Overview of U.S. Nuclear Regulatory Commission Research Activities to Update Probabilistic Risk Treatment of High Energy Arcing Faults

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ABSTRACT

International nuclear power plant (NPP) operating experience has demonstrated that High Energy Arcing Faults (HEAFs), which result from electrical system failures, can cause a sustained arc that leads to the rapid release of energy in the form of heat, vaporized metal, and mechanical force. Because of their hazard and potential risk significance, the U.S. Nuclear Regulatory Commission (NRC) has implemented a multi-year research plan to develop more realistic models and methods to assess HEAF hazards. This paper summarizes, and provides a status update on, the research objectives and key tasks, including: (1) model development and survey of plant electrical applications and configurations; (2) physical testing needed to inform and validate the HEAF hazard model and assess component fragility; and (3) updates to Probabilistic Risk Assessment data and methods to improve the realism and fidelity of the HEAF hazard model. This work also supports the ongoing international Organisation for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) HEAF 2 Project.

INTRODUCTION

Electrical system failure HEAF events are energetic electrical arcing faults that can lead to the rapid release of energy. This energy release can result in high heat fluxes in the vicinity of the HEAF, vaporization of metal, release of ionized gas and smoke, and mechanical shocks to nearby equipment. The characteristics of HEAF events result in faster development of the fire and associated damage compared to more traditional fire events that include delay time related to the fire ignition and growth stages [1]. As a result, HEAF initiated fire events can rapidly propagate to other equipment and result in unexpected challenges associated with the rapid onset of fire related damage and impacts from smoke and ionized gases.

Because of their potential to induce an initiating event (e.g., loss of feedwater, reactor trip) and lead to failure of adjacent mitigating equipment, HEAF events can have risk-significant impacts. The NRC's Accident Sequence Precursor (ASP) program systematically evaluates U.S. NPP operating experience to identify potential severe accident precursors [2]. An ASP precursor is defined as an initiating event with a conditional core damage probability (CCDP) greater than or equal to 1×10^{-6} (one in a million) or a degraded plant condition resulting in an increase in core damage probability (ΔCDP) greater than or equal to 1×10^{-6}. The ASP program identified nine HEAF related precursor events since 1989. Seven of the nine ASP HEAF precursors were analysed as an initiating event and quantified using CCDP, with results ranging from $\sim 2 \times 10^{-6}$ to $\sim 4 \times 10^{-4}$. For these events, the HEAF events resulted in plant transients, loss of electrical busses, and losses of offsite power. Two of the ASP HEAF events were assessed as a degraded condition due to the nature of the specific condition and were quantified by ΔCDP, with results ranging from ~ 4×10^{-6} to ~ 4×10^{-4}. Key insights derived from these assessments are the risk significance associated plant transients, loss of electrical busses, and loss of offsite power for HEAF events. Further, design and quality control deficiencies that lead to high resistance breaker connections increase the potential for initiation of HEAF events. The insights from the U.S. experience are consistent with international operating experience for HEAF events [3].

Given the potential risk importance of HEAF events, the NRC has undertaken substantial work over the last two decades, in collaboration with the Electric Power Research Institute (EPRI) and the OECD/NEA, to develop methods and models to support the risk assessment of HEAFs. Specific activities include: (1) model development and survey of plant electrical applications and configurations; (2) physical testing needed to inform and validate the HEAF hazard model and assess component fragility; and (3) updates to Probabilistic Risk Assessment (PRA) data and methods to improve the realism and fidelity of the HEAF hazard model. The results of this program are expected to improve the realism of HEAF models in fire probabilistic risk assessment (Fire PRAs).

Regulatory Context

The NRC's fire protection requirements are contained in Title 10 to the U.S. Code of Federal Regulations (CFR) Part 50.48, "Fire protection". These regulations require a NPP to implement a fire protection plan that meets the requirements of 10 CFR 50, Appendix A, General Design Criterion (GDC) 3, "Fire protection". GDC 3 specifies, in part, that NPP systems, structures, and components (SSCs) important to safety be designed and located to minimize the probability and effect of fires and explosions. The NRC's regulations provide two options for meeting this requirement: (1) a deterministic option described under 10 CFR 50.48(b) that references the requirements contained in 10 CFR 50, Appendix R, "Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979," and generally applicable to NPPs licensed before 1979 or as specified in license conditions for later plants; or (2) a risk-informed, performance-based option provided under 10 CFR 50.48(c) which allows use of the National Fire Protection Association (NFPA) Standard NFPA 805, 2001 Edition [4], with some exceptions. The approach described in Appendix R provides deterministic requirements, such as limiting the damage from a fire to ensure that one train of equipment necessary to achieve hot shutdown is free from fire related damage. These criteria generally are supported by prescriptive requirements covering specific fire protection features such as the use of 1-hour or 3-hour fire barriers, installed automatic fire detection and suppression, 20 ft (6.1 m) of horizontal separation with no intervening combustibles, or use of alternate shutdown capability. Conversely, NFPA 805 specifies high level goals, performance objectives, and performance criteria for nuclear safety and radioactive release. The licensee may use engineering analysis, probabilistic risk assessment, or fire modeling calculation to demonstrate that the performance goals, objectives, and criteria are satisfied. As described in the Statements of Consideration for the final rulemaking approving use of NFPA 805 [5], the methodology incorporates a number of attributes consistent with a performance-based approach, notably:

- measurable or calculable parameters exist to monitor the system, including facility performance,
- objective criteria to assess performance are established based on risk insights, deterministic analyses, and/or performance history,
- flexibility to determine how to meet established performance criteria in ways that will encourage and reward improved outcomes, and

- a framework exists to assess the failure to meet performance criterion and to ensure that such failures, while undesirable, will not constitute or result in an immediate safety concern.

The NRC provides guidance for implementing the NFPA-805 option in Regulatory Guide (RG) 1.205, "Risk-Informed, Performance-Based Fire Protection for Existing Light-Water Nuclear Power Plants" [6]. Although a Fire PRA is not mandatory to transition to NFPA 805, RG 1.205 notes that a plant-specific Fire PRA enables a licensee to fully realize the safety and cost benefits of making a transition to NFPA 805, particularly by supporting risk-informed changes to the fire protection program that can be made without prior NRC approval. To the extent that a Fire PRA is used to support NFPA 805 implementation, the NRC must find the PRA approach, methods, and data acceptable. The NRC endorsed NUREG/CR-6850/EPRI 1011989, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Final Report" [7] and its Supplement 1 [8], as one acceptable method for conducting a Fire PRA. For the purposes of assessing HEAF events, NUREG/CR-6850 and its supplement define a zone of influence (ZOI) surrounding the initiation point of a HEAF event within which certain equipment is assumed to be damaged. For example, the following ZOI guidelines are provided for HEAF events in NUREG/CR-6850:

- For HEAF events within an electrical cabinet, any unprotected cables in the first overhead cable tray within 1.5 m (5 ft) vertical distance of the top of the cabinet and 0.3 m (1 ft) horizontally from the cabinet face will be within the ZOI and assumed to damaged. Additionally, any equipment within 0.9 m (3 ft) horizontal distance from the cabinet front or rear panel and at or below the top of the cabinet will be within the ZOI (NUREG/CR-6850, Volume 2, Appendix M).
- For HEAF events within an iso-phase bus ducts, the ZOI is assumed to be a sphere centred on the fault point and measuring 1.5 m (5 ft) feet in radius (NUREG/CR-6850, Supplement 1).
- For HEAF events within non-iso phase bus ducts, the ZOI includes: (1) a downward expanding cone from the point of arcing enclosing a total solid angle of 30° to a maximum diameter of 6.0 m (20'); (2) a sphere with a radius of 0.45 m (1.5 ft) from the point of arcing (assumed to be the center of the bus duct) (NUREG/CR-6850, Supplement 1).

Motivation for HEAF Research

In 2013 the OECD/NEA FIRE (*F*ire *I*ncidents *R*ecords Exchange) Database Project published an analysis of HEAF events that occurred up to mid-2012 [3], which recommended:

> *"…to perform experiments for obtaining comprehensive scientific fire data on the HEAF phenomena known to occur in nuclear power plants through carefully designed experiments, to be able to develop more realistic models to account for failure modes and consequences of HEAF, to advance the state of knowledge and provide better characterization of HEAF in fire PRA, and, in particular, to answer key questions, which cannot yet be answered form analyzing the HEAF events in the OECD FIRE Database. Such key questions can be how to prevent and to detect HEAF or what would be the best way for limiting pressure phenomena and minimizing fire barrier element failures."*

In response to this recommendation, during the period of 2014 through 2016, twenty-six full-scale HEAF experiments were conducted under an OECD/NEA HEAF Project testing program [9]. These experiments used equipment typically found in NPP applications and controlled for four primary parameters: (1) location of arcing within the electrical enclosure; (2) arcing fault current; (3) voltage; and (4) arc duration. Key findings included the potential for increased severity of a HEAF event when aluminum was present and the increased likelihood of a HEAF event leading to ensuing fires for longer duration arcing events (i.e., greater than 2 seconds). As a result of the insights developed from this testing campaign, in addition to other relevant U.S. HEAF operating experience, the NRC issued Information Notice (IN) 2017-04, “High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components” [10]. IN 2017-04 noted that the equipment with copper components exhibited similar damage states as those postulated in NUREG/CR-6850; however, results obtained for equipment containing aluminum components exhibited damage states beyond NUREG/CR-6850 predictions. This observation was a key motivation for additional HEAF research activities.

OVERVIEW OF HEAF RESEARCH PROJECT PLAN

The NRC’s HEAF research project plan [11] is built upon earlier operating and experimental experience, including the results of the OECD/NEA HEAF Project testing program. This test program also provided valuable insights for measuring HEAF phenomena, including the sensor design requirements for measurement of heat release rates and total incident energy. In addition, the NRC developed an International Phenomena Identification and Ranking Table (PIRT) expert elicitation in 2017 [12] to prioritize research and regulatory needs.

The project plan consists of five main tasks:

1. Development and validation of a computational fluid dynamics (CFD) model capable of predicting HEAF hazards for a wide variety of electrical (e.g., system voltage, available current, fault duration) and equipment configurations (e.g., geometry and materials). The development of a verified and validated predictive model will reduce the amount of testing required to provide representative HEAF results applicable to a broad range of nuclear power plants. However, as discussed below, the development of the CFD (*c*omputational *f*luid *d*ynamics) model required additional physical testing to assess HEAF phenomena and configuration information regarding operating plant electrical distribution systems.
2. Survey of the U.S. nuclear fleet to ensure that full-scale HEAF experiments are representative of plant configurations, and to better understand the location, configuration, and material composition of equipment to support PRA method development. The survey provides information on equipment manufacturers, models, voltages, insulation, and the materials (e.g., aluminum, copper, steel).
3. Physical testing to support the development and validation of the CFD model. This includes a limited set of experiments that span the range of critical parameters to ensure that the development and validation of the model provide acceptable results. Three scales of experiments are included: small, medium (or “open-box”), and full-scale tests, with each series designed to investigate aspects of the HEAF phenomena that are best observed at these different length scales. As noted in the research project plan:
    - Small-scale experiments characterize the morphology and oxidation states of aluminum and copper particles generated by a HEAF event,
    - Medium-scale “open box” experiments characterize the electrical arc to support prediction of arc energy emitted during a HEAF event and provide information on enclosure and electrode mass loss data for both copper and aluminum electrodes, and
    - Full-scale experiments provide prototypical nuclear power plant data on enclosure breach, pressure effects, and serve as the representative scenarios for CFD models validated.
4. Fragility testing to assess target damage considering the shorter, higher energy source term associated with HEAF events and support development of a fragility model. The fragility model supports the development of the PRA method for assessing HEAF risk.

5. PRA method development to improve the realism and fidelity of the HEAF hazard model. This task includes an evaluation of U.S. operating experience, updated fire ignition frequencies, updated target fragility thresholds, and updated non-suppression probabilities.

Figure 1 provides an overview of the HEAF research project plan activities. These activities are grouped into three main areas: analytical tasks shown in blue (e.g., tasks 1, 2, and 5), experimental tasks shown in red (e.g., tasks 3 and 4), and outputs from this work shown in green (tools, methods, and data).

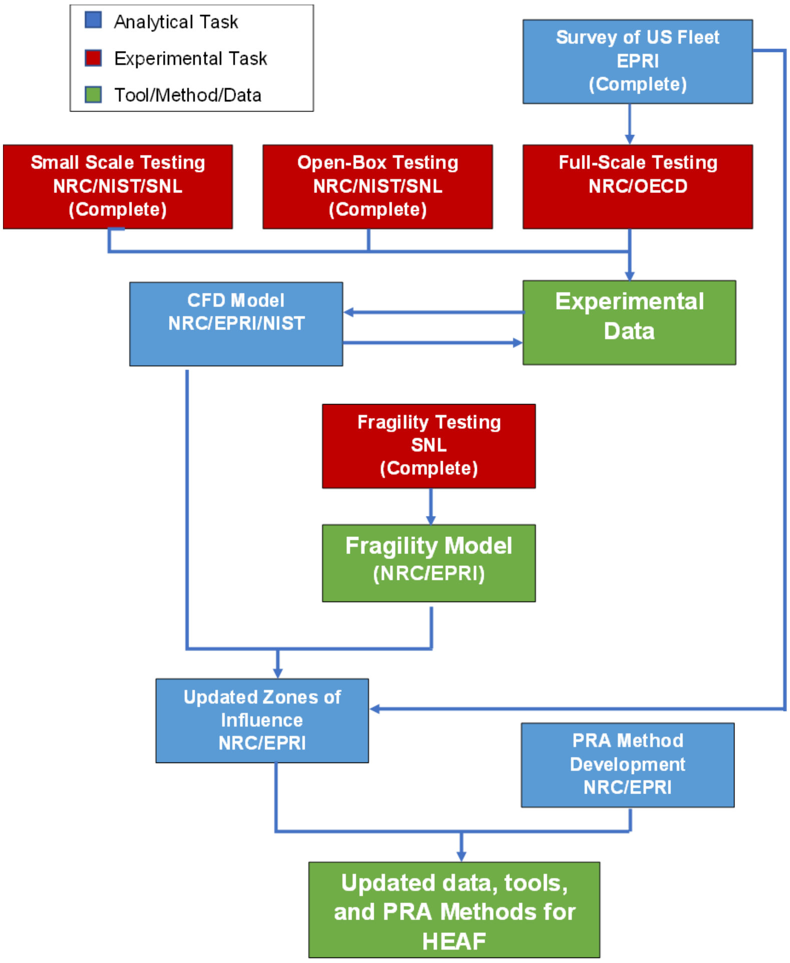

Figure 1 Overview of HEAF research project activities

A significant portion of the research project plan is being performed under the auspices of the NRC / EPRI Memorandum of Understanding (MOU). This arrangement allows the research activity to better leverage the knowledge and expertise to support the objectives of this work.

Each of the tasks is discussed in more detail in the following sections.

DEVELOPMENT AND VALIDATION OF A HEAF CFD MODEL

This activity focused on the development of a CFD model of HEAF events capable of calculating the incident energy for a variety of equipment configurations and materials. The predicted incident energy at various distances from the modelled electrical enclosure is subsequently used to determine the ZOIs for specific equipment. The objective of this work was the development of a tool that could leverage experimental data but provide information for configurations that were not subject to full-scale testing. This provided a more cost-effective and flexible approach considering the high costs associated with conducting full-scale HEAF experiments. The Fire Dynamics Simulator (FDS) was used to support this effort. FDS was initially released in 2000, has undergone extensive verification and validation, and provides significant capabilities to study fire dynamics and combustion. FDS includes a hydrodynamic model capable of solving the low-speed, thermally driven flow using a large eddy simulation turbulence model [13]. FDS includes a combustion model and a radiative heat transport model, in addition to capabilities for accommodating a wide variety of geometric configurations. A calculation matrix for FDS simulation runs was built on information gathered from surveying the U.S. nuclear fleet (e.g., switchgear manufacturer, bus bar materials, potential fault locations), operating experience, and previous testing. Over 130 simulation runs were identified, covering the following characteristics:

- Low voltage switchgear – bus bar material (aluminum, copper), arc duration, arc location, arc energy (34 FDS simulations);
- Medium voltage switchgear - bus bar material (aluminum, copper), arc duration, arc location, arc energy (42 FDS simulations);
- Non-segregated bus ducts – duct and bus bar material (aluminum, copper), arc duration, arc location, and arc energy (57 FDS simulations).

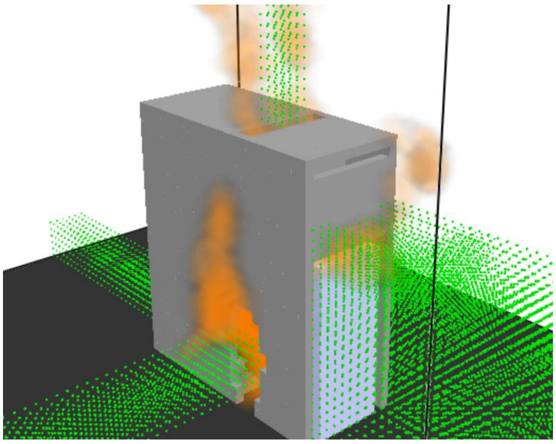

Figure 2 FDS calculated thermal plume for a 226 MJ HEAF (medium voltage switchgear cabinet)

An overview of the preliminary results of this work was published for public comment in May 2022 [14].

To provide additional confidence in the ZOIs calculated using FDS, the NRC staff also developed a modified model based on IEEE 1584-2018, “IEEE Guide for Performing Arc-Flash Hazard Calculations” [15]. This standard was developed to estimate incident energy at various distances from an arc flash event for the purpose of electrical safety. The NRC effort modified the IEEE arc flash model and its application in several ways, including fault current input (arc current rather than bolted fault current), inclusion of an enclosure breaching time, and solving for incident energy to determine a ZOI based on plant specific target fragilities [16]. Results obtained from the modified arc-flash confirmatory calculations are consistent with the more detailed FDS analysis for orientation experience of the more severe exposure conditions, thereby providing additional confidence in the CFD-derived ZOIs.

SURVEY OF THE U.S. NUCLEAR FLEET

EPRI developed and implemented a survey of U.S. nuclear power plants to obtain information about electrical distribution systems, including materials used, fault clearing times, electrical distribution configurations, switchgear manufacturer, and switchgear configuration. The results of this survey are summarized in an EPRI technical report [17].

Physical Testing to Characterize HEAF Phenomena

The physical testing portion of the research project plan was focused on obtaining information needed to develop and validate the FDS CFD model. Three types of experiments were performed:

- Small-scale experiments were conducted to better characterize aluminum and copper particle size distribution, rates of particle production, and particle morphology produced during electrical arc faults. Additionally, these tests provided accurate current measurements from which other electrical characteristics (e.g., arc impedance, energy, and power) could be determined. Thirty-six experiments were conducted, using variations in voltage, arc current, arc duration, arc gap size, and bus bar materials. The results from these small-scale experiments inform the energy balance model used in the FDS CFD model to predict additional energy release from particle involvement in the arc fault. The results of these experiments are documented in a Sandia National Laboratories (SNL) report [18].

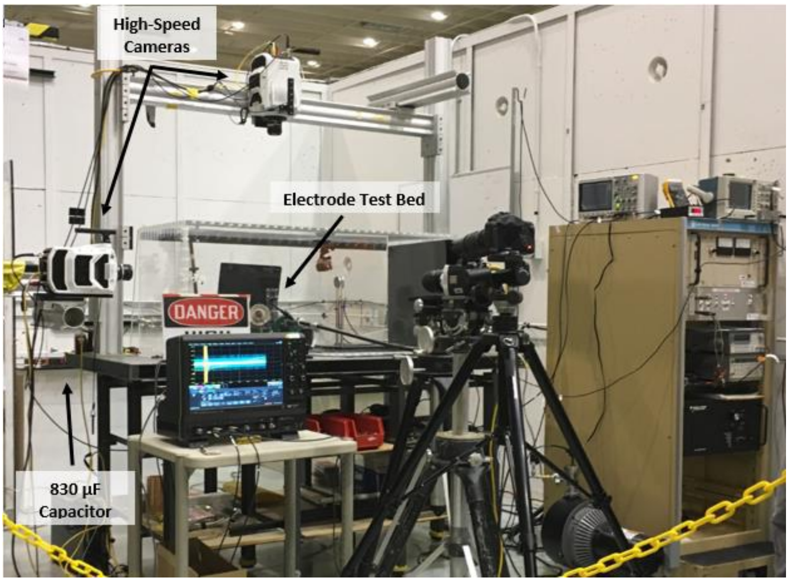

Figure 3 Small-scale arc fault test system

- Medium-scale “open box” experiments were similar to the small-scale experiments, but conducted at a larger scale. The “open box” allowed for more direct observation of the arc, enclosure breach, material loss, and electrical properties. The experiments were conducted in steel cubic metal boxes with one open face and a three-phase arcing fault located in the center of the box. Low- and medium-voltage experiments were run with both aluminum and copper electrodes. The experiments varied arc current and arc duration. Eleven low voltage (~ 1000 V) and six medium voltage (~ 6900 V) experiments were conducted to obtain mass loss information form the enclosure and electrodes. The results are summarized in an NRC Research Information Letter [19].

Figure 4 Open box experiment OB2 (copper electrode, 1000 V, 15 kA)

- Full-scale experiments were conducted in 2018 for nearly identical medium-voltage (~ 6900 V) switchgear with aluminum bus bars. These experiments used two different current and arc durations for a total of four full-scale tests. Insights from the experimental series included timing information related to enclosure breach, event progression, mass loss measurements for electrodes and steel enclosures, peak pressure rise, particle analysis, along with visual and thermal imaging data to better understand and characterize the hazard [20]. These experiments were run by the NRC to evaluate the aluminum HEAF hazard and are identified in the test matrix for the broader OECD/NEA HEAF 2 Project, an international joint project conducted under the auspices of the NEA [21].

Figure 5 Medium voltage switchgear testing, Test 2-19 (6.9 kV, 25.8 kA rms)

Collectively, these experimental campaigns enhanced the state-of-knowledge about HEAF phenomena, enabled more realistic modelling of HEAF events, and provided numerous lessons learned for experimental and sensor design to capture key HEAF phenomena.

EQUIPMENT FRAGILITY TESTING AND MODELLING

The objective of this portion of the research project plan was to establish the target fragilities for equipment that might be present within the HEAF ZOI. HEAF events generate short duration, extremely high heat fluxes and have different characteristics than traditional combustion fires. Therefore, the existing fragility for equipment exposed to a longer duration thermal fire, particularly cables, may not be applicable to the shorter duration higher heat flux expected from HEAF exposures. The fragility testing was conducted at the Solar Furnace at Sandia National Laboratories [22]. This facility is capable of concentrating sunlight to generate a heat flux of up to 6 MW/m^2 within a circle that is approximately 5 cm in diameter. Several different failure modes were evaluated, including ignition, damage as a function of total energy, electrical failure of cables, and sub-jacket temperature.

Figure 6 Parabolic dish at the Solar Furnace

Figure 7 Solar Furnace Test 1-34 (3 cable bundle, ~ 25 MJ/m^2**)**

Results from this testing, along with the full- and medium-scale data was used to develop a fragility model by the joint NRC/EPRI working group. The fragility model was based on experimental data, operating experience, and the current state of HEAF knowledge [23]. The working group focused on electrical cables; the most common target assessed for Fire PRA.

Damage thresholds for both thermoplastic and thermoset cables were developed as a function of total incident energy. In addition, the working group developed damage criteria for electrical bus ducts and provided guidance for crediting electric raceway fire barrier systems. These damage criteria are used in conjunction with the hazard modelling results to determine the ZOI.

HEAF PRA METHOD DEVELOPMENT

The previously described HEAF research activities supported the development of new methods and data to assess HEAF events more realistically within a nuclear plant PRA. In addition to providing updated ZOI limits based on operating experience and experimental testing, the research also led to updated HEAF ignition frequency and non-suppression probabilities [24]. While NUREG/CR-6850 and its supplement provided only one ZOI for each equipment type (switchgear, bus ducts, and isophase bus ducts), the new method provides a more realistic ZOI estimates based mainly on fault clearing time and arc energy. The new ZOIs were determined based on FDS simulations for load centers, switchgear, and non-segregated bus ducts. Based on the current state of knowledge, the working group could not make any distinction in the ZOIs based on the type of conductor material (copper or aluminum) in the PRA method. Future testing as part of the OECD/NEA HEAF Phase 2 Project, is expected to provide confirmatory evidence regarding this modelling conclusion.

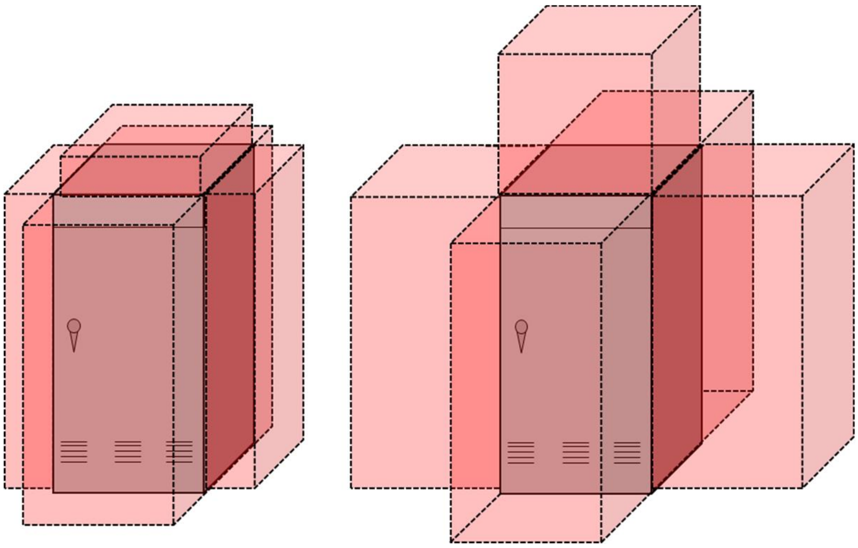

Figure 8 Representative changes in ZOI based on fault clearing time (left figure has shorter time)

The final PRA method report is expected to be issued in final form in late calendar year 2022 or early 2023, following the public comment period.

CONCLUSIONS

The NRC's fire research program has an overarching objective to improve the realism of fire modelling based on operating experience, experimental data, and analysis. The HEAF research project plan has effectively leveraged U.S. and international experience, in addition to a productive collaborative relationship between the USNRC and EPRI, to improve the modelling of this important phenomenon and guidance on its application.

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REFERENCES

[1] United States. Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES): Proceedings of the Information-Sharing Workshop on High Energy Arcing Faults (HEAFs), NUREG/CP-0311, Washington, DC, USA, 2019, https://www.nrc.gov/docs/ML1921/ML19212A150.pdf.

[2] United States. Nuclear Regulatory Commission (U.S. NRC): Accident Sequence Precursor (ASP) Program, 2022, online, https://www.nrc.gov/about-nrc/regulatory/research/asp.html, [accessed 18 July 2022].

[3] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI): OECD FIRE Project – Topical Report No. 1, Analysis of High Energy Arcing Fault (HEAF) Fire Events, NEA/CSNI/R(2013)6, Paris, France, June 2013, http://www.oecd-nea.org/documents/2013/sin/csni-r2013-6.pdf.

[4] National Fire Protection Association (NFRA): NFPA 805, Performacne-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition, Quincy, MA, USA, 2001.

[5] Office of the Federal Register: Voluntary Fire Protection Requirements for Light Water Reactors; Adoption of NFPA 805 as a Risk-Informed, Performance-Based Alternative, 69 FR 33536, June 16, 2004, https://www.federalregister.gov/d/04-13522.

[6] United States Nuclear Regulatory Commission (U.S. NRC): Regulatory Guide 1.205, Risk-Informed, Performance-Based Fire Protection for Existing Light-Water Nuclear Power Plants, Revision 2, 2021. https://www.nrc.gov/docs/ML0611/ML061100174.pdf.

[7] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI): Fire PRA Methodology for Nuclear Power Facilities, Final Report, EPRI/NRC-RES, NUREG/CR-6850 (EPRI 10191989), Washington, DC, and Palo Alto, CA, USA, 2005, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/index.html.

[8] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI): Fire PRA Methodology for Nuclear Power Facilities, Supplement 1: Fire Probabilistic Risk Assessment Methods Enhancements, EPRI/NRC-RES, NUREG/CR-6850 (EPRI 10191989), Washington, DC, and Palo Alto, CA, USA, 2010, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/s1/index.html.

[9] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI): Experimental Results from the International High Energy Arcing Fault (HEAF) Research Program Testing Phase 2014 to 2016, NEA/CSNI/R(2017)7, Paris, France, 2017, http://www.oecd-nea.org/documents/2016/sin/csni-r2017-7.pdf.

[10] United States Nuclear Regulatory Commission (U.S. NRC): High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components, Information Notice 2017-04, Washington, DC, USA, August 21, 2017, https://www.nrc.gov/docs/ML1705/ML17058A343.pdf.

[11] Hamburger, K.: NRC High Energy Arc Fault (HEAF) Research, online, 2022, available: https://www.nrc.gov/about-nrc/regulatory/research/fire-research/heaf-research.html, [accessed 20 July 2022].

[12] United States Nuclear Regulatory Commission(U.S. NRC) Office of Nuclear Regulatory Research (RES): An International Phenomena Identification and Ranking Table (PIRT) Expert Elicitation Exercise for High Energy Arcing Faults (HEAFs), NUREG-2218, Washington, DC, USA, January 2018, https://www.nrc.gov/docs/ML1803/ML18032A318.pdf.

[13] McGrattan, K., et al.: Fire Dynamics Simulator User's Guide, NIST Special Publication 1019, National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, 2022.

[14] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI): Determining the Zone of Influence for High Energy Arcing Faults Using Fire Dynamics Simulator, Draft Research Information Letter for Public Comment, (ML22095A237), 2022, https://www.nrc.gov/docs/ML2209/ML22095A237.pdf.

[15] Institute of Electrical and Electronics Engineers (IEEE): IEEE Guide for Performing Arc-Flash Hazard Calculations, IEEE 1584-2018, ISBN:978-1-5044-5262-5, November 2018, .https.//doi.org/10.1109/IEEESTD.2018.8563139.

[16] United States Nuclear Regulatory Commission (U.S. NRC): Predicting High Energy Arcing Fault Zones of Influence for Aluminum Using a Modified Arc Flash Model, Draft Research Information Letter, (ML22095A236), May 2022, https://www.nrc.gov/docs/ML2209/ML22095A236.pdf.

[17] Electric Power Research Institute (EPRI): Survey and Analysis of U.S. Nuclear Industry Relative to High Energy Arcing Faults in the Presence of Aluminum, Report EPRI 3002020692, Palo Alto, CA, USA, May 2021, https://www.epri.com/research/programs/061177/results/3002020692.

[18] Armijo, K. M., et al.: P , Electrical Arc Fault Particle Size Characterization, Sandia Report SAND2019-11145, Sandia National Laboratories (SNL), Albuquerque, NM and Livermore, CA, USA, September 2019, htps://www.osti.gov/servlets/purl/1592574.

[19] United States Nuclear Regulatory Commission (U.S. NRC): Report on High Energy Arcing Fault Experiments - Experimental Results from Open Box Enclosures, Research Information Letter (RIL) 2021-18, (NIST TN 2198, SAND2021-16075 R), Washington, DC, USA, December 2021, https://www.nrc.gov/docs/ML2136/ML21361A176.pdf.

[20] United States Nuclear Regulatory Commission (U.S. NRC): Report on High Energy Arcing Fault Experiments - Experimental Results from Medium Voltage Electrical Enclosures, Research Information Letter (RIL) 2021-10, (NIST TN 2188, SAND2021-12049 R), Washington, DC, USA, December 2021, https://www.nrc.gov/docs/ML2133/ML21334A196.pdf.

[21] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA): High Energy Arcing Fault Events (HEAF) Project, Paris, France, Limited to Project Members only, https://www.oecd-nea.org/jcms/pl_24977, [accessed 24 July 2022].

[22] United States Nuclear Regulatory Commission (U.S. NRC): HEAF Cable Fragility Testing at the Solar Furnace at the National Solar Thermal Test Facility, Research Information Letter (RIL) 2021-09, (SAND2021-11327), Washington, DC, USA, September 2021, https://www.nrc.gov/docs/ML2125/ML21259A256.pdf.

[23] United States Nuclear Regulatory Commission (U.S. NRC) and Electric Power Research Institute (EPRI): Target Fragilities for Equipment Vulnerable to High Energy Arcing Faults, Research Information Letter (RIL) 2022-01, (EPRI 3002023400), Washington, DC, and Palo Alto, CA, USA, May 2022, https://www.nrc.gov/docs/ML2213/ML22131A339.pdf.

[24] United States Nuclear Regulatory Commission (U.S. NRC) and Electric Power Research Institute (EPRI): High Energy Arcing Fault Frequency and Consequence Modeling, Draft Report for Comment, Draft NUREG-2262, Washington, DC, and Palo Alto, CA, USA, July 2022, https://www.nrc.gov/docs/ML2215/ML22158A071.pdf.