U.S. NRC ACTIONS AND PATH FORWARD AS A RESULT OF INTERNATIONAL HIGH ENERGY ARCING FAULT PHASE 1 TESTING RESULTS

Nicholas Melly, Gabriel Taylor, Kenneth Hamburger, David Stroup, Mark Henry Salley

United States Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research, Washington, DC USA

ABSTRACT

International nuclear power plant (NPP) operating experience has shown electrical distribution equipment (e.g., switchgear, bus ducts, etc.) can be subject to a failure mode that causes extensive damage known as High Energy Arcing Faults (HEAF). Equipment failures that result in HEAFs cause a rapid release of electrical energy in the form of heat, vaporized metals such as copper and aluminum, plasma, and explosive mechanical force. The energetic fault typically consists of two distinct phases, each with its own damage characteristics. The first phase is characterized by the short, rapid release of electrical energy. The second phase is characterized as the ensuing fire and modelled using classical fire-modelling tools.

Due to the potential safety significance of HEAF events, the Nuclear Energy Agency (NEA) Working Group on Integrity and Ageing (WGIAGE) initiated a task on HEAF events in 2009 to provide an in-depth investigation. The results of this test program identified the interaction with aluminum materials to be a potential exacerbating contributor to the extent of damage, commonly referred to as the zone of influence (ZOI). The test program also revealed a previously unidentified failure mechanism whereby conductive aluminum products of combustion are discharged to distances that greatly exceed current ZOI boundaries.

In light of these recent findings, the U.S. Nuclear Regulatory Commission (NRC) has taken additional steps to assess the potential safety impacts including the issuance of generic communication to alert licensees of the potential vulnerability associated with HEAFs involving aluminum components. The NRC has entered the aluminum HEAF safety concern into its congressionally mandated Generic Issues (GI) program. The GI program required three technical evaluation phases: screening, safety assessment, and regulatory response. As part of this process, the NRC staff will systematically evaluate plant safety, obtain additional data, and use expert judgement where necessary to assess the safety impact of aluminum HEAFs on NPP operation and inform future agency actions.

INTRODUCTION

The Working Group on Integrity and Ageing (WGIAGE) under the Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) defined a "High Energy Arcing Fault (HEAF)" as (cf. [2]):

- *"High Energy Arc Faults (HEAF) are energetic or explosive electrical equipment faults characterized by a rapid release of energy in the form of heat, light, vaporized metal and pressure increase due to high current arcs between energized electrical conductors or between energized electrical components and neutral or ground. HEAF events may also result in projectiles being ejected from the electrical component or enclosure of origin and result in fire.*

  The energetic fault scenario consists of two distinct phases, each with its own damage characteristics and detection/suppression response and effectiveness.

  - *First phase: short, rapid release of electrical energy which that may result in projectiles (from damaged electrical components or housing) and/or fire(s) involving the electrical device itself, as well as any external exposed combustibles, such as overhead exposed cable trays or nearby panels that may be ignited during this energetic phase.*
  - *Second phase (i.e., the ensuing fire[s]): is treated similar to other postulated fires within the zone of influence.*

  An arc is a very intense abnormal discharge of electrons between two electrodes that are carrying an electrical current. Since arcing is not usually a desirable occurrence, it is described as an "arcing fault." The arc is created by the flow of electrons through charged particles of gas ions that exist as a result of a vaporization of the conductive material."

International nuclear power plant (NPP) operating experience data clearly show that a significant number of HEAF events have occurred worldwide in operating plants. A report published by the OECD/NEA in June 2013 [1] documents 48 different HEAF fire events reported by the 12 member countries of the OECD/NEA Fire Incidents Records Exchange (FIRE) Project. This number, which has further increased in recent years, represents about 10 percent of all fire events reported to the FIRE database.

In analysing relevant operating experience, it becomes readily apparent that HEAF events tend to create challenges that complicate the plant's ability to safely shutdown the reactor and maintain it in a safe condition. The electrical disturbance that initiates the HEAF often causes loss of essential electrical power, while products of combustion tend to create challenges that complicate the plants' ability to safely shutdown the reactor and to the operators and fire brigade members handling the emergency. For many plants in the United States, fires are a dominant contributor to plant risk. HEAF-initiated scenarios were found to be significant contributors to the overall fire risk on a preliminary assessment of 10 U.S. National Fire Protection Association (NFPA) 805 NPP's risk assessment information. The range of fire risk contributed by HEAF-initiated fire scenarios ranged from 1 percent to 27 percent on a per-unit basis. The average per-unit risk contribution was about 15 percent [3].

INFORMATION NOTICE

The U.S. NRC issued information notice (IN) 2017-04, "High Energy Arcing Faults in Electrical Equipment Containing Aluminium Components" on August 21, 2017, to inform the industry of operating experience and recent NRC testing results pertaining to the magnitude of arcing fault hazards in electrical equipment containing aluminium components [4]. The NRC expects the information notice addressees to review the information for applicability to their facilities and consider actions, as appropriate. This information notice was based on U.S. NPP operating experience and an NRC-led international HEAF testing program performed through the OECD NEA.

As part of the testing program, a total of 26 tests were performed consisting mostly of electrical equipment with copper conductors. The equipment with copper components exhibited similar damage states to those postulated in the current methodology presented in NUREG/CR-6850, Appendix M [5]. However, results obtained for equipment containing aluminium components exhibited damage states well beyond those postulated in current HEAF damage models.

The increased physical damage to the test specimens, measurement devices, and the testing facility observed during tests involving aluminium components was attributed to the presence and interaction of aluminium with the arc during the HEAF. Aluminium in the components, subcomponents, or parts that form part of the normal current carrying pathway caused more energetic plasma development when involved in the electrical arcing process. The increased energetic plasma caused a larger amount of cabinet damage and/or the transport of gaseous high energy particles/plasma farther than was assumed in the current zone of influence (ZOI).

Another observation made during testing was the deposition of aluminium products on most surfaces within the electrical enclosure (i.e., cabinet) including electrical equipment external to the electrical enclosure tested. This aluminium by-product layer caused shorting problems in the test facility's electrical power supply and required significant repair. The extent of damage observed from the electrical enclosures containing aluminium components far exceeded that of the electrical enclosures which did not contain aluminium components.

In addition to the evidence from testing, the Information Notice also compiled relevant operating experience that demonstrates that the hazards from a HEAF may be substantially greater for electrical equipment that contains aluminium components than for those with copper components. The operating experience also documents the spread of electrically conductive aluminium by-products that could lead to additional failures. A summary of the aluminium impact from operational experience is stated below:

- Fort Calhoun Station, Unit 1, June 7, 2011: This event illustrates the adverse effects caused by large quantities of conductive aluminium by-products in the smoke produced by HEAF events involving aluminium which can adversely affect adjacent equipment. The event further resulted in significant unexpected system interactions (specifically, loss of power to both train A and train B buses). The event also resulted in grounds on both trains of safety-related DC power used for breaker operation and electrical protection. The fire resulted in a loss of power to six of nine safety-related 480 VAC electrical distribution buses, one of two safety-related 4160 VAC buses, and one of two non-safety-related 4160 VAC buses. The event resulted in the loss of the spent fuel pool cooling function [6], [7].
- Columbia Generating Station, August 5, 2009: This event involved aluminium bus bars enclosed in aluminium ducts. The event vaporized about 1.2 m (4 ft.) of each of the three buses and 2.4 m (8 ft.) of the bus duct enclosure, and smoke and heat effects were observed at all metal joints and covers for a distance of 6 m (20 ft.) south and about 3 m (10 ft.) north of the missing section [8], [9].
- Diablo Canyon Nuclear Power Plant, Unit 1, May 15, 2000: This event damaged both the 12 kV bus duct and the 4 kV bus duct. Conductors from both bus ducts were made of aluminium. The event led to the loss of both offsite electrical sources and the reliance on emergency diesel generators [10].
- Zion Nuclear Power Station, Unit 2, April 3, 1994: This event initiated a fire that the onsite fire brigade could not control without offsite brigade assistance. The bus duct was made of aluminium. The Phase A and B isophase bus ducts showed signs of excessive arcing. The licensee found extensive aluminium spatter in the general area of the fault as well as large amounts of white powder that was later determined to be aluminium oxide. In addition, the licensee stated that the physical damage observed during inspections was greater than other documented failures of this nature [11].

- Shearon Harris Nuclear Power Plant, Unit 1, October 9, 1989: This event damaged over a 15.2 m (50 ft.) section of the phase A bus. The bus duct enclosure was made of aluminium. The event also destroyed the neutral grounding bus and caused three fires: (1) an oil fire at the B main power transformer, (2) a hydrogen fire underneath the main generator, and (3) a third small oil fire in the generator housing [12].
- Kewaunee Power Station, July 10, 1987: This event damaged a 9.1 m (30 ft.) section of the bus bar, and the licensee observed the spread of a metallic dust. The bus bar conductors were made of aluminium [12].

GENERIC ISSUES PROGRAM

In addition to the issuance of an information notice, NRC staff submitted the issue to the NRC's Generic Issue Program on May 6, 2016 [14]. The NRC defines a generic issue (GI) as a well-defined, discrete, technical or security issue, the risk/or safety significance of which can be adequately determined and which: (1) applies to two or more facilities; (2) affects public health and safety, the common defines and security, or the environment; (3) is not already being processed under an existing program or process; and (4) can be resolved by new or revised regulation, policy, or guidance or voluntary industry initiatives. A GI may lead to regulatory changes that either enhance safety or reduce unnecessary regulatory burden.

The agency's Generic Issue Process (GIP) for resolving GIs is described in MD 6.4 [15]. It includes five distinct stages that may be exercised:

1. Identification; (Completed [14])
2. Acceptance Review; (Completed [16])
3. Screening; (Completed [19])
4. Safety / Risk Assessment; (Pending)
5. Regulatory Assessment; (Pending)

During each stage, NRC staff determines if more information is needed, if the issue should proceed to the next stage, or if the issue should exit the GIP. When issues exit the GIP, the possible outcomes include no action, further research, transfer to appropriate regulatory programs, or possible industry initiative. In any case, the GIP provides feedback to the person proposing the GI (requestor) of the outcome at each stage. Issues that proceed through all five stages result in regulatory solutions being provided to program offices for implementation and verification.

The issue was officially entered into this process on May 12, 2016, and an initial safety evaluation was performed that determined this issue does not represent an immediate safety concern to operating NPPs based on several mitigating factors including, but not limited to, contingency plans for loss of large areas due to fire and explosions [16], [17]. On May 20, 2016, a generic issue review panel (GIRP) was formed, and an initial screening evaluation was performed [18], [19]. The GIRP members concluded that the proposed GI met all seven screening criteria outlined in Management Directive (MD) 6.4, "Generic Issues Program." Therefore, the GIRP recommended that this issue continue into the Assessment Stage of the GI program.

Specifically, the staff identified that a potential issue exists for plants having electrical equipment containing components made of aluminium in areas subject to HEAF conditions. A HEAF event involving aluminium may cause greater damage to structures, systems, and components than previous analyses indicated. This decision is based on recent test results indicating that the ZOI around the initiating fault location may be larger than postulated in the current methodology for HEAF.

In addition, a HEAF event involving aluminium may challenge the technical basis of the current deterministic fire protection physical separation requirements described in 10 CFR 50, Appendix R "Fire Protection Program for Nuclear Power Facilities Operating Prior to January

1, 1979”. Section III.G.2.b of Appendix R, states in part: “*Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustible or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area.”*

The GIRP also reviewed the initial evaluation and determined that no immediate safety concerns were evident and found that it continues to remain valid.

GIRP ACTIONS GOING FORWARD

The GIRP proposed a series of short-term and long-term actions to systematically determine how to resolve this proposed GI [20]. The GIRP will lead the staff’s efforts on this GI, with resources and support from the Office of Nuclear Regulatory Research (RES) and the Office of Nuclear Regulatory Regulation (NRR).

The short-term actions are anticipated to occur during the Assessment Stage and include:

1. Determining the extent of condition (e.g., use of aluminium in electrical components in areas subject to potential HEAFs). Based on an NEI (*N*uclear *E*nergy *I*nstitute)-performed survey [21], aluminium components were found to be prevalent in some HEAF-susceptible equipment located in areas of the plants evaluated in fire analyses.
2. Developing an interim zone of influence for NPPs with aluminium components in areas where HEAFs are postulated to occur using either expert elicitation or appropriate operational experience.
3. Determining electrical fault characteristics which correspond to HEAF events as defined in fire frequency documents such as fault current, voltage and duration [22].
4. Developing a risk/safety determination by identifying appropriate pilot plants to assess the risk to operating NPPs with aluminium in the areas where HEAFs can occur.
5. Developing a plan for future testing using the phenomenon identification and ranking table (PIRT) exercise to focus on parameters and phenomena.
6. Determining whether the issue needs to proceed to the next stage, Regulatory Office for Implementation. It is in this stage that changes to regulations would be addressed.

The Long-Term actions are possible actions that NRR may consider during the Regulatory Implementation Stage, including:

1. Issuing generic communications, requests for information, or orders, as deemed necessary.
2. Revising technical guidance documents to reflect potential changes to methodology based on the new information.
3. Assessing risk through long-term performance monitoring. This will be accomplished through training for inspectors on the hazards from a HEAF involving aluminium and identification and revisions to NRC procedures, as necessary, for inspecting licensees’ Fire PRA during fire protection inspections.

GIRP RISK EVALUATION PLAN

To determine an approximate risk profile for HEAF events involving aluminium, several factors need to be considered. First, the staff intends to develop an interim increased ZOI using either expert elicitation or appropriate operational experience. This interim ZOI will be used to calculate a potential increase in plant risk. Second, the staff will also evaluate the characteristics of HEAF events that may affect frequency values used in PRAs. In current modelling approaches, HEAF events are treated with a one-size-fits-all model that assumes all HEAF events will reach a deterministic ZOI or damage profile. The staff believes the best approach to evaluate these risk impacts will be to solicit pilot plants and use their existing

HEAF scenarios and fire PRA plant modelling techniques. These scenarios would be evaluated for the presence of aluminium and modified to account for an increased ZOI using the existing fire PRA internal plant risk model.

This approach will require cooperation from several pilot plants that have configurations possibly reflecting an increase in risk from the increased ZOI. In particular, the pilot plants should verify that targets of significance (i.e., cables and electrical equipment) are out of the ZOI in the existing models but within the increased ZOI. The additional damage estimates, once incorporated into their existing and modified models, will enable calculation of the change or delta in core damage frequency (CDF) or large early-release frequency (LERF). This exercise would be most successfully as a joint activity between the Electric Power Research Institute (EPRI) and the U.S. NRC's Office of Nuclear Regulatory Research (RES) working under the terms of the NRC/EPRI Memorandum of Understanding (MOU) and accompanying Fire Risk Addendum.

Based on the step-by-step approach outlined above, the staff should be able to effectively conclude what the risk and safety significance is from the presence of aluminium in HEAF. The staff believes this evaluation can be performed in a timely manner if detailed plant information is available.

PHASE 2 OECD/NEA INTERNATIONAL HEAF TESTING

The NRC is collaborating with our international partners (in the frame of a common OECD NEA project) to conduct a second set of full-scale experiments to further explore the damage conditions created by HEAF events. The second phase of testing is scheduled to begin in 2018, and the results from this experimental series will report on the thermal and mechanical damage caused by HEAF events. The data collected from the experimental series will support updating and advancing methods to characterize and assess the risk of HEAF events. Previous work in Phase 1 examined electrical cabinets with a wide variety of manufacturers, manufacture dates, materials, and configurations. Although the tested cabinets provided an important view of the performance of available equipment, too many uncontrolled variables exist to fully understand their significance on the severity of the HEAF.

To prioritize the parameters and phenomena in need of further study, the NRC conducted a phenomena identification and ranking table (PIRT) exercise with the international partners. A PIRT is a facilitated expert elicitation designed to identify the important phenomena and parameters of a given subject and to prioritize them for future study. The results of the PIRT exercise suggest a focus on electrical characterization of the arc, the material of components, and mitigation strategies. To increase the repeatability of tests, the electrical enclosures and bus ducts will be uniform and carefully specified. The enclosure configuration will be chosen based on typical plant design, and preliminary tests will be performed to ensure the arc will not extinguish until the power supply to the cabinet is turned off. The bus bar material and configuration will be chosen based on the desire for a known and repeatable arc location and plasma ejection direction. Real-time measurements of voltage and current during the arc will provide data for calculation of arc energy and arc power for comparison to thermal and pressure measurements. The use of a common NPP electrical cabinet and bus duct should increase repeatability between experiments.

The NRC has developed a preliminary draft test plan and is currently in the process of dispositioning comments from international partners and the public. The draft test plan was submitted to the *Federal Register* on August 8, 2017, for a 30 day public comment period under the agency docket number NRC-2017-0168 [23].

CONCLUSIONS

For many NPPs, fire is a dominant contributor to plant risk. HEAF-initiated scenarios can contribute significantly to fire risk, and operational experience shows that HEAFs continue to occur despite the comprehensive electrical protection designed to mitigate such events. Operational experience also suggests that significant complications to shutting down the plant can occur during and after a HEAF [1].

Like most major fire events, HEAF normally generate large quantities of dense smoke, cause significant equipment damage, and in many cases, challenge operators with scenarios that they are unlikely to have been trained on. These conditions contribute to the likelihood of human errors, which can greatly complicate the plant response to these events.

The OECD NEA HEAF testing program identified a potential issue where existing regulations, guidance, and analytical models used for PRA applications may not bound the hazard if aluminium is present. Under these conditions, the ZOI of damage could be substantially larger than indicated in the current guidance. Also, recent HEAF testing and operating experience identified a new potential failure mode (the spread of electrically conductive aluminium by-products in the smoke of HEAF events involving aluminium). This by-product has the potential to damage sensitive electronics beyond the ZOI such as in the Fort Calhoun fire event in 2011. It is possible that an enlarged ZOI accounting for the presence of aluminium could result in loss of redundant equipment during a HEAF event. The severity and risk impact of these events and potential consequences highlight the need for a greater understanding of the underlying phenomena and treatment of HEAF events to provide adequate NPP safety.

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U.S. NRC Actions and Path Forward as a Result of International High Energy Arcing Fault Phase 1 Testing Results

United States Nuclear Regulatory Commission

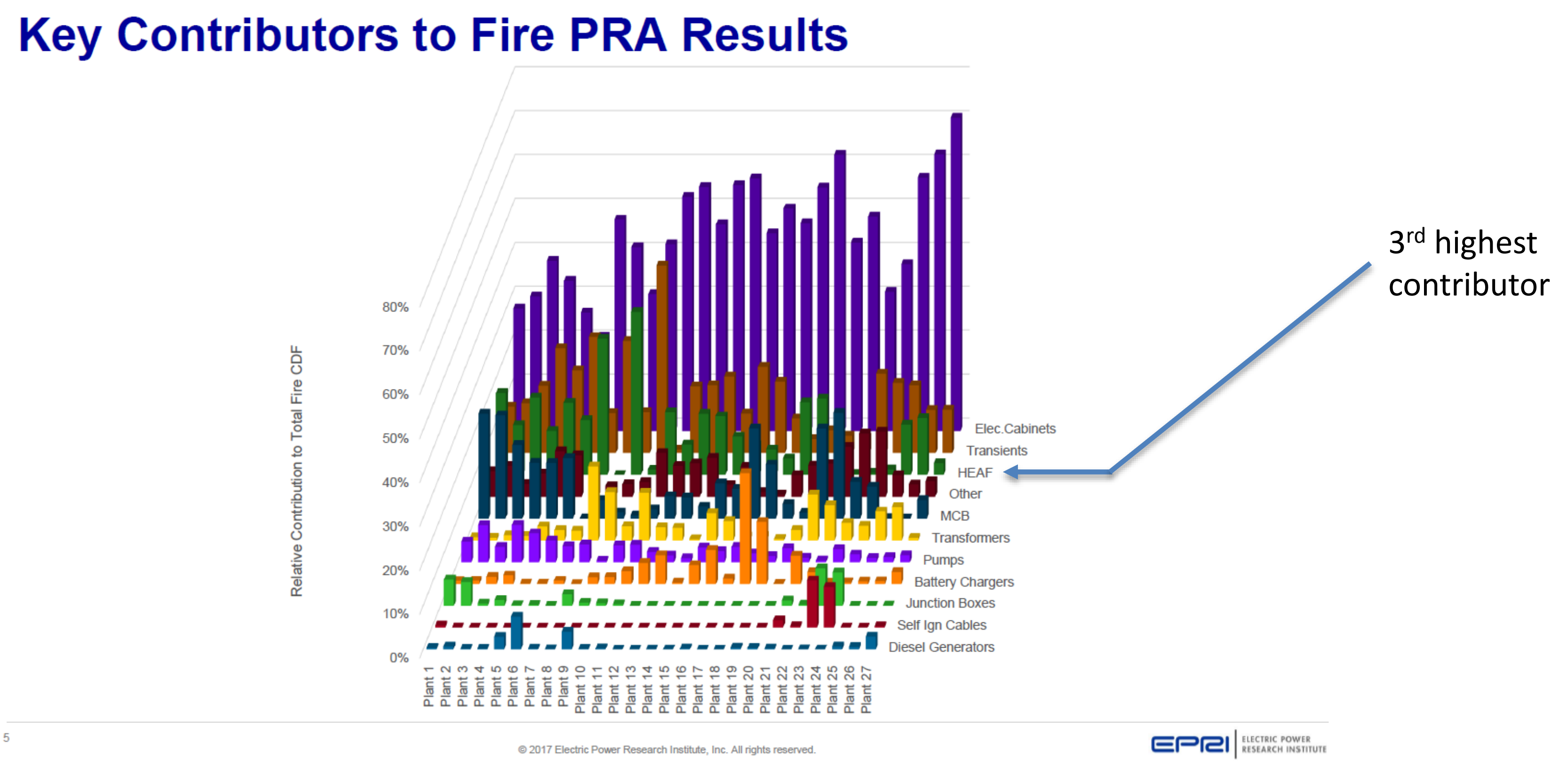
Nicholas Melly
Gabriel Taylor, PE
Kenneth Hamburger
David Stroup, PE
Mark Henry Salley, PE

What is a HEAF?

- High Energy Arcing Faults (HEAFs) are energetic or explosive electrical equipment faults characterized by rapid release of energy in the form of heat, light, vaporized metal and pressure increases due to high current arcs between energized electrical conductors or between energized electrical components and neutral or ground.
  - First phase: short, rapid release of electrical energy which may result in projectiles (from damaged electrical components or housing) and/or fire(s) involving the electrical device itself, as well as any external exposed combustibles, such as overhead exposed cable trays or nearby panels, that may be ignited during the energetic phase
    - Arc Temperatures in the range of 35,000 F (19,426 C)
  - Second phase, i.e., the ensuing fire(s): is treated similar to other postulated fires within the zone of influence

PRA Risk Significant Contribution

- Presentation by EPRI for the Risk and Safety Management (RSM)Integration Committee Meeting August 30, 2017



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HEAF Event Importance

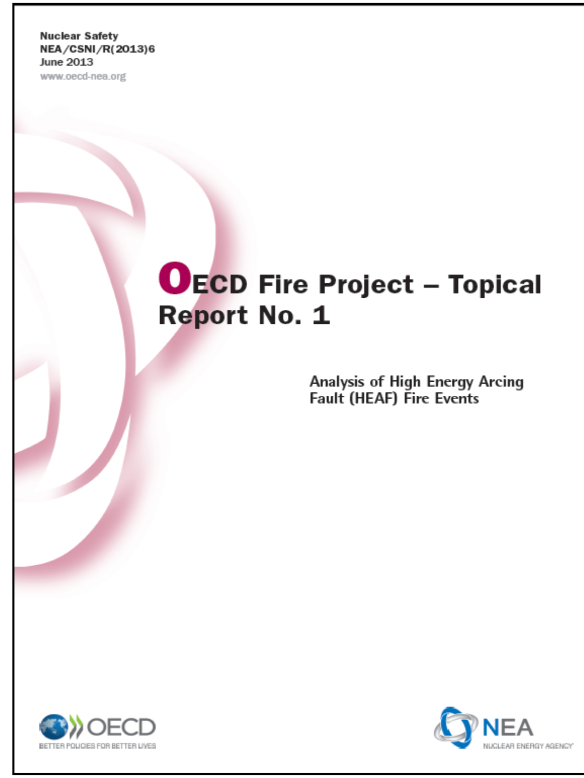
- Unique challenges complicate the ability to safely shutdown
  - Electrical disturbances often causes loss of essential electrical power
  - Extensive physical damage
  - Products of combustion and smoke hinder operators and fire brigade members
  - Potential for loss of fire zone barrier integrity

September 9, 1987
Germany

March 18, 2017
United States
Turkey Point

Background of the HEAF Program

- OECD Fire Incident Records Exchange Project (FIRE)
  - *"Analysis of High Energy Arcing Fault (HEAF) Fire Events,"* NEA/CSNI/R(2013)6
  - 48 of 415 fire events collected represent HEAF-induced fire events (over 10%)

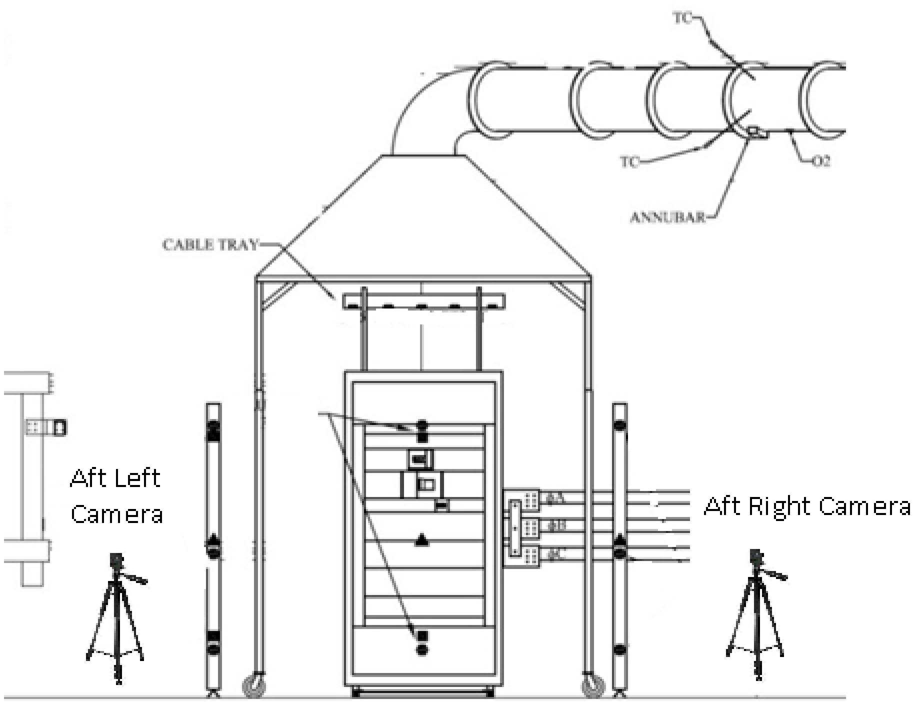


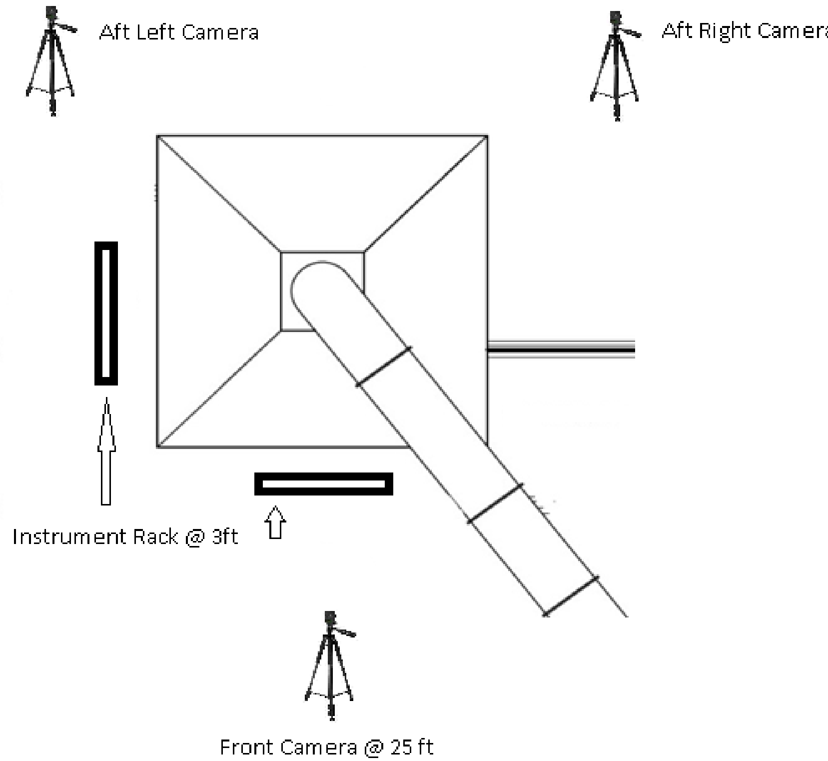
https://www.oecd-nea.org/nsd/docs/2013/csni-r2013-6.pdf

Realistic Quantification of Hazard

- NRC/OECD testing has been, and will continue to be, informed by Operating Experience and NPP configurations:
  - LERs describe numerous three-phase arc faults with failure of an upstream breaker
  - Real plant equipment used in testing
  - Voltage, current, arc duration within the bounds observed in LERs
  - Damage observed comports with LERs

Test Layout (Views)





Phase I Testing Results

- Material Impact of Aluminum
  - Potentially much larger ZOI
  - Potentially greater likelihood of maintaining an arc at low voltages
  - Higher risk of fire propagation

Phase I Testing Results

- New Failure Mode: Conductive Byproducts
  - Conductive AL byproducts coated facility
  - Shorted out equipment and damaged electrical circuits
- Fort Calhoun HEAF event- June 7, 2011
  - Adjacent cabinets affected by conductive smoke and soot

Test 23

Test 26

Information Notice (IN) 2017-04

- *"High Energy Arc Faults in Electrical Equipment Containing Aluminum Components"*
  - OECD/NEA international test program insights
  - 6 U.S. operating experience events involving aluminum components

Plant	Date
Fort Calhoun	June 7, 2011
Columbia	August 5, 2009
Diablo Canyon	May 15, 2000
Zion	April 3, 1994
Shearon Harris	October 9, 1989
Kewaunee	July 10, 1987

  - Issued August 21, 2017 https://www.nrc.gov/docs/ML1705/ML17058A343.pdf

Aluminum HEAF Generic Issue

- Generic Issues Program Pre-GI-018
  - The NRC has performed a screening review as part of the GI process related to HEAF events involving aluminum components
  - The generic issue review panel (GIRP) determined that the seven screening criteria were met in accordance with management directive 6.4 (ML14245A048) and issued the screening evaluation in August 2017 (ML16349A027)
  - The staff has recommended a two phase approach to address the generic issue and identified both short term and long term actions
  - GIRP memo currently in concurrence

NRC Regulatory Actions

- Short Term Actions
  - Industry survey on extent of Aluminum
  - Estimate the risk from potential ZOI increases identified by testing and OpE
  - Determine if additional actions are necessary
- Long Term Actions
  - Perform additional focused HEAF testing designed to quantify the ZOI with Aluminum
  - Update and revise current HEAF guidance in NUREG/CR-6850 Appendix M and FAQ 07-0035

PIRT & Phase II Testing

- Phase II testing to be conducted as an NEA/OECD International Project with more focused objectives and tightly controlled parameters
- International Phenomena Identification and Ranking Table (PIRT) exercise held in February 2017
- Key Parameters (Early Insights):
  - Aluminum oxidation and byproducts
  - Pressure effects
  - Target characterization and sensitivity
  - Mitigating factors (“HEAF shields”)
  - Cabinet to Cabinet Spread
- PIRT NUREG to be issued Fall 2017
- OECD/NEA Phase II Testing currently under development