration

Phenomenon 3: External Bus Duct Housing Configuration Effects

A. Duct ventilation
B. Duct structural design
C. Duct mounting

Phenomenon 4: Arc Characterization

A. Arc electrical characterization
B. Arc migration
C. Arc breeching of enclosure
D. Thermal effects of the arc
E. Magnetic effects of the arc[11]
F. Electromagnetic Interference
G. Arc ejecta

Phenomenon 5: Fire Detection[12]

A. Presence of fire detection
B. Characterizing the detection system

Phenomenon 6: Fire Suppression

A. Presence of fire suppression
B. Characterizing the suppression system

Phenomenon 7: Pressure Effects

A. Projectile/missile damage
B. Pressure wave

Phenomenon 8: Internal Ensuring Fire[13]

A. Fire ignition
B. Characterization of the fire source
C. Fire development

[11] Magnetic effects refers to the applied forces on ferrous materials by a magnetic field that can induce bending and deformation, as opposed to the interference that it may cause. Interference is addressed separately.

[12] Fire detection was assumed not to automatically trigger fire suppression. Fire suppression is considered as a separate phenomenon.

[13] Internal ensuing fire refers to a sustained fire that occurs inside the source cabinet.

D. Smoke generation
E. Altered ventilation effects[14]

Phenomenon 9: External Ensuing Fire

A. Fire ignition from molten metal
B. Fire ignition from arc heat
C. Characterization of the fire source
D. Fire development
E. Smoke generation

Phenomenon 10: Room Configuration Effects

A. Room integrity[15]
B. Room arrangement
C. Room ventilation

Phenomenon 11: Arc Mitigation

A. Intentional shielding
B. Electrical raceway fire barrier system effects[16]
C. Fire-retardant coating effects[17]
D. Cable tray design

Phenomenon 12: Generic Enclosure (Target) Characterization

A. Characterizing target damage criteria
B. Target arrangement effects
C. Target sensitivity to damage

[14] Altered ventilation effects refers to the manner in which changes to the cabinet's structure and integrity as a result of the HEAF impact the ventilation paths for an internal ensuing fire.
[15] Room integrity refers to the pressure boundary of the room in which the HEAF occurs, and how its response to the increased pressure will impact target damage. For example, consider whether blowing open a fire door or damper will affect target damage.
[16] Electrical raceway fire barrier systems refers to a wrap or enclosure that is installed around electrical cable trays with the intent of mitigating fire damage.
[17] Fire-retardant coating refers to a permanently installed coating or spray that is applied directly to the cables in a cable tray.

B.3 Phenomena Importance Rankings

Table B-1 Importance Ranking for Scenario 2, Electrical Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
1. Electrical Configuration Effects							
A. Power supply characterization	H	H	H	H	H	H	
B. Electrical protection coordination	H	H	H	H	H	H	

Table B-2 Importance Ranking for Scenario 2, Internal Bus Duct Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
2. Internal Bus Duct Configuration Effects							
A. Duct compartmentation	M	M	M	H	M	M	
B. Duct combustible loading	L	L	L	L	H	L	
C. Duct bus bar configuration	M	M	M	M	M	L	

Table B-3 Importance Ranking for Scenario 2, External Bus Duct Housing Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
3. External Bus Duct Housing Configuration Effects							
A. Duct ventilation	L	L	L	L	L	L	
B. Duct structural design	H	H	H	H	H	H	
C. Duct mounting	H	L	L	L	L	L	

Table B-4 Importance Ranking for Scenario 2, Arc Characterization

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
4. Arc Characterization							
A. Arc electrical characterization	H	H	H	H	H	H	P5 notes that arc voltage will be higher than that of the switchgear because the arc will move along the duct.
B. Arc migration	H	L	L	M	M	L	
C. Arc breeching of enclosure	H	H	H	H	H	H	Panelists note that HEAFs inside bus ducts always breech the housing, but it remains an important phenomenon. Panelists also note that a HEAF may not have been reported as such if breeching did not occur.
D. Thermal effects of the arc	H	H	H	H	H	H	
E. Magnetic effects of the arc	L	L	L	L	L	L	
F. Electromagnetic interference	L	L	L	L	L	L	
G. Arc ejecta	M-H	M-H	M-H	M-H	M-H	M-H	

Table B-5 Importance Ranking for Scenario 2, Fire Detection

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
5. Fire Detection							
A. Presence of fire detection	H	M	M	L	L	M	
B. Characterizing fire detection system	M	L	L	L	L	L	

Table B-6 Importance Ranking for Scenario 2, Fire Suppression

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
6. Fire Suppression							
A. Presence of fire suppression	H	L	L	L	L	L	
B. Fire suppression effects	H	L	L	L	L	L	

Table B-7 Importance Ranking for Scenario 2, Pressure Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
7. Pressure Effects							
A. Projectile/missile damage	H	L	L	L	L	L	
B. Pressure wave	L	L	L	M	M	M	

Table B-8 Importance Ranking for Scenario 2, Internal Ensuing Fire

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
8. Internal Ensuing Fire							
F. Fire ignition	L	L	L	L	L	L	
G. Characterization of the fire source	L-H	L	L	L	L	L	P1 notes that the importance of characterizing the fire source depends on whether there is aluminum present.
H. Fire development	L	L	L	L	L	L	
I. Smoke generation	L	L	L	L	L	L	P5 raised the possibility that the duct behaves like a chimney and exhausts smoke in a different location. P6 states that in all known cases, the duct breeches, exhausted most of the smoke near the arc origin.
J. Altered ventilation effects	L	L	L	L	L	L	

Table B-9 Importance Ranking for Scenario 2, External Ensuing Fire

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
9. External Ensuing Fire							
A. Fire ignition from molten metal	M-H	L	L	L	L	L	Panelists note that secondary ignition due to molten metal has not been observed in testing. Transient combustibles may be more likely to ignite than fixed SSCs, and need to be considered on a situational basis.
B. Fire ignition from arc heat	H	M	M	M	M	H	
C. Characterization of the fire source	H	H	H	H	H	H	
D. Fire development	H	H	H	H	H	H	
E. Smoke generation	L	L	L	L	L	L	

Table B-10 Importance Ranking for Scenario 2, Room Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
10. Room Configuration Effects							
A. Room integrity	L	L	L	L	L	M	P5 notes that a HEAF occurring in a duct at the point where it penetrates a wall may bypass room integrity features.
B. Room arrangement	M	M	M	L	L	M	
C. Room ventilation	L	H	L	L	L	M	

Table B-11 Importance Ranking for Scenario 2, Arc Mitigation

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
11. Arc Mitigation							
A. Intentional shielding	H	H	H	H	H	H	
B. Electrical raceway fire barrier system	H	H	H	H	H	H	
C. Fire-retardant coating	M	M	H	H	H	H	
D. Cable tray design	M	M	M	M	M	M	

Table B-12 Importance Ranking for Scenario 2, Generic Enclosure (Target) Characterization

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
12. Generic Enclosure (Target) Characterization							
A. Characterizing target damage criteria	H	H	H	H	H	H	
B. Target arrangement effects	H	H	H	H	H	H	
C. Target sensitivity to damage	H	H	H	H	H	H	

B.4 Phenomena State of Knowledge Rankings

Table B-13 State of Knowledge Ranking for Scenario 2, Electrical Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
1. Electrical Configuration Effects				
A. Power supply characterization	H	H	N/A	
B. Electrical protection coordination	H	H	N/A	

Table B-14 State of Knowledge Ranking for Scenario 2, Internal Bus Duct Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
2. Internal Bus Duct Configuration Effects				
A. Duct compartmentation	M	M	M-H	
B. Duct combustible loading	H	H	N/A	
C. Duct bus bar configuration	M	M	M	

Table B-15 State of Knowledge Ranking for Scenario 2, External Bus Duct Housing Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
3. External Bus Duct Housing Configuration Effects				
A. Duct ventilation	L	H	N/A	P6 notes that any model for duct ventilation is likely useless, as the duct housing is breeched by the arc in all known cases.
B. Duct structural design	M	M	H	
C. Duct mounting	L	L	L	

Table B-16 State of Knowledge Ranking for Scenario 2, Arc Characterization

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
4. Arc Characterization				
A. Arc electrical characterization	M-H	H	N/A	
B. Arc migration	M-H	M-H	N/A	
C. Arc breeching of enclosure	L	L-M	L-M	Panelists note that the only data that exists is observational. No quality data set exists.
D. Thermal effects of the arc	M	M	M	
E. Magnetic effects of the arc	M-H	M-H	N/A	
F. Electromagnetic interference	L	L	M-H	
G. Arc ejecta	L	L	L	Panelists note again that only minimal observational data is available, and that is extremely difficult to separate the ejecta into its constituents.

Table B-17 State of Knowledge Ranking for Scenario 2, Fire Detection

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
5. Fire Detection				
A. Presence of fire detection	H	H	N/A	P2 notes that models for detection are good, but there is no specific data for HEAF conditions—the detectors may be destroyed.
B. Characterizing fire detection system	H	H	N/A	

Table B-18 State of Knowledge Ranking for Scenario 2, Fire Suppression

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
6. Fire Suppression				
A. Presence of fire suppression	H	H	N/A	
B. Fire suppression effects	M	M	H	

Table B-19 State of Knowledge Ranking for Scenario 2, Pressure Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
7. Pressure Effects				
A. Projectile/missile damage	M-H	M-H	N/A	P5 notes that predicting missile damage is not very difficult if the identity of the projectile is known. Identifying it is more challenging.
B. Pressure wave	H	H	N/A	

Table B-20 State of Knowledge Ranking for Scenario 2, Internal Ensuing Fire

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
8. Internal Ensuing Fire				
A. Fire ignition	M	L	M	
B. Characterization of the fire source	H	M-H	N/A	
C. Fire development	M-H	M	M-H	P6 notes that observational data indicates no fire development in bus ducts.
D. Smoke generation	M-H	M-H	N/A	
E. Altered ventilation effects	M-H	M-H	N/A	

Table B-21 State of Knowledge Ranking for Scenario 2, External Ensuing Fire

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
9. External Ensuing Fire				
A. Fire ignition from molten metal	M	M	H	
B. Fire ignition from arc heat	M	L-M	H	P1 notes that exposure time concerns make modeling less than adequate.
C. Characterization of the fire source	M	M-H	H	P1 notes that cabinets are complex fuel sources—characterization is not perfect.
D. Fire development	M	M-H	H	
E. Smoke generation	H	H	N/A	

Table B-22 State of Knowledge Ranking for Scenario 2, Room Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
10. Room Configuration Effects				
A. Room integrity	M	M	H	P1 and P6 note that there are some models for room integrity, but not specifically applicable to HEAF.
B. Room arrangement	H	H	N/A	
C. Room ventilation	H	H	N/A	

Table B-23 State of Knowledge Ranking for Scenario 2, Arc Mitigation

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
11. Arc Mitigation				
A. Intentional shielding	M	M	M-H	Panelists note that some small-scale experiments exist, and solid mechanics tools can possible be applied, but no directly applicable model currently exists.
B. Electrical raceway fire barrier system	M	M	H	
C. Fire-retardant coating	M	M	H	P4 notes that the original status of the cables should be considered—i.e. if the coating was applied as a remedial measure, this is important.
D. Cable tray design	M	M	H	

Table B-24 State of Knowledge Ranking for Scenario 2, Generic Enclosure (Target) Characterization

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
12. Generic Cable Tray (Target) Characterization				
A. Characterizing target damage criteria	M	M	H	
B. Target arrangement effects	M	M	H	
C. Target sensitivity to damage	L-M	L-M	M	Panelists noted models exist that can evaluate the effects of target sensitivity to a few items, but others are neglected entirely.

B.5 Phenomena Key Parameters Ranking

Table B-25 Key Parameters Ranking for Scenario 2, Electrical Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
1A. Power Supply Characterization								
1. Line Voltage	H	H	H	H	H	H	H	
2. Rated Current	H	H	H	H	M	H	H	
3. Short Circuit Current	H	H	H	H	H	H	H	
4. Frequency	L	L	L	L	L	L	H	
5. Grounded/Ungrounded	M	L	L	L	L	L	H	
6. MVA Available	H	H	H	H	H	H	H	

Table B-26 Key Parameters Ranking for Scenario 2, Internal Bus Duct Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
2A. Duct Compartmentation								
1. Dimensions	M	M	M	M	M	M	H	P6 notes that the dimensions of the duct aren't particularly important as the duct is likely to be breeched.
2. Internal Partitions	H	H	H	H	H	H	H	
2B. Duct Combustible Loading								
3. Combustible Mass	H	H	H	H	H	M	H	
4. Combustion Properties	H	H	H	H	H	M	H	
2C. Duct Bus Bar Configuration								
5. Bus Bar Spacing	H	H	H	H	H	H	H	
6. Bus Bar Material	H	H	H	H	H	H	H	
7. Bus Bar Insulation	M	M	M	M	M	M	L	
8. Bus Bar Orientation	M	M	M	M	M	M	H	
9. Bus Bar Cross-Sectional Area	M	L-M	M	M	M	M	H	P2 notes that cross-sectional area is not important for power supply, but can become important when considering bus bar oxidation.
10. Bus Bar Joints	H	H	H	H	H	H	H	Panelists ranked this high because the joints are the likely arc locations.
11. Bus Bar Mounting/Supports	L	L	L	L	L	L	H	

Table B-27 Key Parameters Ranking for Scenario 2, External Bus Duct Housing Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
3A. Duct Ventilation								
1. Ventilation Opening Area	H	H	H	H	H	H	H	
2. Ventilation Opening Location	M	M	M	M	M	M	H	
3B. Duct Structural Design								
3. Wall Material	H	H	H	H	H	H	H	
4. Wall Thickness	H	H	H	H	H	H	H	
5. Access Ports	M	M	M	M	M	M	H	
3C. Duct Mounting								
6. Robustness	H	L	L	M	L	L	L	
7. Orientation	H	H	H	M	H	H	H	

Table B-28 Key Parameters Ranking for Scenario 2, Arc Characterization

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
4A. Arc Electrical Characterization								
1. Arc Voltage	H	H	H	H	H	H	M	
2. Arc Current (Asymmetric)	L	H	H	H	L	H	H	
3. Arc Current (RMS)	H	H	H	H	H	H	H	
4. Arc Energy	H	H	H	H	H	H	M-H	
5. Arc Duration	H	H	H	H	H	H	M	
6. Arc Location	M	L	L	L	L	L	L	
4B. Arc Migration								
7. Arc Migration Speed	H	H	H	H	H	H	M-H	
8. Type (Ionized Gas/Magnetic Field)	U	H	H	H	H	H	L-M	
4D. Thermal Effects of the Arc								
9. Arc Heat Flux	H	H	H	H	H	H	M	
10. Bus Bar Melting	H	H	H	H	H	H	M	
11. Oxidation of Adjacent Materials	H	H	H	H	H	H	L	
4G. Arc Ejecta								
12. Ionized Gas	L	H	H	H	H	H	L	
13. Smoke	L	L	L	L	L	L	L	
14. Conductive Particulate	H	H	H	H	H	H	L	

Table B-29 Key Parameters Ranking for Scenario 2, Fire Detection

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
5B. Detection Characteristics								
1. Detector Type (Heat/smoke/optical)	H	H	H	H	H	H	H	

Table B-30 Key Parameters Ranking for Scenario 2, Fire Suppression

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
6A. Presence of Fire Suppression								
1. Proximity	H	H	H	H	H	H	H	
6B. Characterizing the Suppression System								
2. Actuation (Manual/Automatic)	H	M	M	M	M	M	H	
3. Survivability	M	H	H	H	H	H	L	
4. Suppression Type	M	H	H	H	H	H	M-H	

Table B-31 Key Parameters Ranking for Scenario 2, Pressure Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
7B. Pressure Wave								
1. Magnitude	H	H	H	H	H	H	M-H	
2. Propagation		H	H	H	H	H	H M	

Table B-32 Key Parameters Ranking for Scenario 2, Internal Ensuing Fire

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
8A. Fire Ignition								
1. Internal Duct Temperature	H	H	H	H	H	H	L-M	
8B. Characterization of Fire Source								
2. Heat Release Rate	H	H	H	H	H	H	M-H	
3. Heat Release Rate per unit Area	M	M	M	M	M	L	M	
8C. Fire Development								
4. Time to Peak	H	H	H	H	H	H	M-H	
5. Fire Growth Rate	H	H	H	H	H	H	M-H	
8E. Altered Ventilation Effects								
6. Altered Duct Vent Properties	M	H	M	M	M	M	M	

Table B-33 Key Parameters Ranking for Scenario 2, External Ensuing Fire

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
9B. Characterization of Fire Source								
1. Heat Release Rate	H	H	H	H	H	H	H	
2. Heat Release Rate per unit Area	M	M	M	M	M	M	M-H	
3. Fire Geometry	L	M	M	L	H	M	M-H	
9C. Fire Development								
4. Time to Peak	H	H	H	H	H	H	M-H	
5. Fire Growth Rate	H	H	H	H	H	H	M-H	

Table B-34 Key Parameters Ranking for Scenario 2, Room Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
10A. Room Integrity								
1. Fire Dampers	M	L	L	L	L	L	L-M	
2. Penetrations	M	L	L	L	L	L	L-M	
10B. Room Arrangement								
3. Dimensions	M	M	M	M	M	M	H	
4. Contents	H	M	L	M	L	L	H	
5. Construction Material	L	M	M	M	M	M	H	
6. Location of Source within Room	L	M	L	L	L	L	M-H	
10C. Room Ventilation								
7. Type (Active/Passive)	H	H	H	H	H	H	M-H	

Table B-35 Key Parameters Ranking for Scenario 2, Arc Mitigation

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
11A. Intentional Shielding								
1. Thickness	H	H	H	H	H	H	H	
2. Material	H	H	H	H	H	H	H	
11B. Electrical Raceway Fire Barrier System								
3. Rating	U	U	U	U	U	U	H	
11C. Fire-Retardant Coating Effects								
4. Thickness	H	H	H	H	H	H	M	
5. Material	H	H	H	H	H	H	H	
6. Age	L	U	U	U	U	L	M-H	

Table B-36 Key Parameters Ranking for Scenario 2, Generic Enclosure (Target) Characterization

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
12A. Target Damage								
1. Damage Criteria	H	H	H	H	H	H	M	
2. Critical Heat Flux	H	H	H	H	H	H	M	
3. Critical Temperature	H	H	H	H	H	H	M	
4. Exposure Time	H	H	H	H	H	H	M	
12B. Target Arrangement Effects								
5. Distance to HEAF Source	H	H	H	H	H	H	M-H	
6. Orientation Relative to HEAF Source	H	H	H	M	H	M	M-H	
12C. Target Sensitivity								
7. Sensitivity to Shock	M	M/H	M	H	M-H	M	M	
8. Sensitivity to Heat	H	H	H	H	H	H	M-H	
9. Sensitivity to EMI/RFI	M	M	M	M	U	M	L-M	
10. Sensitivity to Light	L	L	L	L	L	L	L-M	
11. Sensitivity to Ionized Gas	L	L/H	L/H	L	L/H	L/M	M	The split responses indicate differences depending on whether the target considered is the cable tray or the cabinet itself.
12. Sensitivity to Conductive Particulate	L/M	L/H	L/H	L	L/H	L/M	M	The split responses indicate differences depending on whether the target considered is the cable tray or the cabinet itself.
13. Sensitivity to Smoke	H	L	L	L	L	L	L-M	

B.6 Scenario 2 Phenomena Calculated Rank Values and Grouping

Table B-37 Summary of Scenario 2 Average Rankings and Grouping

Phenomenon	Importance	State of Knowledge	Rank	Grouping
Target Characterization (12)	5	3.1	1.61	Level 1
Arc Characterization (4)	3.3	2.6	1.27	Level 1
Arc Mitigation (11)	4.3	3.6	1.19	Level 1
External Duct Housing Configuration Effects (3)	2.6	2.5	1.04	Level 1
Electrical Configuration Effects (1)	5	5	1.00	Level 2
External Ensuing Fire (9)	3.2	3.9	0.82	Level 2
Internal Bus Duct Configuration Effects (2)	2.6	3.6	0.72	Level 2
Room Configuration (10)	1.9	4.4	0.43	Level 2
Suppression Effects (6)	1.7	4.2	0.40	Level 3
Fire Detection (5)	2	5	0.40	Level 3
Pressure Effects (7)	1.8	4.5	0.40	Level 3
Internal Ensuing Fire (8)	1.1	3.6	0.31	Level 3

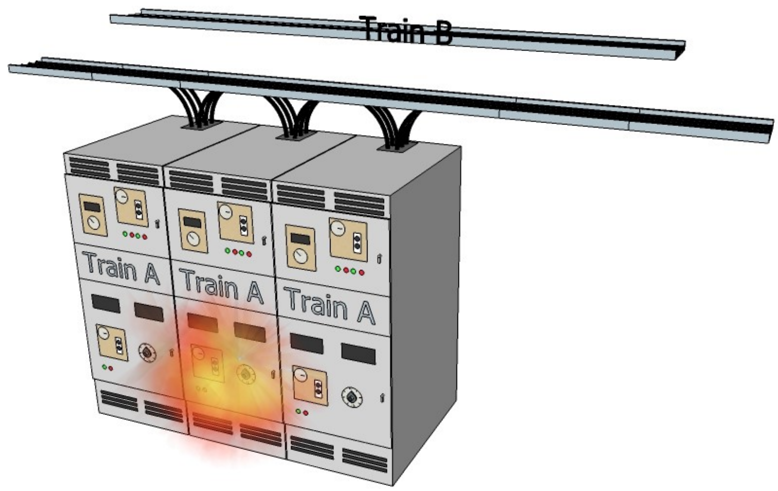
33rd percentile for Rank: 0.42

66th percentile for Rank: 1.01

APPENDIX C PIRT HEAF SCENARIO 3

C.1 HEAF Scenario 3

C.1.1 Scenario Description



A high energy arcing fault occurs in a low/medium voltage switchgear supplying power to “Train A” systems in a bank of similar switchgears. The cables from an overhead cable tray enter the cabinets from the top (air-drop configuration). A cable tray carrying cables that supply power to “Train B” systems is located nearby.

C.1.2 Figure of Merit

Determining the extent of damage to the adjacent switchgears and the cables in “Train B” cable tray.

C.2 List of Identified Phenomena

Phenomenon 1: Electrical Configuration Effects

A. Power supply characterization
B. Electrical protection coordination[18]

Phenomenon 2: Internal Cabinet Configuration Effects

A. Cabinet compartmentation
B. Breaker configuration

[18] Electrical protection coordination refers to the coordination and configuration of upstream breakers with the objective of minimizing the duration of an electrical fault

C. Cabinet combustible loading
D. Cabinet bus bar configuration

Phenomenon 3: External Cabinet Enclosure Configuration Effects

A. Cabinet ventilation
B. Cabinet structural design
C. Cabinet penetrations

Phenomenon 4: Cabinet Lineup Effects

A. Cabinet-cabinet barrier effects
B. Cabinet position within bank effects[19]
C. Cabinet-cabinet penetration effects

Phenomenon 5: Arc Characterization

A. Arc electrical characterization
B. Arc migration
C. Arc breeching of enclosure
D. Thermal effects of the arc
E. Magnetic effects of the arc[20]
F. Electromagnetic interference
G. Arc ejecta
H. Plasma characterization

Phenomenon 6: Fire Detection[21]

A. Presence of fire detection
B. Characterizing the detection system

Phenomenon 7: Fire Suppression

A. Presence of fire suppression
B. Characterizing the suppression system

[19] The effects of the cabinet position within the bank does not refer to the location of targets around the source cabinet. This refers to the manner in which the position (middle of the bank, end of the bank) affects the extent of damage to whatever targets are present.

[20] Magnetic effects refers to the applied forces on ferrous materials by a magnetic field that can induce bending and deformation, as opposed to the interference that it may cause. Interference is addressed separately.

[21] Fire detection was assumed not to automatically trigger fire suppression. Fire suppression is considered as a separate phenomenon.

Phenomenon 8: Pressure Effects

A. Projectile/missile damage
B. Pressure wave

Phenomenon 9: Internal Ensuring Fire[22]

A. Fire ignition
B. Characterization of the fire source
C. Fire development
D. Smoke generation
E. Altered ventilation effects[23]

Phenomenon 10: External Ensuing Fire

A. Fire ignition
B. Characterization of the fire source
C. Fire development
D. Cabinet-to-cabinet propagation
E. Smoke generation

Phenomenon 11: Room Configuration Effects

A. Room integrity[24]
B. Room arrangement
C. Room ventilation

Phenomenon 12: Arc Mitigation

A. Intentional shielding
B. Electrical raceway fire barrier system effects[25]
C. Fire-retardant coating effects[26]

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[22] Internal ensuing fire refers to a sustained fire that occurs inside the source cabinet.

[23] Altered ventilation effects refers to the manner in which changes to the cabinet's structure and integrity as a result of the HEAF impact the ventilation paths for an internal ensuing fire.

[24] Room integrity refers to the pressure boundary of the room in which the HEAF occurs, and how its response to the increased pressure will impact target damage. For example, consider whether blowing open a fire door or damper will affect target damage.

[25] Electrical raceway fire barrier systems refers to a wrap or enclosure that is installed around electrical cable trays with the intent of mitigating fire damage.

[26] Fire-retardant coating refers to a permanently installed coating or spray that is applied directly to the cables in a cable tray.

Phenomenon 13: Generic Enclosure (Target) Characterization

A. Characterizing target damage criteria
B. Target sensitivity to damage

Phenomenon 14: Generic Cable Tray (Target) Characterization

A. Characterizing target damage criteria
B. Target arrangement effects
C. Target sensitivity to damage

C.3 Phenomena Importance Rankings

Table C-1 Importance Ranking for Scenario 3, Electrical Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
1. Electrical Configuration Effects							
A. Power supply characterization	H	H	H	H	H	H	
B. Electrical protection coordination	H	H	H	H	H	H	

Table C-2 Importance Ranking for Scenario 3, Internal Cabinet Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
2. Internal Cabinet Configuration Effects							
A. Cabinet compartmentation	H	M	M	M	M	M	
B. Breaker configuration	M	M	M	M	M	M	
C. Cabinet combustible loading	H	H	H	H	H	H	
D. Cabinet bus bar configuration	M	M	M	H	M	M	

Table C-3 Importance Ranking for Scenario 3, External Cabinet Enclosure Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
3. External Cabinet Enclosure Configuration Effects							
A. Cabinet ventilation	M	M	M	M	H	M	
B. Cabinet structural design	H	M	M	M	M	L	
C. Cabinet penetrations	H	M	M	M	M	M	

Table C-4 Importance Ranking for Scenario 3, Cabinet Lineup Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
4. Cabinet Lineup Effects							
A. Cabinet-cabinet barrier effects	H	H	H	H	H	H	
B. Cabinet-position within bank effects	H	M	M	M	M	M	
C. Cabinet-cabinet penetration effects	H	H	H	H	H	H	

Table C-5 Importance Ranking for Scenario 3, Arc Characterization

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
5. Arc Characterization							
A. Arc electrical characterization	H	H	H	H	H	H	
B. Arc migration	H	M	M	M	M	M	P6 notes that the migration of the arc in this scenario is more important than scenarios 1 & 2.
C. Arc breeching of enclosure	H	H	H	H	H	H	P5 notes that arc breeching in a cabinet lineup increases the probability of a secondary arc in an adjacent cabinet.
D. Thermal effects of the arc	H	H	H	H	H	H	
E. Magnetic effects of the arc	L	M	M	H	U	M	
F. Electromagnetic interference	H	L	L	H	L	L	P4 notes that digital upgrades have increased equipment susceptibility to EMI/RFI.
G. Arc ejecta	H	H	H	H	H	H	
H. Plasma characterization	M	M	M	M	M	M	P6 notes that the properties of the arc plasma is inherently tied to the characteristics of the arc, and as such, may not need to be considered separately.

Table C-6 Importance Ranking for Scenario 3, Fire Detection

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
6. Fire Detection							
A. Presence of fire detection	H	L	L	L	L	L	
B. Characterizing fire detection system	L	L	L	L	L	L	

Table C-7 Importance Ranking for Scenario 3, Fire Suppression

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
7. Fire Suppression							
A. Presence of fire suppression	M	M	M	M	M	M	P6 notes that there is in increased risk for fire spreading in a cabinet lineup.
B. Fire suppression effects	M	M	M	M	M	M	

Table C-8 Importance Ranking for Scenario 3, Pressure Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
8. Pressure Effects							
A. Projectile/missile damage	H	H	H	H	H	H	
B. Pressure wave	H	H	H	H	H	H	

Table C-9 Importance Ranking for Scenario 3, Internal Ensuing Fire

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
9. Internal Ensuing Fire							
A. Fire ignition	H	H	H	H	H	H	
B. Characterization of the fire source	H	H	H	H	H	H	
C. Fire development	H	H	H	H	H	H	
D. Smoke generation	H	L	L	L	L	L	
E. Altered ventilation effects	H	H	H	H	H	H	

Table C-10 Importance Ranking for Scenario 3, External Ensuing Fire

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
10. External Ensuing Fire							
A. Fire ignition	L-H	H	H	H	H	H	P1 notes that this depends highly on the type of target cabinets in the lineup.
B. Characterization of the fire source	H	H	H	H	H	H	
C. Fire development	H	H	H	H	H	H	
D. Cabinet-cabinet propagation	H	H	H	H	H	H	Panelists note that this is the singularly outstanding risk in this scenario, and rate this phenomenon of the highest priority.
E. Smoke generation	L	L	L	L	L	L	

Table C-11 Importance Ranking for Scenario 3, Room Configuration Effects

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
11. Room Configuration Effects							
A. Room integrity	M	M	L	L	M	M	P2 notes that this is more important for the cable tray target.
B. Room arrangement	M	M	M	M	M	M	
C. Room ventilation	L	H	M	M	M	M	

Table C-12 Importance Ranking for Scenario 3, Arc Mitigation

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
12. Arc Mitigation							
A. Intentional shielding	H	M	H	H	H	H	
B. Electrical raceway fire barrier system	M	M	H	H	H	M	
C. Fire-retardant coating	L	M	M	M	M	L	

Table C-13 Importance Ranking for Scenario 3, Generic Enclosure (Target) Characterization

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
13. Generic Enclosure (Target) Characterization							
A. Characterizing target damage criteria	H	H	H	H	H	H	
B. Target sensitivity to damage	H	H	H	H	H	H	

Table C-14 Importance Ranking for Scenario 3, Generic Cable Tray (Target) Characterization

Phenomenon Description	Importance Ranking						Additional Notes & Comments
	P1	P2	P3	P4	P5	P6	
14. Generic Cable Tray (Target) Characterization							
A. Characterizing target damage criteria	H	H	H	H	H	H	
B. Target arrangement effects	M	H	H	H	H	H	
C. Target sensitivity to damage	H	H	H	H	H	H	

C.4 Phenomena State of Knowledge Rankings

Table C-15: State of Knowledge Rankings for Scenario 3, Electrical Configuration

Effects Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
1. Electrical Configuration Effects				
A. Power supply characterization	H	H	N/A	
B. Electrical protection coordination	H	H	N/A	

Table C-16 State of Knowledge Ranking for Scenario 3, Internal Cabinet Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
2. Internal Cabinet Configuration Effects				
A. Cabinet compartmentation	H	H	N/A	
B. Breaker configuration	M-H	M	H	
C. Cabinet combustible loading	M-H	M	M	
D. Cabinet bus bar configuration	M-H	M-H	N/A	

Table C-17 State of Knowledge Ranking for Scenario 3, External Cabinet Enclosure Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
3. External Cabinet Enclosure Configuration Effects				
A. Cabinet ventilation	M-H	M-H	N/A	
B. Cabinet structural design	M-H	M-H	N/A	
C. Cabinet penetrations	M-H	H	N/A	

Table C-18 State of Knowledge Ranking for Scenario 3, Cabinet Lineup Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
4. Cabinet Lineup Effects				
A. Cabinet-cabinet barrier effects	M	M	M-H	
B. Cabinet-cabinet penetration effects	M	M	M-H	
C. Cabinet position within bank effects	M	M-H	N/A	

Table C-19 State of Knowledge Ranking for Scenario 3, Arc Characterization

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
5. Arc Characterization				
A. Arc electrical characterization	L-M	M	M	
B. Arc migration	M	L-M	L-M	
C. Arc breeching of enclosure	L	L	L	
D. Thermal effects of the arc	M	M	M-H	
E. Magnetic effects of the arc	L-M	L-M	M	
F. Electromagnetic interference	L	L	L-M	
G. Arc ejecta	L	L	L	
H. Plasma characterization	L-M	L-M	M	

Table C-20 State of Knowledge Ranking for Scenario 3, Fire Detection

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
6. Fire Detection				
A. Presence of fire detection	H	H	N/A	
B. Characterizing fire detection system	H	H	N/A	

Table C-21 State of Knowledge Ranking for Scenario 3, Fire Suppression

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
7. Fire Suppression				
A. Presence of fire suppression	H	H	N/A	
B. Fire suppression effects	M-H	M-H	N/A	

Table C-22 State of Knowledge Ranking for Scenario 3, Pressure Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
8. Pressure Effects				
A. Projectile/missile damage	M	L-M	L-M	
B. Pressure wave	M-H	M-H	N/A	

Table C-23 State of Knowledge Ranking for Scenario 3, Internal Ensuing Fire

Phenomenon Description	State of Knowledge Ranking: Model Adequacy	State of Knowledge Ranking: Data Availability	State of Knowledge Ranking: Ability to Collect New Data	Additional Notes & Comments
9. Internal Ensuing Fire				
A. Fire ignition	L	L	L-M	
B. Characterization of the fire source	H	M	M	
C. Fire development	M	M	M	
D. Smoke generation	M	L-M	M-H	
E. Altered ventilation effects	M	M	M	

Table C-24 State of Knowledge Ranking for Scenario 3, External Ensuing Fire

Phenomenon Description	State of Knowledge Ranking: Model Adequacy	State of Knowledge Ranking: Data Availability	State of Knowledge Ranking: Ability to Collect New Data	Additional Notes & Comments
10. External Ensuing Fire				
A. Fire ignition	L-M	L-M	M	
B. Characterization of the fire source	M-H	M-H	H	
C. Fire development	M	M	H	
D. Cabinet-to-cabinet propagation	L-M	L-M	M	
E. Smoke generation	M	L-M	M	

Table C-25 State of Knowledge Ranking for Scenario 3, Room Configuration Effects

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
11. Room Configuration Effects				
A. Room integrity	M	M	M-H	
B. Room arrangement	H	H	N/A	
C. Room ventilation	H	H	N/A	

Table C-26 State of Knowledge Ranking for Scenario 3, Arc Mitigation

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
12. Arc Mitigation				
A. Intentional shielding	L	L-M	M-H	
B. Electrical raceway fire barrier system	L-M	M	H	
C. Fire-retardant coating	L-M	M	H	

Table C-27 State of Knowledge Ranking for Scenario 3, Generic Enclosure (Target) Characterization

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
13. Generic Enclosure (Target) Characterization				
A. Characterizing target damage criteria	M	M	H	
B. Target arrangement effects	M	M	H	
C. Target sensitivity to damage	L-M	L-M	M	

Table C-28 State of Knowledge Ranking for Scenario 3, Generic Cable Tray (Target) Characterization

Phenomenon Description	State of Knowledge Ranking			Additional Notes & Comments
	Model Adequacy	Data Availability	Ability to Collect New Data	
14. Generic Cable Tray (Target) Characterization				
A. Characterizing target damage criteria	M	M	H	
B. Target arrangement effects	M	M	H	
C. Target sensitivity to damage	L-M	L-M	M	

C.5 Key Parameter Rankings

Table C-29 Key Parameters Ranking for Scenario 3, Electrical Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
1A. Power Supply Characterization								
1. Line Voltage	H	H	H	H	H	H	H	
2. Rated Current	H	H	H	H	M	H	H	
3. Short Circuit Current	H	H	H	H	H	H	H	
4. Frequency	L	L	L	L	L	L	H	
5. Grounded/Ungrounded	U	H	M	L	L	L	H	
6. Number of Phases	L	L	L	L	L	L	H	
7. MVA Available	H	H	H	H	H	L	H	

Table C-30 Key Parameters Ranking for Scenario 3, Internal Cabinet Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
2A. Cabinet Compartmentation								
1. Dimensions	H	H	H	M	H	H	H	
2. Internal Partitions	H	M	M	M	M	M	M-H	
2B. Breaker Configuration								
3. Arc Extinguishing Mechanism	L	L	L	L	L	L	H	
4. Breaker Combustible Load	H	H	M	H	H	H	H	
5. Extinguishing Medium	L	L	M	L	M	L	H	
6. Breaker Connection Material	M	M	M	H	H	H	H	
2C. Cabinet Combustible Loading								
7. Combustible Mass	H	H	M	H	H	H	M	
8. Bundle Tightness	H	M	M	M	M	H	M	
9. Thermoset/Thermoplastic	H	H	M	H	M	H	M-H	
10. Jacketed/Unjacketed	H	H	H	H	M	H	M-H	
11. Combustion Properties	H	H	H	H	H	H	M	
2D. Cabinet Bus Bar Configuration								
12. Bus Bar Spacing	H	H	H	H	H	H	H	
13. Bus Bar Material	H	H	H	H	H	M	H	
14. Number of Bus Bars per Phase	M	M	L	M	M	L	M-H	
15. Bus Bar Insulation	M	M	M	M	M	M	M-H	
16. Bus Bar Orientation	L	M	M	M	M	U	H	
17. Bus Bar Cross-Sectional Area	M	M	L	M	L	L	H	
18. Bus Bar Mounting/Supports	L	L	M	L	L	H	H	

Table C-31 Key Parameters Ranking for Scenario 3, External Cabinet Enclosure Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
3A. Cabinet Ventilation								
1. Active/Passive Ventilation	H	H	H	H	H	H	H	
2. Ventilation Opening Area	H	H	H	H	H	H	H	
3. Ventilation Deflection	L	L	M	M	M	L	M-H	
4. Ventilation Opening Location	L	M	H	M	H	H	M-H	
5. Presence of Active Louvres	U	U	U	U	U	L	H	
3B. Cabinet Structural Design								
6. Wall Material	M	H	H	H	L	H	H	
7. Wall Thickness	H	M	M	H	M	M	H	
8. Door Latch Type	M	M	M	M	M	M	H	
9. Door Gasketing	M	M	M	M	M	M	H	
10. Wall Fastening (welded, bolted, riveted)	L	M	L	M	M	L	H	
11. Single/Double Wall	H	M	M	M	M	M	H	
3C. Cabinet Penetrations								
12. Location of Penetrations	H	H	M	H	M	H	H	
13. Penetration Sealing	H	M	M	H	M	M	H	
14. Penetration Type (Compression, conduit, raceway)	L	L	M	M	M	L	H	
15. Viewing Ports/Mechanical Openings	H	U	M	H	M	M	H	

Table C-32 Key Parameters Ranking for Scenario 3, Cabinet Lineup Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
4A. Cabinet-Cabinet Barrier Effects								
1. Walls (None/Single/Double)	H	H	H	H	H	H	M-H	
2. Air Gap	M-H	M-H	M-H	U	M-H	M	L-M	
4B. Cabinet Position Within Bank Effects								
3. Middle/End	H	H	H	H	H	H	M-H	
4C. Cabinet-Cabinet Penetration Effects								
4. Bus Bar Penetrations	H	H	H	H	H	H	M-H	
5. Cable Penetrations	H	H	H	H	H	H	M-H	
6. False Floor	H	H	H	L	H	H	M	

Table C-33 Key Parameters Ranking for Scenario 3, Arc Characterization

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
5A. Arc Electrical Characterization								
1. Arc Voltage	H	H	H	H	H	H	M	
2. Arc Current (Asymmetric)	H	H	H	H	L	H	H	
3. Arc Current (RMS)	H	H	H	H	H	H	H	
4. Arc Energy	H	H	H	H	H	H	M	
5. Arc Duration	H	H	H	H	H	H	M	
6. Arc Location	H	M	M	M	H	M	L	
5B. Arc Migration								
7. Arc Migration Speed	U	M	M	H	M	L	M-H	
8. Type (Ionized Gas/Magnetic Field)	U	H	M	H	M	M	L	
5D. Thermal Effects of the Arc								
9. Arc Heat Flux	H	H	H	H	H	H	M	
10. Bus Bar Melting	H	H	H	H	H	H	M-H	
11. Oxidation of Adjacent Materials	H	H	H	H	H	H	L	
5G. Arc Ejecta								
12. Ionized Gas	M	H	H	H	H	H	L	
13. Smoke	M	L	M	L	M	L	L	
14. Conductive Particulate	H	H	H	H	M	H	L	

Table C-34 Key Parameters Ranking for Scenario 3, Fire Detection

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
6A. Presence of Fire Detection								
1. Detector Location	H	H	H	M	H	M	H	
6B. Detection Characteristics								
2. Detector Type (Heat/smoke/optical)	M	M	M	M	M	M	H	

Table C-35 Key Parameters Ranking for Scenario 3, Fire Suppression

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
7A. Presence of Fire Suppression								
1. Internal/External	M	M	M	M	M	M	M-H	
2. Proximity	H	H	H	H	H	H	M-H	
7B. Characterizing the Suppression System								
3. Actuation (Manual/Automatic)	M	M	M	M	M	M	H	
4. Survivability	X	H	M	M	X	M	L	
5. Suppression Type	M	H	H	H	H	H	M-H	

Table C-36 Key Parameters Ranking for Scenario 3, Pressure Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
8B. Pressure Wave								
1. Magnitude	H	H	H	H	H	H	M-H	
2. Propagation	H	H	H	H	H	M	M	

Table C-37 Key Parameters Ranking for Scenario 3, Internal Ensuing Fire

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
9A. Fire Ignition								
1. Internal Cabinet Temperature	H	H	H	H	H	H	L	
9B. Characterization of Fire Source								
2. Heat Release Rate	H	H	H	H	H	H	M-H	
3. Heat Release Rate per unit Area	M	L	M	M	M	M	M	
9C. Fire Development								
4. Time to Peak	M	M	M	M	M	M	M-H	
5. Fire Growth Rate	H	H	H	H	H	H	M-H	
9E. Altered Ventilation Effects								
6. Altered Internal Vent Properties	H	H	H	H	H	H	M	
7. Altered Enclosure Vent Properties	H	H	H	H	H	H	M	

Table C-38 Key Parameters Ranking for Scenario 3, External Ensuing Fire

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
10B. Characterization of Fire Source								
1. Heat Release Rate	H	H	H	H	H	H	M-H	
2. Heat Release Rate per unit Area	M	L	M	M	M	M	M-H	
3. Fire Geometry	H	H	H	H	H	H	H	
10C. Fire Development								
4. Time to Peak	M	M	M	M	M	M	H	
5. Fire Growth Rate	H	H	H	H	H	H	H	

Table C-39 Key Parameters Ranking for Scenario 3, Room Configuration Effects

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
11A. Room Integrity								
1. Fire Dampers	H	H	H	H	H	H	L-M	
2. Penetrations	H	H	H	H	H	H	L-M	
11B. Room Arrangement								
3. Dimensions	H	H	H	H	H	H	H	
4. Contents	M	H	H	H	H	H	H	
5. Construction Material	M	M	M	M	M	M	H	
11C. Room Ventilation								
6. Type (Active/Passive)	H	H	H	H	H	H	H	

Table C-40 Key Parameters Ranking for Scenario 3, Arc Mitigation

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
12A. Intentional Shielding								
1. Thickness	H	M	H	H	H	H	H	
2. Material	H	H	H	H	H	H	H	
12B. Electrical Raceway Fire Barrier System								
3. Rating	U	U	U	U	U	U	H	
12C. Fire-Retardant Coating Effects								
4. Thickness	U	U	U	H	H	U	M	
5. Material	L	U	U	H	H	H	H	
6. Age	L	U	U	U	H	U	H	

Table C-41 Key Parameters Ranking for Scenario 3, Generic Enclosure (Target) Characterization

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
13A. Target Damage								
1. Damage Criteria	H	H	H	H	H	H	M	
2. Critical Heat Flux	H	H	H	H	H	H	M	
3. Critical Temperature	H	H	H	H	H	H	M	
4. Exposure Time	H	H	H	H	H	H	M	
13C. Target Sensitivity								
5. Sensitivity to Shock	L	H	H	H	H	H	M	
6. Sensitivity to Heat	H	H	H	H	H	H	M-H	
7. Sensitivity to EMI/RFI	H	H	H	H	U	H	L-M	
8. Sensitivity to Light	L	L	L	L	L	L	L-M	
9. Sensitivity to Ionized Gas	L	H	H	H	H	H	M	
10. Sensitivity to Conductive Particulate	H	H	H	H	H	H	L-M	
11. Sensitivity to Smoke	L-H	L	L	L	L	L	M	

Table C-42 Key Parameters Ranking for Scenario 3, Generic Cable Tray (Target) Characterization

Parameters	Importance Ranking						State of Knowledge	Additional Notes & Comments
	P1	P2	P3	P4	P5	P6		
14A. Target Damage								
1. Damage Criteria	H	H	H	H	H	H	M	
2. Critical Heat Flux	H	H	H	H	H	H	M	
3. Critical Temperature	H	H	H	H	H	H	M	
4. Exposure Time	H	H	H	H	H	H	M	
14B. Target Arrangement Effects								
5. Distance to HEAF Source	H	H	H	H	H	H	H	
6. Orientation Relative to HEAF Source	H	H	H	H	H	H	H	
14C. Target Sensitivity								
7. Sensitivity to Shock	M	M	H	M	M	M	M	
8. Sensitivity to Heat	H	H	H	H	H	H	M-H	
9. Sensitivity to EMI/RFI	H	U	U	L	U	L	M	
10. Sensitivity to Light	L	L	L	L	L	L	M	
11. Sensitivity to Ionized Gas	L	M	M	L	M	M	M	
12. Sensitivity to Conductive Particulate	H	L	L	L	L	L	M	
13. Sensitivity to Smoke	H	L	L	L	L	L	M	

C.6 Scenario 3 Phenomena Calculated Rank Values and Grouping

Table C-43 Summary of Scenario 3 Average Rankings and Grouping

Phenomenon	Importance	State of Knowledge	Rank	Grouping
Arc Characterization (5)	4	2	2.00	Level 1
Pressure Effects (8)	5	3	1.67	Level 1
Enclosure (Target) Characterization (13)	5	3.2	1.56	Level 1
Internal Ensuing Fire (9)	4.3	2.8	1.54	Level 1
Cable Tray (Target) Characterization (14)	4.9	3.2	1.53	Level 1
External Ensuing Fire (10)	4.1	3.1	1.32	Level 2
Cabinet Lineup Effects (3)	4.4	3.4	1.29	Level 2
Arc Mitigation (12)	3.7	3	1.23	Level 2
Electrical Configuration (1)	5	5	1.00	Level 2
Internal Cabinet Configuration (2)	3.7	4	0.93	Level 3
External Enclosure Configuration (3)	3.2	4.2	0.76	Level 3
Suppression Effects (7)	3	4.5	0.67	Level 3
Room Configuration (10)	2.8	4.3	0.65	Level 3
Fire Detection (6)	1.3	5	0.26	Level 3

33rd percentile for Rank: 0.95

66th percentile for Rank: 1.44

APPENDIX D PANELIST RÉSUMÉS

CURRICULUM VITAE

Name Hajime Kabashima

Address Division of Research for Reactor System Safety,
Regulatory Standard and Research Department,
Secretariat of Nuclear Regulation Authority (S/NRA/R),
1-9-9 Roppongi, Minato-ku, Tokyo, Japan 106-8450
E-Mail: hajime_kabashima@nsr.go.jp

Date of Birth June 16, 1970

Marital Status Married, One child

Education

1995-1998 Ph.D. Engineering, Molecular Chemistry, Hokkaido University, Sapporo, Japan

1993-1995 M. Environmental Earth Science, Materials Science, Hokkaido University, Sapporo, Japan

Professional experience

2015-Present Chief Researcher, Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority (S/NRA/R), Tokyo, Japan

2014-2015 Researcher, Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority (S/NRA/R), Tokyo, Japan

2012-2014 Senior Researcher, Japan Nuclear Energy Safety Organization (JNES), Tokyo, Japan

2003-2012 Researcher, Honda R&D Co., Ltd., Tochigi, Japan

2001-2003 NEDO* Research Fellow, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan

2000-2001 NEDO* Research Fellow, National Institute for Resources and Environment (NIRE), Tsukuba, Japan

1998-2000 Researcher, Center for Advanced Research of Energy Technology, Hokkaido University, Sapporo, Japan

*New Energy and Industrial Technology Development Organization of Japan (NEDO)

Awards

2003 *IEEE-IAS* Prize Paper Award (Honorable Mention)

2004 *IEEE-IAS* Innovation and Creativity Prize Paper Award

2004 *ELSEVIER* Top Cited Article Award for CATALYSIS TODAY

RESUME

PERSONAL DATA

FAMILY NAME(s) :	FIRST NAME(s) :	SEX	Date of Information
Lee	Sangkyu	M	Jan. 19 2017

Private address :	Office/Mailing address :
Gyeongnam honorsville. 201-203 Yongsan-dong Yuseong-gu Daejeon, Korea	62 Gwahak-ro, Yuseong-gu, Daejeon, Korea, 305-600 Telephone : 82-42-868-0521 FAX. No. : 82-42-861-9945

Date of Birth	Place of Birth (Town/City/Country)	Nationality :	Marital Status :
June 2, 1973	Korea	Korea	Married

Name and address of person to notify in case of emergency :	Relationship :
Mr. Joo-Seong Kim, 62 Gwahak-ro, Yuseong-gu, Daejeon, Korea, 305-600 +82-42-868-0769	Colleague

EDUCATION

Years attended		Name and place of Institution	Field of study	Diploma or degree
from	to			
1995. 3	1997. 2	Graduate School of Kookmin Univ.	Mechanical Eng.	M.S.
1991. 3	1995. 2	Kookmin Univ.	Mechanical Eng.	B.S.

RECENT EMPLOYMENT RECORD

Years attended		Name and place of employer/organization	Title of position	Department of Work
from	to			
2011.9	present	Korea Institute of Nuclear Safety	Principle Researcher	• Safety Review and Regulatory Inspection (Reactor System Performance Department) • Conduction of R&D Project for Fire Protection System as Project Manager
2002.9	2012.8	Korea Institute of Nuclear Safety	Senior Researcher	
1997.8	2002.8	Korea Institute of Nuclear Safety	Researcher	

ORGANIZATION MEMBERSHIP

Name and Address of Organization	Title of position	Duration of Member/Fellow

Nicholas B. Melly
U.S. Nuclear Regulatory Commission
Office of Research; Division of Risk Analysis;
Fire and External Hazards Analysis Branch

EDUCATION

B.S., Fire Protection Engineer, University of Maryland, 2008

EXPERIENCE

U.S. Nuclear Regulatory Commission - Rockville, MD January 2010- Present Fire Protection Engineer

- Chair Person of the High Energy Arcing Fault (HEAF) Task Group
- Lead project engineer for HEAF test program and author of "Report on the Testing Phase (2014-2016) of the High Energy Arcing Fault Events (HEAF) Project Experimental Results from the International Energy Arcing Fault Research Programme"
- Instructor of Module 2 NUREG/CR-6850 Fire PRA training related to Sections 2, 4, 5, 7, 14, and 15
- Project engineer for NUREG-2169, "Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability Estimation Using the Updated Fire Events Database: United States Fire Event Experience Through 2009"
- NRC Representative for the International OECD Fire Events Database Task Group

U.S. Nuclear Regulatory Commission - Rockville, MD July 2009 - December 2011 NSPDP General Engineer

- Graduate of Nuclear Safety Professional Development Program (NSPDP) 2011
- Rotational assignment to Region III; Component Design Bases Inspection at the Duane Arnold Nuclear Power Plant (NPP) and Triennial Fire Protection Inspection at the Byron NPP
- Rotational assignment to Sandia National Laboratories
- Rotational assignment to Division of Risk Analysis (DRA) Probabilistic Risk Assessment Branch (PRAB) working with the Standardized Plant Analysis Risk (SPAR) Model Program to develop standardized risk analysis models and tools for staff analysts to support various fire protection regulatory activities

Jacobs Engineering Group Inc. - Conshohocken, PA December 2008 – July 2009 Fire Protection Engineer

- System hydraulic analysis
- Probabilistic risk assessment and heat transfer analysis
- Fluid dynamics simulator (FDS) evaluation

Triad Fire Protection - Springfield, PA May 2008 – December 2008 Fire Protection Engineer

- Smoke detection system design
- Fire Protection Systems Hydraulic network analysis
- Nuclear Power Plant Fire Pre-Plan documentation upgrade

PUBLICATIONS

1. NUREG-2169, "Nuclear Power Plant Fire Ignition Frequency and Non- Suppression Probability Estimation Using the Updated Fire Events Database: United States Fire Event Experience Through 2009"
2. NUREG-2128, "Electrical Cable Test Results and Analysis During Fire Exposure (ELECTRA-FIRE), A Consolidation of Three Major Fire-Induced Circuit Cable Failure Experiments Performed Between 2001 and 2011
3. Enhancements in the OECD FIRE Database - Fire Frequencies and Severity of Events, W. Werner, R. Bertrand, A. Huerta, J. S. Hyslop, N. Melly, and M. Röwekamp, Proceedings of SMiRT 21, 12th International Seminar on Fire Safety in Nuclear Power Plants and Installations, München, Germany
4. Incorporation of NFPA-805 Internal Fire Scenarios into SPAR all Hazard Models S. Sancaktar, F. Ferrante, N. Melly U.S. Nuclear Regulatory Commission, Washington DC, USA 20555-0001, 2011
5. OECD FIRE Database Applications and Challenges – A Recent Perspective, Marina Roewekamp, Matti Lehto, Heinz-Peter Berg, Nicholas Melly, Wolfgang Werner Paper presented at OECD/NEA/CSNI/WGRISK International Workshop on Fire PRA, Garching, Germany
6. Expert Judgment: An Application in Fire-Induced Circuit Analysis, Gabriel Taylor P.E., Nicholas Melly, Tammie Pennywell, Paper presented at OECD/NEA/CSNI/WGRISK International Workshop on Fire PRA, Garching, Germany
7. U.S. NRC Fire Safety Research Activities, N. Melly, G. Taylor, and D. Stroup Paper presented at OECD/NEA/CSNI/WGRISK International Workshop on Fire PRA Garching, Germany
8. Siu N.O., Melly N., Nowlen S.P., Kazarians M. (2016) Fire Risk Analysis for Nuclear Power Plants. In: Hurley M.J. et al. (eds) SFPE Handbook of Fire Protection Engineering. Springer, New York, NY, ADAMS ML14084A314

CURRICULUM VITAE

Dr. Marina Roewekamp

Senior Chief Expert for Hazards
Reactor Safety Analyses Division
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
Schwertnergasse 1
50667 Köln
GERMANY

Phone: +49-(0)221-2068-898
Fax: +49-(0)221-2068-10898
E-mail: Marina.Roewekamp@grs.de

Education:

- Diploma in Experimental Physics from Rheinische Friedrich-Wilhelms-University Bonn, Germany

- Doctoral degree (PhD, Dr. rer. nat.) in Physical Chemistry from Rheinische Friedrich-Wilhelms-University Bonn, Germany

Technical skills in the field:

- Deterministic analysis and assessment of internal and external hazards for different types of nuclear installations, in particular for fires and explosions including fire hazards analysis (FHA)and fire modeling

- Probabilistic risk assessment of hazards, in particular fire, explosion, and flooding PRA

- Evaluation of NPP operational experience with respect to fire safety issues including reliability data for fire protection systems and equipment

Professional experience

- Since 1988: employed by GRS gGmbH

- Present position:
  Senior Chief Expert for Internal and External Hazards including PRA, Key Project Leader

Specific experience in the field:

- Member of different expert groups drafting and revising IAEA standards and Guidelines in the field of internal and external hazards including PRA

- Chair of German nuclear standards group KTA 2101 “Fire Safety in Nuclear Power Plants”
- Member of GRS experts groups supporting the Dutch authorities in reviewing periodic safety review (PSR) for existing NPP and the PSAR (preliminary safety analysis report) for new reactors
- Chair on Project Leader for Review of Internal Hazards Approach within GDA process for new reactors supporting the United Kingdom regulatory body ONR
- Chair of Project Review Group (PRG) and National Coordinator of OECD/NEA Database Project “OECD FIRE” for Phase 1 to 5
- Chair of OECD/NEA “PRISME”, “PRISME 2” and “PRISME 3” experimental projects Program Review Groups (PRG)
- German member of OECD/NEA/CSNI Task Group on “High Energy Arcing Faults (HEAF)” and OECD/NEA experimental project “HEAF”
- Member of German PSA experts committee (German: “Facharbeitskreis (FAK)“ PSA) responsible for developing guidelines on PSA methods and data (lead on
- Member of ESReDA experts group on “Fire Risk Analysis”
- Chair and German member of OECD/NEA/CSNI WGRISK
- Member of IAPSAM Board of Directors
- Member of international expert groups (mainly related to PSA) for EU TACIS projects RF/TS/15, UK/TS/27, HU/RA/3, UK/TS/36 (in 2011 on Khmelnitzky PSA)
- Member of an international TACIS expert group for supporting the Russian authority in writing a guideline for Fire PSA review
- Member of an IAEA expert group performing a seminar on “External Hazards PSA” for GUS and MOE state experts

Dr. Sylvain SUARD
Head of Fire Experimentation Laboratory
Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
PSN/RES/SA2I/LEF
Centre de Cadarache – Bât 346
13115 Saint-Paul-Lez-Durance Cedex
France
Phone: +(33) 4.42.19.92.65
E-mail: sylvain.suard@irsn.fr

Technical skills

- Fire modelling, numerical simulations and fire safety study,
- Fluid mechanics, energetic and numerical methods,
- Field (CFD) and zone models,
- Sensitivity analysis of fire safety models,
- Specification and validation of physical models in combustion, turbulence and heat transfer

General skills

- Management of an Experimental Laboratory
- Fire research with a fire field model (CFD code ISIS),
- Research management in the OECD/NEA PRISME project,
- Research management in the ETIC laboratory (joint laboratory IRSN/University of Provence)

Professional Experience

*2016 - : **Head of the Fire Experimental Laboratory at the French Nuclear Safety Institute (IRSN)***
Project Leader of the PRISME 2 and PRISME 3 OCDE programme

*2005-2015: **Fire safety Researcher at the French Nuclear Safety Institute (IRSN)***

- Fire research with the ISIS fire field model, development and validation of the code, Writing of the user guide, the physical modelling and the validation document,
  Comparison of field and zone fire models, sensitivity analysis
- OECD/NEA PRISME project (experimental research program conducted by IRSN):
  Specification of fire tests, Fire studies and researches within the Analytical Working Group,
  Technical presentations, Synthesizing the results for conferences and peer-reviewed journals

Education

2004: PhD degree in Combustion, Energetic and Thermal Sciences, mark: very honourable mention, University of Provence. Title: Theoretical study of pulsating spray flames

2000: DEA (Master 2) of Science in Fluids Dynamics and Energetic with distinction, Pierre et Marie Curie University – ENSAM Paris VI

Publications

First name publication

- **S. Suard**, A. Koched, H. Pretrel, L. Audouin, **2015**, Numerical simulations of fire-induced doorway flows in a small scale enclosure, **International Journal of Heat and Mass Transfer**

- **S. Suard**, S. Vaux, M. Forestier, **2013**, Toward predictive simulations of pool fires in mechanically ventilated compartments, **Fire Safety Journal.**

- **S. Suard**, S. Hostikka, J. Baccou, **2013**, Sensitivity analysis of fire models using a fractional factorial design, **Fire Safety Journal**

- **S. Suard**, C. Lapuerta, A. Kaiss, B. Porterie, **2013**, Sensitivity analysis of a fire field model in the case of a large-scale compartment fire scenario, **Numerical Heat Transfer, Part A: Applications**

- **S. Suard**, C. Lapuerta, F. Babik, Laurence Rigollet, **2011**, Verification and Validation of a CFD model for simulations of large-scale compartment fires , **Nuclear Engineering and Design**, Volume: 241, Issue: 9, Pages: 3645-3657.

- L. Audouin, L. Chandra, J-L Consalvi, L. Gay, E. Gorza, V. Hohm, S. Hostikka, T. Ito, W. Klein-Hessling, C. Lallemand, T. Magnusson, N. Noterman, J.S. Park, J. Peco, L. Rigollet, **S. Suard**, P. Van-Hees, **2011**, Quantifying differences between computational results and measurements in the case of a large-scale well-confined fire scenario, **Nuclear Engineering and Design**, Volume: 241, Issue: 1, Pages: 18-31.

- **S. Suard**, P. Haldenwang C. Nicoli, **2004**, Different spreading regimes of spray-flames, **Comptes Rendus Mécanique**, Volume 332, Issues 5-6, Pages 387-396.

Others

- H. Pretrel, **S. Suard**, L. Audouin, **2016**, Experimental and numerical study of low frequency oscillatory behaviour of a large-scale hydrocarbon pool fire in a mechanically ventilated compartment, in **Fire Safety Journal**

- Kacem, M. Mense, Y. Pizzo, G. Boyer, **S. Suard**, P. Boulet, G. Parent, B. Porterie, **2016**, in **Combustion and Flame**

- A. Nasr, **S. Suard**, H. El-Rabii, J.P. Garo, L. Gay, L. Rigollet, **2013**, Heat feedback to the fuel surface of a pool fire in an enclosure, **Fire Safety Journal**

APPENDIX E TECHNICAL EXPERT AND ADVISOR RÉSUMÉS

SCOTT BAREHAM

PHONE (301) 975-6567 EMAIL scott.bareham@nost.gov

MILITARY EXPERIENCE

Honorably retired from the United States Air Force after 20 years of distinguished service.

Performed duties as an F-16 Avionics System Specialist, Air Education and Training Command F-16 Avionics Master Instructor, C-17 Curriculum Manager, and C-141 and C-5 Training Manager.

Directed the use and repair of 56 Maintenance Trainers, valued at $33.8 million, by 59 instructors.

Team leader in development of two Avionics Maintenance Trainers valued at $20 million.

EDUCATION

Bachelor of Science in Electrical Engineering; University of Tennessee at Chattanooga, Chattanooga, Tennessee, 2009.

Passed the Fundamentals of Engineering Exam.

Bachelor of Science in Education; Valdosta State University, Valdosta, Georgia, 1997

WORK EXPERIENCE

National Institute for Standards and Technology (NIST) in the Fire Research Division.

Efforts supported the Nuclear Regulatory Commission's(NRC) Cable Heat Release, Ignition, and Spread in Tray Installations during Fire (CHRISTIFIRE). Designed and manufactured the vertical and horizontal test apparatuses. Wrote the test plan. Completed all safety documentation ensuring Federal and Maryland OSHA safety requirements were met. Performed bench scale and large scale tests. Analyzed resultant test data to determine behavior of burning electrical cables. Ref: NUREG/CR-7010 Volumes 1 & 2

Efforts supported NRCs Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE). Researched and assisted in the procurement of electrical enclosures. Assisted in writing the test plan. Completed safety documentation. Performed large scale tests. Analyzed resultant test data. Ref: NUREG/CR-7197

Efforts supported NRCs High Energy Arc Fault Events (HEAF). Supervised the shipment of electrical enclosures from several foreign nations. Assisted in designing and manufacturing prototype plate thermocouples. Assisted in designing, procuring, and developing a data acquisition system that was not adversely affected by electromagnetic interference. Assisted in designing and manufacturing a smoke and gas collection hood system used in oxygen depletion calorimetry. Collected and processed videos. Analyzed resultant test data determining the Heat Release Rate of arc ensuing fires, energy released by arc events, and other pertinent information relating to the arc events.

Kenneth A Hamburger – PIRT Facilitator
U.S. Nuclear Regulatory Commission
Office of Research, Division of Risk Analysis
Fire and External Hazards Analysis Branch

Education
M.S., Fire Protection Engineering, University of Maryland, 2013
Thesis: *Optimization and Implementation of a Thermoacoustic Flashover Detector*
B.S., Fire Protection Engineering, University of Maryland, 2012

Experience

U.S. Nuclear Regulatory Commission 2014- Present Fire Protection Engineer
- Graduate of the Nuclear Safety Professional Development (NSPDP) program.
- Completed the NRC's Pressurized Water Reactor (PWR) technology series courses.
- Completed the NRC's in-house facilitation program.
- Rotational assignments at Vogtle Electrical Generating Plant and Watts Bar Nuclear Generating Station.

Nat'l Institute of Standards and Technology 2015-Present Guest Researcher
- Assisted with the verification and validation of fluid dynamics models for fire scenario analysis.

University of Maryland 2012-2013 Graduate Assistant
- Performed original research in the area of thermodynamics, heat transfer, and fire dynamics. Co-author of scientific papers related to current issues in firefighting safety and technology.

RESUME

PERSONAL DATA			
Family Name(S) : Ko	First Name(S) : Heejin	Sex	Male
Private Address : 65, Sungdae-ro 12Gagil, Dongjak-gu, Seoul, 070497, Republic of Korea	Office/Mailing Address : KEPCO-E&C, 269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, 39660, Republic of Korea Email : heeklo@kepco-enc.com Tel : +82 54 421 6405		
Data of Birth (Month/Day/Year) 09/10/57	Place of Birth (Town/City/Country) Hoihyun/Jinhae-si/Korea	Nationality : KOREAN	Marital Status : Married
Name and Address of Person to notify in case of emergency : Minhee, Park, 65, Sungdae-ro 12Gagil, Dongjak-gu, Seoul, 070497, Republic of Korea			Relationship : Wife

EDUCATION/TRAINING

Years attended		Name and Place of Inst.	Field of Study	Diploma or Degree
From	To			
1976	1980	Hanyang Univ.	Nuclear Engineering	B.S.
1980	1987	Hanyang Univ.	Nuclear Engineering	M.S.
1987	1987	KEPCO	11th Nuclear System Course	
1988	1988	Sargent & Lundy (Chicago)	NUC-4 "Nuclear Analysis"	

RECENT EMPLOYMENT RECORD

Year attended		Name and Place of Employer/Organization	Title of Position	Type of Work
From	To			
1983	1992	Nuclear Engineering Department/KEPCO-E&C		Nuclear Engineer (Safety Analysis)
1993	2010	Nuclear Engineering Department/KEPCO-E&C	Group Supervisor	Nuclear Engineer (Severe Accident Analysis)
2010	2013	Nuclear Division/ KEPCO-E&C	Project Manager	APR+, EU-APR Projects
2014	Present	Power Engineering Research Institute/KEPCO-E&C	Chief of New Reactor Development RG	New Reactor Development (APR+, EU-APR, Passive Reactor, SFR, Passive Safety Systems)

R E S U M E

PERSONAL DATA

Family Name(S) : Lee	First Name(S) : Cheoung Joon	Sex	Male
Private Address : Sindong-a 401-1103, Dongjakdea-ro 29gil, Dongjak-gu, Seoul, 06998, Republic of Korea	Office/Mailing Address : KEPCO-E&C, 269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, 39660, Republic of Korea Email : trex@kepco-enc.com Tel : +82 54 421 7396		
Data of Birth (Month/Day/Year) 05/03/69	Place of Birth (Town/City/Country) Wanju-gun/Jellabuk-do/Korea	Nationality : KOREAN	Marital Status : Married
Name and Address of Person to notify in case of emergency : Mikyoung, Hong, Sindong-a 401-1103, Dongjakdea-ro 29gil, Dongjak-gu, Seoul, 06998, Republic of Korea			Relationship : Wife

EDUCATION/TRAINING

Years attended		Name and Place of Inst.	Field of Study	Diploma or Degree
From	To			
1987	1994	Chonbuk National Univ.	Electrical Engineering	B.S.
1994	1994	KEPCO Nuclear Training Center	Nuclear Theory & Operation	
2002	2002	KPEA Construction Management Training Center	Corse of Construction Management Professional	
2009	2009	Korea Institute of Plant Engineering & Construction	Corse of Professional Plant Engineering	

RECENT EMPLOYMENT RECORD

Year attended		Name and Place of Employer/Organization	Title of Position	Type of Work
From	To			
1994	1996	Start-up Operation Department/KEPCO	Employee	Reactor Operator (RO)
1996	2012	Electrical Engineering Department/KEPCO-E&C	Engineer	Electrical Engineer (UCN5,6, SKN 1~4, O&M, ITER, LIRWD facility, SHN1,2 Projects)
2012	2014	Electrical Engineering Department/ KEPCO-E&C	Functional Group Leader	SWN1,2, SKN3,4, SHN1,2, ITER LIRWD project
2014	Present	Electrical Engineering Department/ KEPCO-E&C	Functional Group Leader	BNPP, SMART PPE Projects

ANTHONY D. PUTORTI JR., Ph.D., P.E. *Fire Protection Engineer*

Engineering Laboratory
Fire Research Division
National Institute of Standard and Technology, Gaithersburg, MD, USA

Ph.D., Mechanical Engineering, University of Michigan
M.S., Fire Protection Engineering, Worcester Polytechnic Institute
B.S., Mechanical Engineering, Worcester Polytechnic Institute

Dr. Putorti is a Fire Protection Engineer in the Fire Research Division of the National Institute of Standards and Technology (NIST). His primary areas of research currently include characterizing high energy arcing faults in electrical equipment and studying past fire incidents. Putorti has extensive experience in fire research, forensic investigations, and fire protection engineering.

As a fire researcher at NIST for more than fifteen years, Putorti has studied fire phenomena using scientific principles, modeling, and experimentation. Past studies include the high temperature performance of firefighter SCBA facepieces, performance of fire fighter locator / tracking systems, fire sprinkler activation, fire suppression spray characterization and modeling, fire burn pattern formation, full scale studies of building fire environments, and *in-situ* burning of oil spills.

Prior to his most recent tour at NIST, Putorti conducted fire and injury investigations for civil and criminal litigation involving buildings, fire protection systems, vehicles, commercial products, and consumer products. His experience includes performing investigations as a consulting forensic expert and as a senior product analysis specialist at DaimlerChrysler and Chrysler LLC.

As a fire protection engineering consultant, Putorti conducted a wide range of fire protection engineering activities, including code consulting, fire protection analysis, egress analysis, materials evaluation, suppression system evaluation, modeling, and performance based design. Fire protection projects included warehouses, museums, healthcare facilities, offices, laboratories, convention centers, courthouses, and industrial facilities.

Dr. Putorti has served on many technical committees, including the National Fire Protection Association (NFPA) Technical Correlating Committee on Fire and Emergency Services Protective Clothing and Equipment, Technical Committee on Electronic Safety Equipment, Technical Committee on Structural and Proximity Fire Fighting Protective Clothing and Equipment, Technical Committee on Fire Investigations, and Technical Committee on Hazard and Risk of Contents and Furnishings; the ASTM International E5 Committee on Fire Standards; and the SAE International Fire Safety Committee and Motor Vehicle Fire Investigation Task Force.

Dr. Putorti is a Professional Engineer in California and Pennsylvania.

Tom Stefanski, M.Sc., P.Eng.

EDUCATION and MEMBERSHIPS

- M.Sc. degree in Electrical Engineering (specialty Power Engineering), Technical University of Warsaw, 1978.
- Registration with the Association of Professional Engineers and Geoscientists of British Columbia, 1991
- Short Circuit Testing Liaison of the Nations of the Americas, Technical Director, 2014
- Institute of Electrical and Electronic Engineers (IEEE): Member of the Switchgear Committee and several Subcommittees and Working Groups.

PROFESSIONAL BACKGROUND

May 2016 – present KEMA Laboratories Chalfont, Pennsylvania, USA

Director and leader of the largest high power testing laboratory in the United States. Responsible for operations, maintenance, profitability, sales, service, reporting and maintaining high technical standards of the facility.

1988 – 2016 Powertech Labs Inc., Surrey BC, Canada

Power Labs Business Unit, Senior Engineer, Manager of the High Power Laboratory since 1994. Responsible for the operations, maintenance, safety, marketing and project management of the High Power Lab, with a three-phase capacity of 1500 MVA, one of the best equipped and most technologically advanced electrical testing facilities in North America.

High Power Lab duties included development and certification testing, preparation of quotations and test reports, accident investigations, lab maintenance, lab expansion and upgrades. The testing included: short circuit and interrupting tests, load-switching and fault making tests, arc resistance, pressure relief, power arc and temperature rise tests. Field testing and investigation included failure analysis of high voltage circuit breakers, transformers, fuses and underground cables. Major lab upgrades included design and installation of X/R banks, make switches, test transformers, load components, TRV circuits, reclosing breakers, oil separation and containment system and data acquisition system.

1978-1987 ZWAR - the largest Polish company producing high voltage apparatus and switchgear. Warsaw, Poland.

Designer, Senior Designer, Head of the High Voltage Circuit Breakers Design Department. Responsible for design, testing, modernization and customer support of air blast, oil, and SF_6 circuit breakers rated 123 kV to 420 kV.

CAREER HIGHLIGHTS

Over 37 years of Power Engineering experience in design, testing, failure analysis, troubleshooting and maintenance of utility and industrial electrical equipment, including switchgear, circuit breakers, reclosers, switches, fuses, transformers, arresters, separable connectors, insulators, safety grounding systems, busbars and cables.

Over 25 years of experience in managing electrical departments including leading, team-building and mentoring technical and engineering staff.

Responsible for contract negotiations and customer's support. Extensive experience in development and interpretation of test standards and certification testing to ANSI, IEEE, IEC, UL, CSA and other national and of international standards.

Project manager and test leader for over 1800 projects involving wide range of development, routine, safety, quality and certification short circuit testing of transmission and distribution switchgear equipment performed for world-wide spectrum of electrical manufacturers, utilities and research organizations. Participation in failure analysis, accident investigations and R&D tests on future technologies.

Leading the High Power Lab and participating in making it widely recognized for its efficiency, quality, customer satisfaction and excellence with a perfect safety record and high profitability during every single year.

Participated in design, development, testing and manufacturing of a safety device to protect personnel carrying out measurements on electrical equipment.

Participated in the design and implementation of experimental techniques required for testing of equipment and accessories used on power utility distribution systems.

Representing Nations of the Americas on the Short Circuit Testing Liaison Technical Committee as a Technical Director of the STLNA.

Stephen L. Turner

Leidos, Inc.

301 Laboratory Road

Oak Ridge, Tennessee 37830

Education B.S., M.S. Mechanical Engineering, University of Virginia

Since 1979, Mr. Turner has held various positions at Leidos (formerly Science Applications International Corporation) including Assistant Vice President and Chief Scientist in the area of nuclear safety. He is currently a consultant at Leidos.

Mr. Turner has 38 years of experience in nuclear facility safety and probabilistic analysis and supported the plans and basis for the implementation of risk-informed regulations based on Probabilistic Risk Assessments (PRA) for the Japanese utilities and the nuclear regulator in Japan since 2001. Mr. Turner was project manager 18 projects for fire safety including the methods for analyses and walk downs to support fire safety assessments to NUREG/CR-6850. This included various component fire tests since 2008 at Clemson University for HEPA filter soot loading and at Southwest Research Institute (SwRI) for cable fire and oil fire tests similar to the tests that support NUREG-6850. Since 2012, he was the project manager for four test projects for High Energy Arcing Faults (HEAF) at KEMA Laboratories completing a total of 24 HEAF tests on switchgear, distribution panels, and motor control centers. Three of these tests duplicated the conditions of the HEAF at the Onagawa power plant that occurred in the 2011 Tohoku Earthquake. He also was the project manager at SwRI for six tests using rocket fuel to create HEAF-like conditions in a 5-cabinet switchgear lineup. He was a principal contributor to NUREG/IA-0470 that documents these HEAF tests. For the last two years he was the project manager research for modeling and analysis methods for HEAF phenomenon compiling results for published methods and developing models in ANSYS-Fluent.

R E S U M E

PERSONAL DATA			
Family Name(S) : YI / First Name(S) : SEONGHYEON		Sex	Male
Private Address : 9, Yongjeon 1-ro Gimcheon-si, Gyeongsanbuk-eo, 070497, Republic of Korea	Office/Mailing Address : KEPCO-E&C, 269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, 39660, Republic of Korea Email : sh.yi@kepco-enc.com Tel : +82 54 421 7469		
Data of Birth (Month/Day/Year) 03/06/78	Place of Birth (Town/City/Country) Geumho-ro/Seoul-si/Korea	Nationality : KOREAN	Marital Status : Married
Name and Address of Person to notify in case of emergency : Joohee, Park, 9, Yongjeon 1-ro Gimcheon-si, Gyeongsanbuk-eo, 070497, Republic of Korea			Relationship : Wife

EDUCATION/TRAINING

Years attended		Name and Place of Inst.	Field of Study	Diploma or Degree
From	To			
1997	2004	Hongik Univ.	Electrical Engineering	B.S.

RECENT EMPLOYMENT RECORD

Year attended		Name and Place of Employer/Organization	Title of Position	Type of Work
From	To			
2004	2008	Electrical Engineering Department/Samsung	Engineer	Electrical Engineer
2010	2014	Electrical Engineering Department/KEPCO-E&C	Engineer	Electrical Engineer (O&M Plant)
2014	Present	Electrical Engineering Department/KEPCO-E&C	Engineer	Electrical Engineer (BNPP Project, SMART PPE)

APPENDIX F INTRODUCTORY MATERIALS PRESENTED AT THE FIRST PANEL MEETING

F.1 PIRT Process Refresher

Phenomena Identification and Ranking Table

PIRT Process

OECD
BETTER POLICIES FOR BETTER LIVES

Office of Nuclear Regulatory Research

Presentation of Scenario

- Description of scenario
  - Scenarios are purposefully vague – this gives the panel more latitude to choose the important parameters
- Figure of merit
  - The figure of merit is the specific goal to be achieved through analysis. The phenomena identified by the panel should be in the context of achieving this goal.

Example Scenario

Description: A high energy arc fault occurs in a low/medium voltage switchgear that supplies power to "Train A" systems. The cables from an overhead cable tray enter the cabinet from the top (air-drop configuration). A similarly-configured switchgear supplying power to redundant "Train B" systems is located close by.

Figure of Merit: Determining the extent of damage to the "Train B" switchgear.

Identification of Phenomena

- The group will identify *all* phenomena that could be important in achieving the figure of merit.
  - At this stage, no judgement regarding the importance of the phenomena is necessary.
- The phenomena will be recorded and organized into categories as needed.

Phenomena vs. Parameters

- If it has units, or can be measured directly, it is probably a parameter. For example, cabinet voltage is a parameter. The underlying phenomenon would be the cabinet's electrical configuration.

- I will record key parameters as well, but they will be ranked separately.

Ranking of Phenomena

- Once the phenomena are identified, the individuals on the panel will rank each as being of high (H) medium (M) or low (L) importance.

- This will be done individually first, and then the rankings will be discussed as a group.

Ranking of State of Knowledge

- For each phenomenon, the panel will rank the state of knowledge in 3 categories:
  - Model adequacy
  - Data adequacy
  - Obtainability of new data

- Again, we will use a high (H) medium (M) or low (L) scale.

Ranking of Key Parameters

- Finally, the panel will rank the key parameters identified earlier for both importance and state of knowledge.

F.2 Recent Experimental Work Performed by NRA

U.S.NRC United States Nuclear Regulatory Commission Protecting People and the Environment

RIC 2016

TH32 - Improving Realism in Fire Probabilistic Risk Assessments

Experimental Studies of High Energy Arcing Fault (HEAF) by S/NRA/R

Hajime KABASHIMA and Susumu Tsuchino

Regulatory Standard and Research Department,
Secretariat of Nuclear Regulation Authority
(S/NRA/R), Tokyo, Japan

Outline

1. Background
2. Objectives of HEAF tests
3. S/NRA/R HEAF tests
4. S/NRA/R HEAF test results
5. Discussion topics
6. Summary

1. Background

A High Energy Arcing Fault (HEAF) occurred in the high-voltage (6,900V) metalclad switchgear (M/C) at Unit 1 of Onagawa Nuclear Power Station (NPS) of the Tohoku Electric Power Company Co., Inc. on March 11, 2011 due to the 2011 off the Pacific coast of Tohoku Earthquake.

HEAF events, although their impacts differ each other, have occurred in the electrical equipment and components in the NPSs worldwide. Efforts are being taken to understand the phenomena and to develop evaluation methods.

(http://warp.da.ndl.go.jp/info:ndljp/pid/9483636/www.nsr.go.jp/archive/nisa/earthquake/files/houkoku230530-2.pdf)

2. Objectives of HEAF tests

- To understand the basic characteristics and behavior of HEAF
- To understand what occurred in the Onagawa NPS Unit 1 due to HEAF event during the 2011 off the Pacific coast of Tohoku Earthquake

- - - - - - - - - - - - - - (In the future) - - - - - - - - - - - - - -

- Develop regulatory guidance for Fire Hazards Analysis Methods for HEAF
  - Models for damage predictions and setting Zone of Influence (ZOI)
  - Methods for the Protection against HEAF

3. S/NRA/R HEAF tests

Collaboration with
NRC
NIST
KEMA

S/NRA/R HEAF Tests

- Low Voltage HEAF Tests
  - Distribution Panel (DP)
  - Motor Control Center (MCC)
- Onagawa Configuration Tests
  - Metalclad Switchgear (M/C) 5-cabinet lineup

5-cabinet lineup
Heat source : Rocket fuel
Burned test

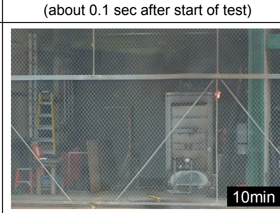
Distribution Panel (DP)	Motor Control Center (MCC)	Metalclad Switchgear (M/C)
Voltage : 480V (Set point)	Voltage : 480V (Set point)	Voltage : 7000V or 7100V (Set point)
Current : 52.3kA (Target value)	Current : 63.5kA (Target value)	Current : 22.6kA - 25.0kA (Target value)
Arc discharge	Arc discharge	Arc discharge
Duration: 2s	Duration: 2s	Duration: 1s, 2s, 3s
HEAF tests: 3 times	HEAF tests: 4 times	HEAF tests 6 times

4.1 S/NRA/R HEAF test results <Distribution Panel>

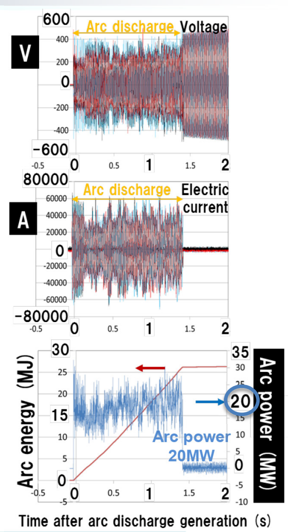
(1) Before test

(2) Arc discharge occurrence (about 0.1 sec after start of test)

(3) Generation of metallic fume (about 1 second after start of test)

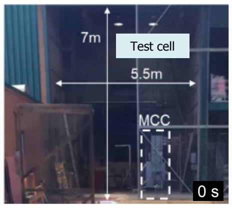


(4) Ensuing Fire (about 10 minutes after start of test)



In the DP HEAF tests, ensuing fire occurred in two out of three tests.
Arc power was approximately 20MW for all the tests.

4.2 S/NRA/R HEAF test results <Motor Control Center>

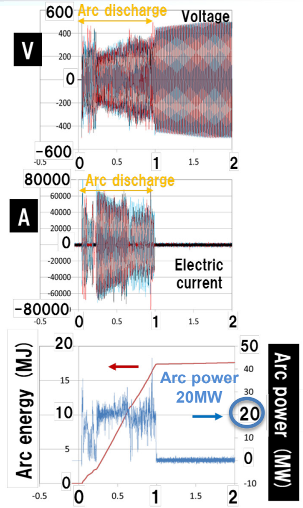


(1) Before test

(2) Arc discharge occurrence (about 0.2 sec. after start of test)

(3) Blowout of arc discharge metallic fume (about 0.5 second after start of test)

(4) Generation of metallic dust (about 2 second after start of test)



In MCC HEAF test, the ensuing fire did not occur for all four tests.
Arc power was approximately 20MW for all tests.

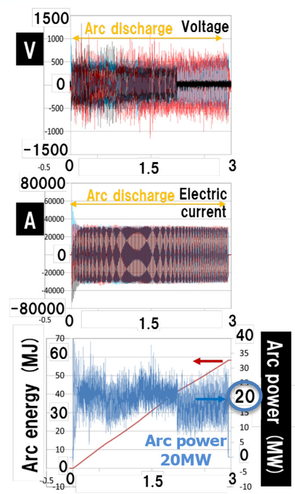
4.3 S/NRA/R HEAF test results <Metalclad Switchgear>

(1) Before test

(2) Arc discharge occurrence (about 0.2 sec after start of test)

(3) Generation of metallic fume (about 2 second after start of test)

(4) Ensuing Fire (about 10 minutes after start of test)



In the M/C HEAF tests, ensuing fire occurred in four out of six tests.
Arc power was approximately 20MW for four tests and larger than 20MW for two tests.

5.1 Discussion topics <Arc power>

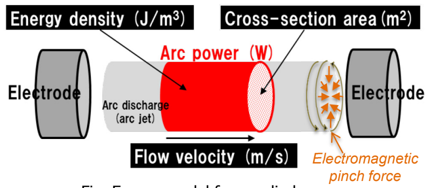


Fig. Energy model for arc discharge

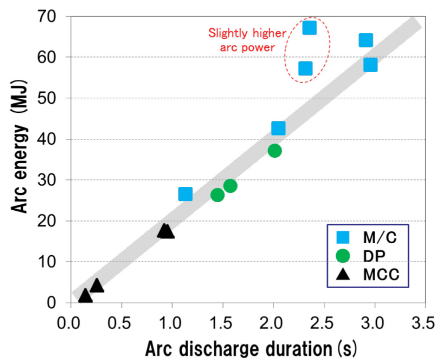


Fig. Relationship between arc discharge duration and arc energy

- Proportional relationship is confirmed between the arc energy and the arc duration for each electric cabinet, and the arc power is almost constant.
  - The arc power is a value multiplied by an **energy density**, a **flow velocity** and a **cross-sectional area** of arc jet.
  - Two key factors;
    - ・Saturation phenomena of **energy density**
    - ・Inverse relationship between **flow velocity** and **cross-sectional area**.
- Two data with slightly higher arc power were obtained. It needs further consideration.

5.2 Discussion topics <Ensuing fire>

- S/NRA/R HEAF tests showed that the arc energy required for initiating ensuing fire differed between distribution panels and metalclad switchgears.
  - The values of arc energy which can cause ensuing fire were between 26.3 and 28.6 MJ for the distribution panels and between 42.6 and 57.2 MJ for the metalclad switchgears.
  - Values of arc energy required for causing ensuing fire were obtained. This triggering energy is considered to be dependent on the characteristics of individual electric cabinets such as interior volume and ventilation opening area.

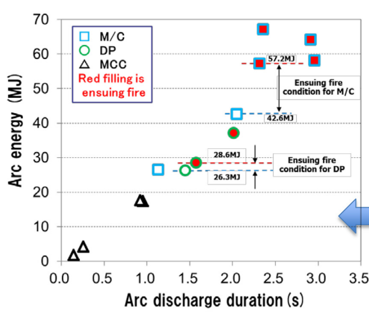


Fig. Arc energy required for causing ensuing fire

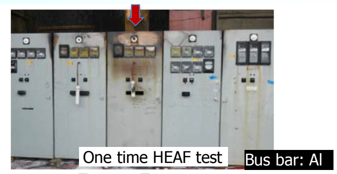
Distribution Panel	Metalclad Switchgears
Cubicle size: **Middle**	Cubicle size: **Large**
Ventilation opening area: **Middle**	Ventilation opening area: **Large**
Length: 0.9 m	Length: 2.1 m
Depth: 1.2 m	Depth: 0.9 m
Height: 2.3 m	Height: 2.3 m

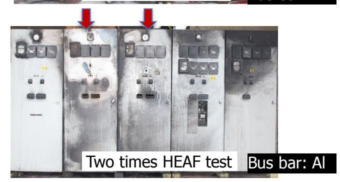
If arc discharge duration could be reduced, arc energy would be decreased and consequently ensuing fire could be prevented.

5.3 Discussion topics <Onagawa HEAF event>

(http://warp.da.ndl.go.jp/info:ndljp/pid/9483636/www.nsr.go.jp/archive/nisa/earthquake/files/houkoku230530-2.pdf)

HEAF event at Onagawa NPS Unit 1, it is supposed from observation of the damage condition that the arc discharge was occurred two times in the different Metalclad switchgears.





- The damage of metalclad switchgears at Onagawa NPS Unit 1 was more severe than that after HEAF tests.
  - Aluminum bus bars of the metalclad switchgears at Onagawa NPS Unit 1 were severely damaged compared with those of HEAF tests.
  - Burning (oxidation) of the bus bar made of aluminum can cause huge heat energy release by oxidation of aluminum. Therefore, in addition to the arc energy due to HEAF, the high energy of aluminum bus bar oxidation should be considered in the consequence evaluation for HEAF events in electric cabinets.

6. Summary

- HEAF tests were conducted to obtain the insights about progress of HEAF events, energy level of arcs and condition for ensuing fire. Based on the test results, an energy model of arc discharge has been studied.
  - For various electric cabinets, insights of event progress were obtained pertaining to generation and leakage of arcs, generation of metal fume and ensuing fire.
  - Proportional relationship was observed between arc energy and arc duration irrespective of types of electric cabinets for all cases.
  - Values of arc energy required to cause ensuing fire were obtained. This triggering energy is considered to be dependent on the characteristics of individual electric cabinets such as interior volume and ventilation opening area.

F.3 Recent Experimental Work Performed by CRIEPI

Summary of Experimental Studies of the HEAF Fire Event for High and Low Voltage Switchgears

K. SHIRAI[1], M. IWATA[2], T. MIYAGI[2]
Y. GODA[2], K. NAMBA[1], K. TASAKA[1]
Central Research Institute of Electric Power Industry
(CRIEPI)

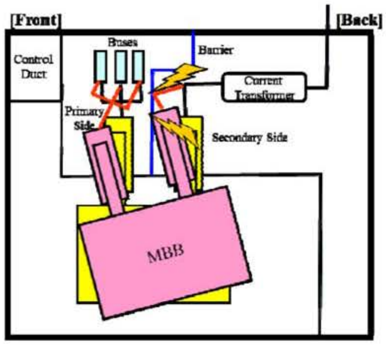
1) Civil Engineering Research Laboratory
1646, Abiko, Abiko-Shi, Chiba 270-1194, Japan
2) Electric Power Engineering Research Laboratory
High Power Testing Laboratory
2-6-1 Nagasaka, Yokosuka-shi, Kanagawa 240-0196, Japan

Contents

- *Background and Objective*
- Internal Arc Tests for High Voltage Switchgear
- Internal Arc Tests for Low Voltage Switchgear
- Summary

Background

- Great East Japan Earthquake as of March 11 in 2011
- *Damages by earthquake at Onagawa NPP Unit.1*
  - ➢ Two of Ten connecting cabinets completely damaged by the seismic induced HEAF fire event

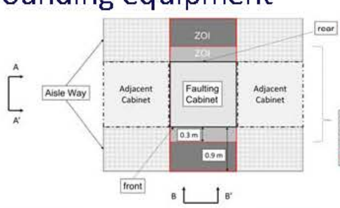


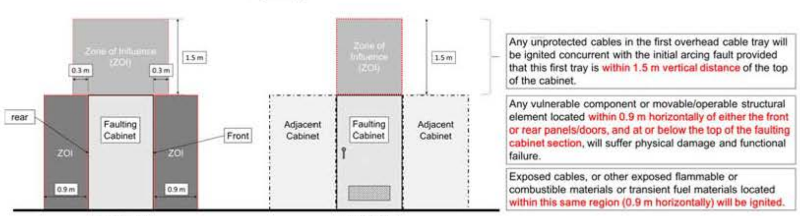
Non-fixed Magnet Blast Breaker (MBB), hung up by buses in the cabinet, was damaged during seismic strong motion

Objective

- Clarify the mechanism of pressure rise in the cabinet and thermal propagation through cabinets due to HEAF fire
- Evaluate the zone of influence (ZOI) for the neighboring cabinets and surrounding equipment

NUREG/CR-6850, Appendix M (2005)
- ✓ Components within ZOI are assumed to fail or ignite



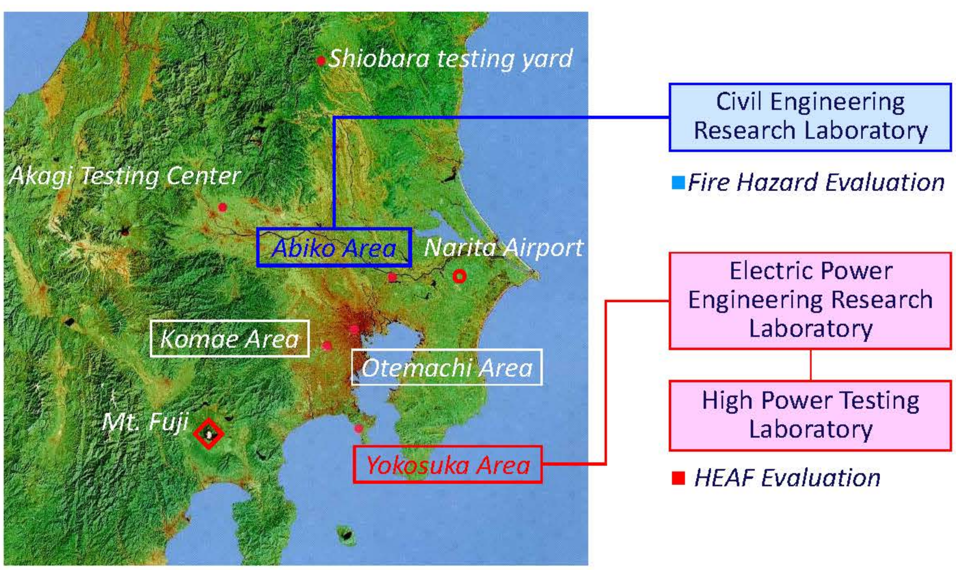


Internal Arc Test Plan

- Phase I (FY2012) : Primitive Internal Arc Tests at High Power Testing Facility
  - 10 tests using Non-Seismic, Non-Arc-Proof High Voltage Switchgear
- Phase II (FY2013) : Demonstrative Internal Arc Tests
  - 3 tests using Seismic, Non-Arc-Proof High Voltage Switchgear
- Phase III (FY2013) : Demonstrative Internal Arc Tests
  - 4 tests using Seismic, Non-Arc-Proof Low Voltage Switchgear

Items	2012	2013	2014
Phase I ➢Preparation of HV Switchgears ➢Primitive Internal Arc Tests (4series)	***8 units***		
Phase II ➢ Preparation of HV Switchgears ➢ Demonstrative Internal Arc Tests	***2 units***		
Phase III ➢ Preparation of LV Switchgears ➢ Demonstrative Internal Arc Tests		***2 units***	

Locations of Testing Laboratories



High Power Testing Laboratory

- Accredited High Power Testing Laboratory based on ISO/IEC guide25 on Dec., 2001, and ISO/IEC 17025 on Dec., 2002 by JAB (The Japan Accreditation Board for Conformity Assessment)

Automatic control system and computer measurement system for short-circuit test

Indoor test cell with soundproofing
40m X 25 m X 29 m (H)

- **Accreditation Tests**
- **General Tests**
  - High power arc test (AC/DC)
  - Short time current test (AC/DC)
  - Synthetic test, etc.

Short-circuit generator
15kV 2,500MVA 50/60Hz

High voltage short-circuit transformer
15kV/12, 24, 36, 48 kV
1,000 MVA 1phase 3units

Contents

- *Background and Objective*
- *Internal Arc Tests for High Voltage Switchgear*
- Internal Arc Tests for Low Voltage Switchgear
- Summary

Test Condition

JEM1425-2011, Appendix A -Internal Fault-

"A.C. metal-enclosed switchgear and control-gear for rated voltages above 1kV and up to and including 36kV",
Standards of the Japan Electrical Manufacturers' Association (JEMA)

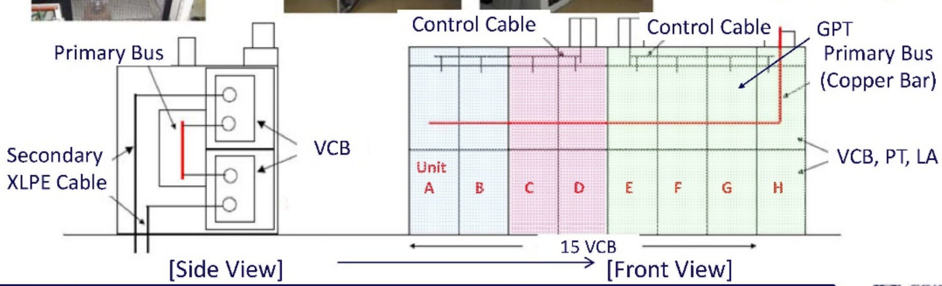
- *Tested in the unloaded condition (no primary load)*
  - ➢ *6.9 kV for non-seismic, and 8.0 kV for seismic switchgear*
- *Arcing current : 20 kA considering Max. 3-phase short circuit current from the designated power system*
- *Arc duration : between 0.1 and 1.0 s referring JEM1425-2011,*
  and 2.0 s from the safety point of view
- *Arc discharge points: Secondary bus in the cable room and VCB terminal*
- *Ignition of the arc : by means of a copper wire of 0.5mm in diameter*
- *Cabinet doors were closed considering normal operational condition*
- *Provide a representative configuration and verify the occurrence of the ignition*
  - ➢ *Associated electrical equipment*
  - ➢ *Secondary combustibles, such as control cables*

Test Configuration – Phase1 -

8 units of non-seismic/non-arc-proof 3-6.9 kV metal-clad switchgears

- ✓ *Series1: Cabinets A+B*
- ✓ *Series2: Cabinets C+D*
- ✓ *Series3: Cabinets E+F+G+H*
- ✓ *Series4: Cabinets A+B (reused)*

[Series3]



Test Matrix and Results - Phase1-

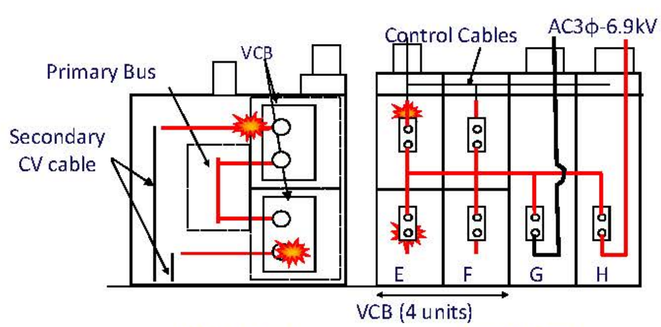
Test #	*Arc Discharge Location*			*Current [kV]*	*Voltage [kA]*	*Duration [s]*	*Fire*
	Cabinet	*Room*	*Location*				
1-1	A	Upper	Secondary bus	6.9	18.9	0.1	No
1-2	B	Upper	Secondary bus			0.3	No
2-1	C	Upper	Secondary bus			0.5	No
2-2	D	Upper	VCB Terminal			0.5	No
3-1	E	Upper	Secondary bus			1.0	No
3-2	F	Upper	VCB Terminal			1.0	No
3-3	*E*	*Lower*	*Secondary bus*			*1.0*	*Yes**
3-4	*F*	*Lower*	*VCB Terminal*			*2.0*	*Yes***
4-1	*A*	*Lower*	*VCB Terminal*			*2.0*	*Yes***
4-2	B	Lower	VCB Terminal			1.0	No

Remarks:
* *Self-extinguished after 20 min*
** *Extinguished by portable fire extinguisher using water as suppression agent at 7-10 min after ignition*

Damage to Cabinets - Phase1 -

[4 units before Test]

[After Test 3-1 and 3-2]



[Side View] [Front View]

[During and after Test 4-1]

Test Images for Test 3-3, 3-4

Test 3-3
[Cabinet E, Lower Room, Secondary bus]

Test 3-4
[Cabinet F, Lower Room, VCB Terminal]

HEAF Test Video (DV)

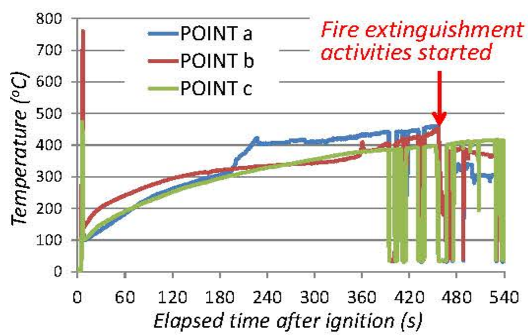
[Test 4-1: Lower VCB Terminal, Arc duration 2.39s, Arc Energy 44.6MJ]

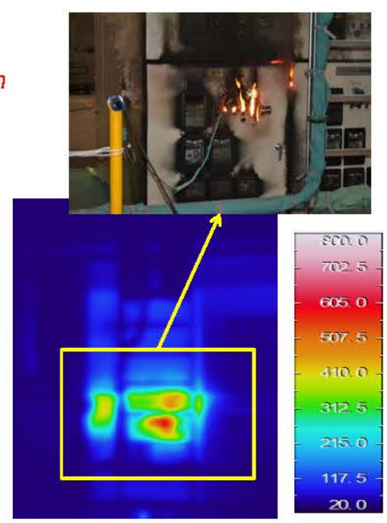
HEAF Test Video (HSC)

[Test 4-1: Lower VCB Terminal, Arc duration 2.39s, Arc Energy 44.6MJ]

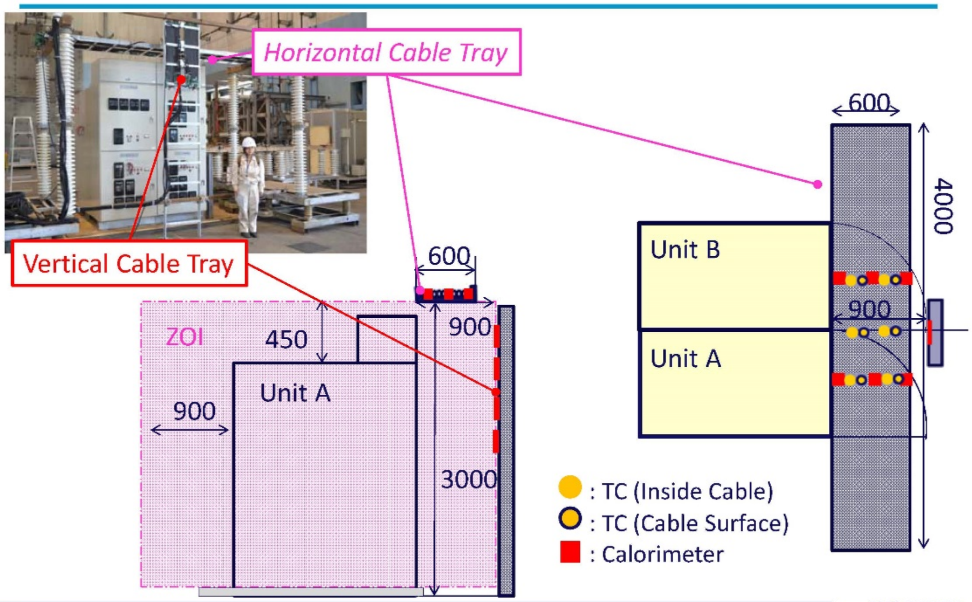
Cabinet Surface Temperature -Test 4-1-

- *Test 4-1 : measured by thermography*
  - *Arcing duration : 2.0s*
  - *Arc Discharge Location : VCB Terminal*
  - *Rapid increase of temperature after 3 min*
  - *Max. temp. about 460°C just before fire extinguishment activities (7.5min)*

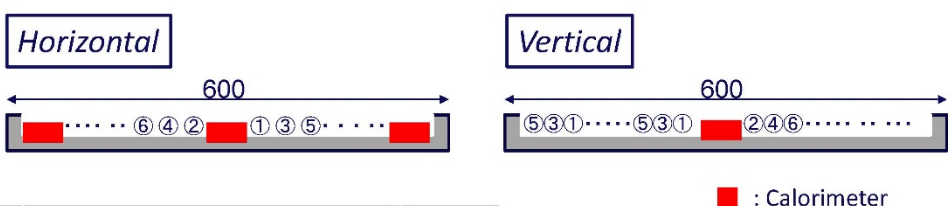




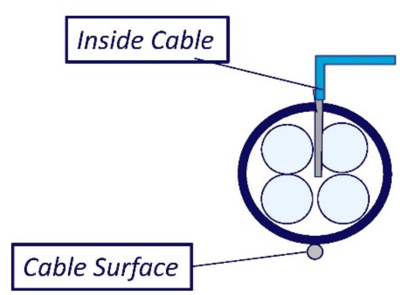
Cable Tray Setup -Test 4-1-



Measuring Points on Cable Tray -Test 4-1-

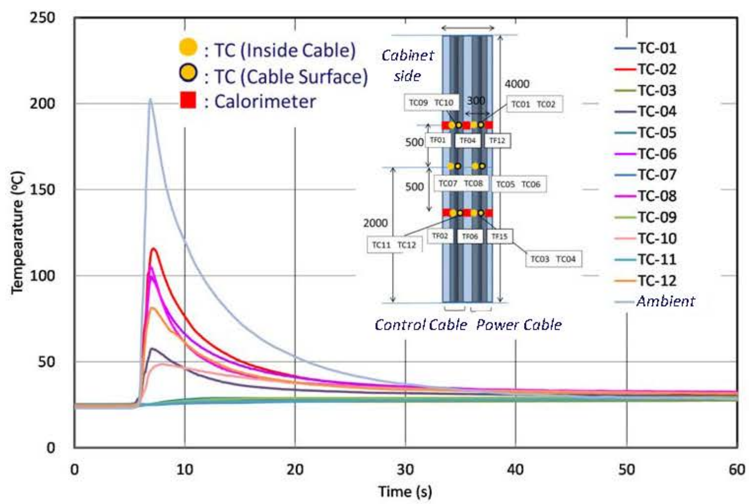


No.	Cable Type	Core #
①	Non-Flammable Power Cable	4
②	Non-Flammable Control Cable	4
③	Non-Flammable Power Cable	2
④	Non-Flammable Control Cable	2
⑤	Flammable Power Cable	4
⑥	Flammable Control Cable	6



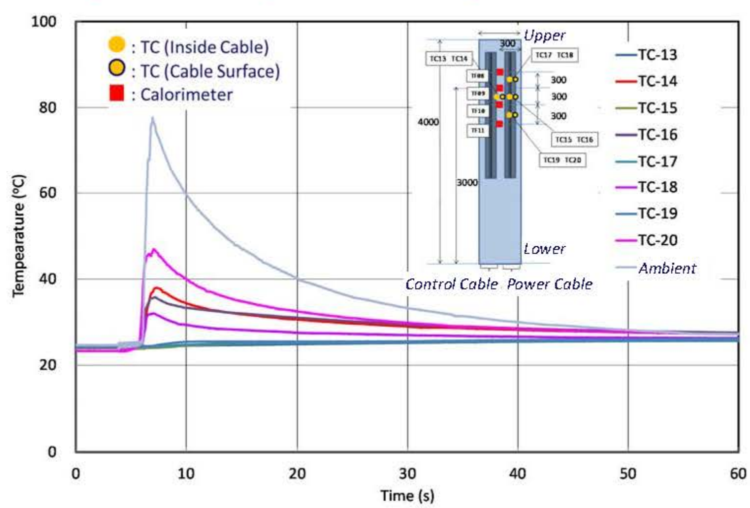
Temperature Profile (1) -Test 4-1-

➢ Horizontal Tray : Max. Temp. on Cable Surface 116˚C



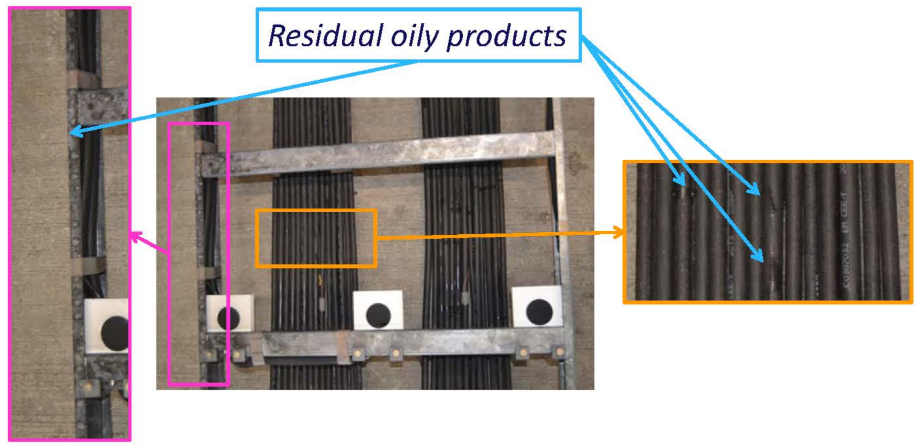
Temperature Profile (2) -Test 4-1-

➢ Vertical Tray : Max. Temp. on Cable Surface 47˚C



Observation Results -Test 4-1-

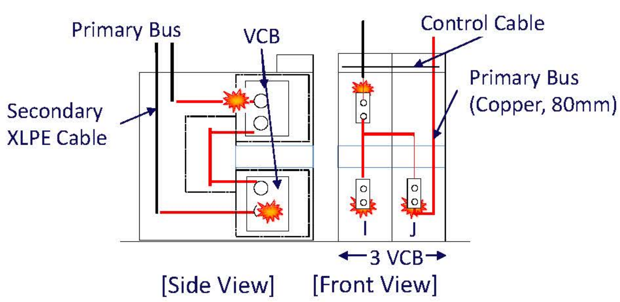
- *No loss of Insulation and thermal damage*
- *Residual oily products on the cable/tray surface observed (due to the evaporation of the associated equipment of the cabinet)*



Test Matrix and Results - Phase2-

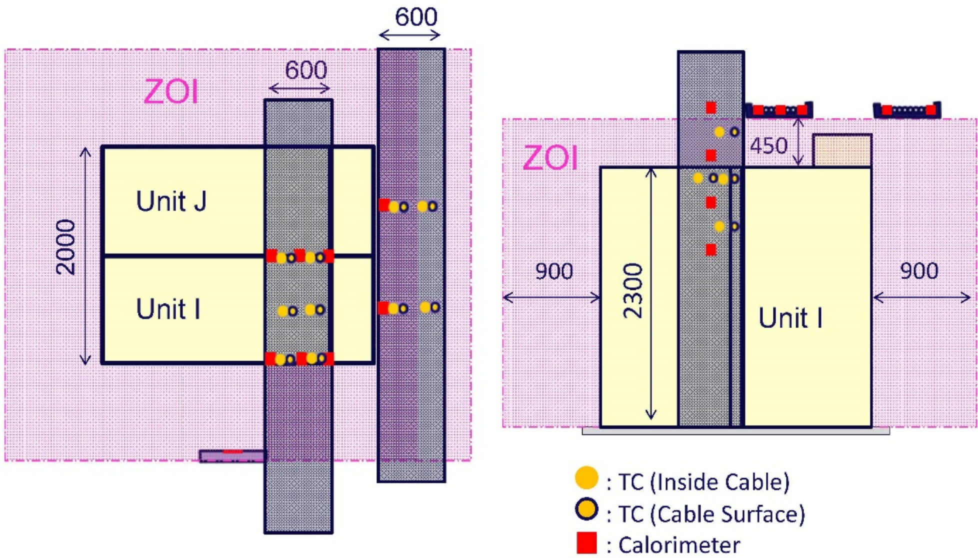
2units of seismic/non-arc-proof 3 - 8.0 kV metal-clad switchgears

✓ Series5: Cabinets I+J



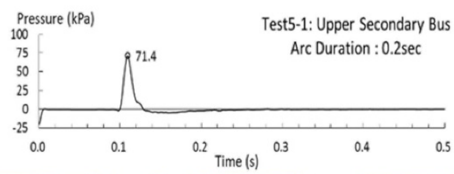
Test #	Arc Discharge Location			Current [kV]	Voltage [kA]	Duration [s]	Fire
	Cabinet	Room	Location				
5-1	I	Upper	Secondary bus	8.0	20.0	0.2	No
5-2	I	Lower	VCB Terminal			0.2	No
5-3	J	Lower	VCB Terminal			0.5	No

Cable Tray Setup -Test 5-1-

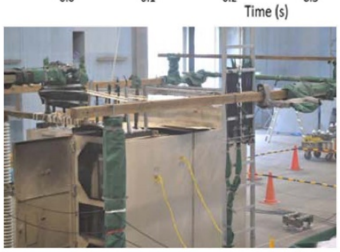


Damage to Cabinets -Test 5-1-

- *No Successive Fire, however*
- Roof and rear panels detached (Max. P >70kPa)
- Cable tray deformed remarkably due to the impact of the detached roof panel



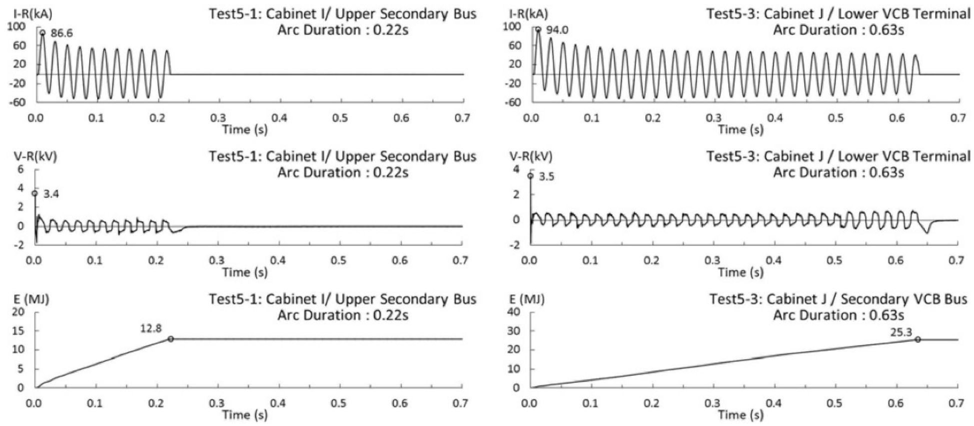
[Test 5-1]



[After Test 5-1]

Example of Measured Data

- Average arc voltage less than 1.4kV

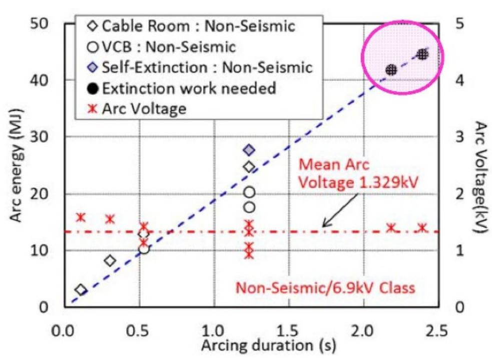


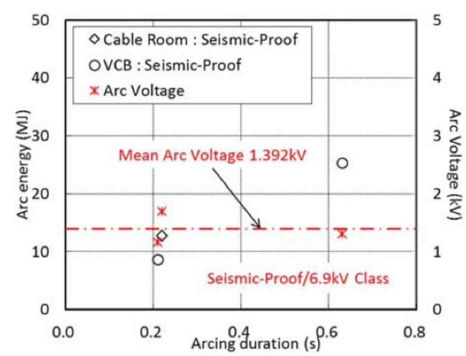
[Test 5-1: Upper Secondary Bus]
(Arc duration 0.22s, Arc Energy 12.8MJ)

[Test 5-3: Secondary VCB Terminal]
(Arc duration 0.63s, Arc Energy 25.3MJ)

Arc Energy and Voltage

- Arc Voltage seems to be constant, 1.34kV
- Arc Energy increase according to arcing duration
  - ➢ Over the arc energy 27 MJ, the fire occurrence was detected
  - ➢ Over the arc energy 40MJ, the fire extinguishment activities to remove the toxic gas release were needed





Enclosure Pressure (1)

- Neglect all transient and hydrodynamic effects
- Discharge of an arc in a cabinet treated as an ideal gas within constant volume system
- Enclosure pressure obtained by

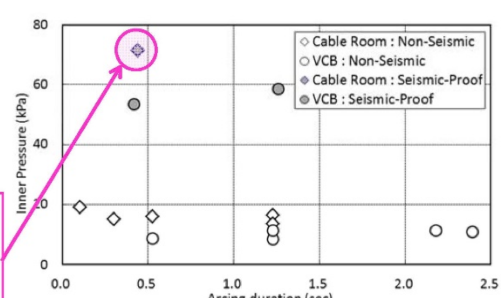
$$\Delta p = (\gamma - 1) \cdot \frac{k_p \Delta Q}{V}$$

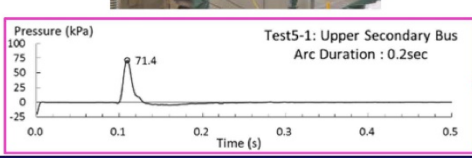
- Thermal transfer coefficient k_p (=0.53)
  Fraction of energy going into raising the gas pressure
- Example: In case of Test No. 1-1

$$\Delta p = (1.4 - 1) \cdot \frac{0.53 \cdot 3MJ}{1m^3} = 636kPa$$

Enclosure Pressure (2)

- *Seismic-proof cabinet could bear pressure at most up to 70kPa*
- *Only one peak appeared in any time history*
- *Panels (roof or side or rear) highly deformed or opened or partially detached just after the first arrival of the shock wave due to the arc discharge*
- *Several pieces of the broken bolts scattered at least 15 m away from cabinet*
- *Broken bolts considered as a projectile which might induce the local damage to the surrounding equipment*



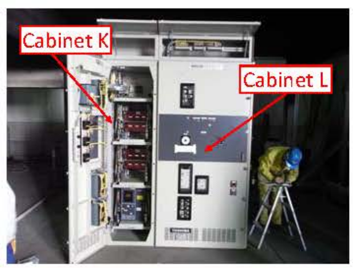


Contents

Test Matrix and Results - Phase3-

2units of Seismic-proof /non-arc-proof 480V metal-clad switchgears

- ✓ Series6: Cabinets K+L
- ✓ IEC/TR 61641 Ed.2
  (Enclosed low-voltage switchgear and control-gear assemblies - Guide for testing under conditions of arcing due to internal faults)



Test #	*Arc Discharge Location*			*Voltage [V]*	*Current [kA]*	*Duration [s]*	*Fire*
	Cabinet	*Room*	*Location*				
6-1	K	Upper	VCB Terminal	480	40.0	0.2	No
6-2	K	Middle	VCB Terminal			0.5	No
6-3	K	Lower	VCB Terminal			1.5	Yes
6-4	L	Lower	Secondary bus			0.2	No

HEAF Test Video (DV)

[Test 6-3: Lower ACB Terminal, Arc duration 1.53s, Arc Energy 19.8MJ]

Damage to Cabinets – Test 6-3 -

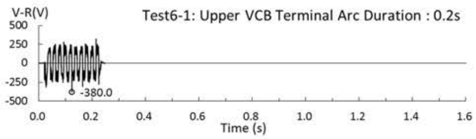
【ACB before test】

【Successive Fire】

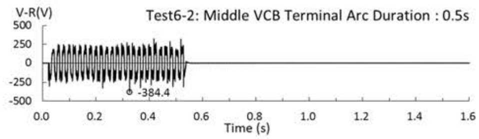
【ACB After test】

Arcing Voltage

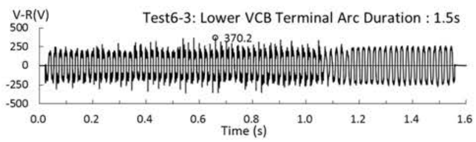
- Average arc voltage less than 400V



[Test 6-1: Upper/ VCB Terminal]
(Arc duration 0.2s, Arc Energy 2.5MJ)



[Test 6-2: Middle/ VCB Terminal]
(Arc duration 0.5s, Arc Energy 6.3MJ)



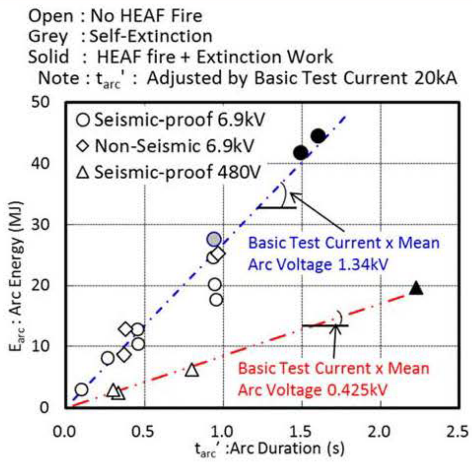
[Test 6-3: Lower/ VCB Terminal]
(Arc duration 1.5s, Arc Energy 19.8MJ)

Contents

- *Background and Objective*
- *Internal Arc Tests for High Voltage Switchgear*
- Internal Arc Tests for Low Voltage Switchgear
- Summary

Summary

- Fire occurrence detected and the fire extinguishment activities needed
  - Over arc energy 40 MJ (1.5 s x 20kA) with High Voltage switchgear
  - Over arc energy 20 MJ (2.2 s x 20kA) with Low Voltage switchgear



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10. SUPPLEMENTARY NOTES
K. Hamburger, NRC Project Manager

11. ABSTRACT (200 words or less)

This report documents the results of a phenomena identification and ranking table (PIRT) exercise performed for nuclear power plant (NPP) high energy arc fault (HEAF) analysis applications conducted on behalf of the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research.
The PIRT exercise was performed via a facilitated expert elicitation process. In this case, the expert panel comprised six international HEAF experts. The panel was facilitated by NRC staff. The objective of a PIRT exercise is to identify key phenomena associated with the intended application and to then rank the current state of knowledge relative to each identified phenomenon. The expert panel was presented with a series of specific HEAF scenarios, each of which is based on the types of scenarios typically considered in NPP applications. Each scenario includes a figure of merit (i.e., a specific goal to be achieved in analyzing the scenario using HEAF analysis or modeling tools). Given each scenario, the panel identified phenomena that are of potential interest to an assessment based on the figure of merit. The identified phenomena are then ranked relative to their importance in predicting the figure of merit. Each phenomenon is then further ranked for the existing state of knowledge and the adequacy of existing modeling tools to predict that phenomenon.
The PIRT panel covered three HEAF scenarios and identified a number of areas potentially in need of further analysis and model development. This report discusses the results in detail.

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