High Energy Arcing Faults (HEAF) Research Update for Federal Fire Working Group

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June 7, 2018
Purpose

• Provide Overview of NRC Fire Research Program:
  – Electrical Enclosure Fires
  – Arc Flash /Arc Blast Events
  – High Energy Arcing Faults (HEAF)
• Provide update on HEAF program
• Promote Safety across Federal Agencies
  – HEAFs are not unique to the Nuclear Industry
Reference Material

• All program reference materials including links to NUREG’s, international reports and publically available test documentation can be found at the end of this presentation
Categories of Electrical Enclosures - Failure Modes

- **Thermal Fires**
  - ZOI A
  - HRR<sub>α</sub>X
  - System 2
  - Cable Tray 2

- **High Energy Arcing Fires**
  - ZOI
  - 1.5 m (5 ft)
  - 0.9 m (3 ft)

**Electrical Cabinet Heat Release Rate Test Program (Pending)**

**Joint Analysis of Arc Faults**
OECD International Testing Program for High Energy Arc Faults (HEAF)
PRA Risk Significant Contribution

• Presentation by EPRI for the Regulatory Information Conference **TH30 - Improving Realism in Fire PRA** — March 15, 2018

**Key Contributors to Fire PRA Results**
HEAF Hazard

Electrical Arc

- 35,000 °F
- Molten Metal
- Pressure Waves
- Sound Waves
- Shrapnel
- Hot Air-Rapid Expansion
- Intense Light

Copper Vapor:
Solid to Vapor
Expands by 67,000 times

Ref. UAW Electrical Safety in the Workplace
HEAF Definition (Bin 16)

• Event Frequency classification
• Need for clear definitions
  – Subdivide Bin 16
  – Arc Fault Class 1 (Arc Flash)
  – Arc Fault Class 2 (Arc/Blast/HEAF)
  – Arc Fault Class 3 (Arc Blast/HEAF)
• NRC working with NFPA/IEEE
  – Continued discussion to finalize definitions for arc fault events
Arc Fault Class 1 (Arc Flash) Working Definition

• **Arc Fault Class 1 (Arc Flash)** – Damage is contained in within the general confines of the component of origin.
  – These events are associated with minor damage and minimal bus bar degradation from melting/vaporization.
Arc Fault Class 2 (Arc Blast/HEAF) Working Definition

• Arc Fault Class 2 (Arc Blast/HEAF) – Damage is contained in within the general confines of the component of origin. However, arc blast effects have the potential to damage surrounding equipment through pressure rise effects (i.e. severe equipment deformation, thrown doors, degraded fire barriers).
  – Typically do not create ensuing fires
  – Typically associated with designed electrical coordination and breaker performance
  – Pressure effects are highly dependent on room configuration and electrical characteristics of the event
Arc Fault Class 3 (Arc Blast/HEAF) Working Definition

• Arc Fault Class 3 (Arc Blast/HEAF) – Damage includes the component of origin as well as spread to surrounding equipment within the fire zone. This damage includes pressure rise effects (i.e. severe equipment deformation, thrown doors, degraded fire barriers) which potentially can effect equipment in other fire zone(s).
  - These events are typically contingent with ensuing fire conditions
  - Typically indicative of a level of circuit protection failure and/or design flaw allowing for extended duration arc events
  - Pressure effects are highly dependent on room configuration and electrical characteristics of the event
## Arc Fault Classifications

<table>
<thead>
<tr>
<th>Arc Severity Classifications</th>
<th>Arc Fault Class 1 (Arc Flash)</th>
<th>Arc Fault Class 2 (Arc Blast/HEAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc duration limited by proper electrical protection design</td>
<td><img src="image1.jpg" alt="Image 1" /> <img src="image2.jpg" alt="Image 2" /></td>
<td><img src="image3.jpg" alt="Image 3" /> <img src="image4.jpg" alt="Image 4" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Protective System Performance (Duration)</th>
<th>Arc Fault Class 3 (HEAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc duration persists for an extended duration indicative of a level of circuit protection failure and/or protection design flaw</td>
<td><img src="image5.jpg" alt="Image 5" /> <img src="image6.jpg" alt="Image 6" /> <img src="image7.jpg" alt="Image 7" /> <img src="image8.jpg" alt="Image 8" /></td>
</tr>
</tbody>
</table>
Example of Recent Electrical Enclosure HEAF Experience

San Onofre; 2001

Onagawa; 2011
Example of Recent Bus Duct HEAF Experience

Diablo Canyon Bus Duct (OpE) 2000
Zion Bus Duct (testing) 2016
Columbia Bus Duct (OpE) 2009
NRC Regulations

- 10CFR 50 Appendix A “General Design Criteria (GDC)”
- GDC 3
  “Structures, systems, and components important to safety shall be designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions.”
- GDC 17
  “The onsite electric power supplies, including the batteries, and the onsite electric distribution system, shall have sufficient independence, redundancy, and testability to perform their safety functions assuming a single failure.”
Phase I HEAF Testing

- 26 full-scale experiments carried out at KEMA high energy test facility between 2014-2016.
Phase I HEAF Testing

Test #3: 480 V, 35 kA, 8 seconds
Copper Bus Bars

If audio is not working use this link: Audio file
Phase I HEAF Testing

Test #15: 10 kV, 15 kA, 3 seconds
Oil-filled breaker (oil removed), copper bus bars

If audio is not working use this link: Audio file
Phase I HEAF Testing

Test #23: 480 V, 40 kA, 7 seconds
Aluminum bus bars

If audio is not working use this link: Audio file
Phase I HEAF Testing

Test #26: 4.16 kV, 26 kA, 3.5 seconds
Bus Duct, copper bus bars, aluminum housing

If audio is not working use this link: Audio file
Phase I HEAF 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 HEAF Testing Results

- New Failure Mode: Conductive Products of Combustion
  - Conductive AL byproducts coated facility
  - Shorted out equipment and damaged electrical circuits
- Fort Calhoun HEAF event-June 7, 2011
  - Adjacent cabinets affected by HEAF bi-products
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 is in the process of finalization and release of the screening phase document
  – The staff has recommended a two phase approach to address the generic issue and identified both short term and long term actions
  – GIRP memo issued (ML16349A027)
  – Moving into next phase of Generic Issue Program
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

<table>
<thead>
<tr>
<th>Plant</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>Fort Calhoun</td>
<td>June 7, 2011</td>
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<tr>
<td>Columbia</td>
<td>August 5, 2009</td>
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<tr>
<td>Diablo Canyon</td>
<td>May 15, 2000</td>
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<tr>
<td>Zion</td>
<td>April 3, 1994</td>
</tr>
<tr>
<td>Shearon Harris</td>
<td>October 9, 1989</td>
</tr>
<tr>
<td>Kewaunee</td>
<td>July 10, 1987</td>
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– Issued August 21, 2017
Phase II Draft Test Plan

• Public Comment Period
  – OECD/NEA Phase I members for comment on June 30, 2017
  – Federal Register notice (82 FR 36006) published on August 2, 2017
  – Public comment period closed September 1, 2017

• 64 comments received in total + 27 EPRI comments
Small Scale

• Purpose
  – Characterize HEAF event particles characteristics near arc

• Objectives
  – Investigate particle parameters
    • Density, conductivity, size distribution, rates of production, composition, trajectory, morphology
  – Evaluate physical parameters
    • Temperature, heat flux, HRR, mass loss
  – Measure particle emission characteristics and electrical data
Small Scale

Testing approach

• Sandia National Laboratories lightning simulator
• Single phase arcing between two vertical bus bars
• Variables
  – Voltage, Current, Duration, Material
• Particle collection and post test analysis
• High speed videography
Small Scale Testing apparatus
Small Scale Measurements

- Videography
  - High-speed infrared (IR) imaging
  - Trajectory
- Particle collection
  - Aerogel plates (99.999% SiO₂)
  - Carbon tape
- Particle Analysis
  - Energy dispersive x-ray analysis (EDXA)
  - Electron energy loss spectroscopy (EELs)
  - Scanning electron microscopy (SEM)
  - Raman spectroscopy
  - X-ray photoelectron spectroscopy
April Public Workshop

• Held April 18\textsuperscript{th} and 19\textsuperscript{th} at NRC headquarters

• Objectives
  – Update stakeholders on the status of the research program and GI process
  – Discuss and resolve comments received on the draft test plan
  – Solicit input on equipment and test parameters
April Public Workshop

• Approximately 30 attendees from NRC, industry groups, NIST, EPRI, NFPA, and FM Global

• Outcomes
  – Further revisions of the draft test plan to reflect realistic configurations
  – Better alignment with stakeholders on the objectives and methods of the research program
  – Results, transcripts, and presentations to be preserved in a NUREG/CP
Future Work – Next Steps

• Finalize Test Plans
  – Small Scale Summer 2018
    • Start Testing Summer 2018
  – Large Scale Summer 2018
    • Aluminum Fall 2018
    • OECD/NEA Phase II 2019

• Updated Literature Review
  – Winter 2018
    • Update SNL Survey 2008
  – Future NUREG/IA-0470 Vol 2, 3
    • Recent Japanese Testing
• Electrical Enclosure Fires, Arc Flashes, Arc Blasts and HEAFs are not unique to Nuclear Power Plants
• However, they warrant special attention by the NRC and the Nuclear Industry due to their potential impact on Reactor Safety
• NRC would like to continue to work in collaboration with U.S. and International Partners
• NRC plans to use the FFWG to keep our Federal Partners Informed
References
• Fire PRA Needs
  – Bin 15 Electrical Enclosure Fires
  – Bin 16 HEAF

• Lesson Learned
  – Bin 15 Too Broad
    • Low Voltage Controls considered same risk as Medium Voltage Switchgear
  – Create Realistic Divisions for Bin 16
    • Discussion later in workshop
Electrical Enclosure Fire Experiments (Bin 15)

- **Heat Release Rates of Electrical Enclosure Fires** (HELEN-FIRE) NUREG/CR-7197
- 112 Full Scale Electrical Enclosure Fires
- Developed a Series of Heat Release Rate (HRR) Profiles
- Non- Energized
  - No electrical current

[Link to Report](https://www.nrc.gov/docs/ML1611/ML16110A037.pdf)
Electrical Enclosure Fire Methodology

- NRC/EPRI Working Group
- Classification of Electrical Enclosures (function, size, content, ventilation)
- Determined HRR probability distributions for corresponding categories
- Characterization of Fire Plumes
  - NIST Fire Dynamics Simulator (FDS)

https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2178/
Background of the HEAF Program

- OECD Fire Incident Records Exchange Project (FIRE)
  - 48 of 415 fire events collected represent HEAF-induced fire events (over 10%)
- International Partners
  - Canada, Finland, France, Germany, Japan, Korea, Spain, U.S.

Background of the HEAF Program


  - Insights from operating experience with partly significant HEAF events
  - Literature study on methods for predicting HEAF consequences

Phase I HEAF Testing Report


HEAF PIRT

• International Phenomena Identification and Ranking Table (PIRT) exercise held in February 2017

• Early Insights:
  – Aluminum oxidation and byproducts
  – Pressure effects
  – Target characterization and sensitivity
  – Mitigating factors (“HEAF shields”)

https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2218/
International Agreement Report

• NUREG/IA-0470 Volume 1 “Nuclear Regulatory Authority Experimental Program to Characterize and Understand High Energy Arcing Fault (HEAF) Phenomena”

• International Partnership with Japan Regulator
  – Secretariat of Nuclear Regulation Authority S/NRA/R

https://www.nrc.gov/reading-rm/doc-collections/nuregs/agreement/ia0470/
Small Scale FRN Reference Slide

- [www.regulations.gov](http://www.regulations.gov)
- Docket ID: NRC-2018-0040
- Aluminum High Energy Arc Fault (HEAF) Particle Size Characterization Test Plan – DRAFT

[Link to the PDF document](https://www.nrc.gov/docs/ML1803/ML18036A448.pdf)
Needs and Objectives

- Document to support April Workshop
- General discussion of hazard and identification of information needed to inform testing to be realistic

https://adamswebsearch2.nrc.gov/webSearch2/view?AccessionNumber=ML18081B300