Target Fragilities for Equipment Vulnerable to High Energy Arcing Faults

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Final Report, May 2022
NRC Research Information Letter

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ABSTRACT

This report documents target fragilities for electrical cables subject to the effects of a high energy arcing fault (HEAF) with recommendations for the treatment of other equipment that may be impacted by this phenomena. These fragility estimates are necessary to support the definition of HEAF zones of influence (ZOI) used in fire probabilistic risk assessment (PRA). The conclusions and recommendations presented in this report represent the consensus of the joint Nuclear Regulatory Commission Office of Nuclear Regulatory Research (NRC-RES)/Electric Power Research Institute (EPRI) HEAF working group.

The primary effort involved using an informal expert elicitation process by which the question of, “What is the electrical cable target fragility (damage and ignition) from a HEAF exposure?” was presented and then two teams developed independent proposals which were submitted to an independent technical evaluator/integrator (TE/I) team. The TE/I team objectively evaluated and assessed the proposals and then developed an initial consensus paper. The working group reviewed, deliberated, and provided feedback to the initial consensus paper which was subsequently refined into the working group consensus presented in this report.

The target fragility estimates are specific to electrical cables exposed to a HEAF and include damage thresholds and recommendations on treatment of electrical cable ignition. Recommendations on the treatment for several cable raceway systems, such as electric raceway fire barrier systems (ERFBS) and bus duct damage limits are also presented. The recommendations in this report will be used by the HEAF working group to develop scenario specific ZOIs in the updated HEAF methodology for fire PRA.

Keywords
Arcing fault
Electrical explosion hazard
Fire probabilistic risk assessment
High energy arcing fault (HEAF)

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EXECUTIVE SUMMARY

PRIMARY AUDIENCE: Fire protection, electrical, and probabilistic risk assessment (PRA) engineers conducting or reviewing fire risk assessments related to high energy arcing faults (HEAFs).

SECONDARY AUDIENCE: Engineers, reviewers, utility managers, and other stakeholders who conduct, review, or manage fire protection programs and need to understand the underlying technical basis for the hazards associated with HEAFs.

KEY RESEARCH QUESTION

What is the electrical cable target fragility (damage and ignition thresholds) from a HEAF exposure?

RESEARCH OVERVIEW

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) HEAF working group (WG) has been tasked with improving the methodology for assessing the HEAF hazards at nuclear power plants. A major part of this effort includes updating the zone of influence (ZOI) used to determine target sets assumed damaged in fire PRA scenarios. Target damage, also referred to as "target fragility", is used in conjunction with hazard modeling for a specific HEAF scenario to determine the ZOI (i.e., geometric limits) of equipment damage. The equipment within the ZOI is assumed damaged and that beyond the ZOI is not.

In the context of this effort, electrical cable target fragility includes loss of electrical function (damage) and ignition. To quantify the fragility of electrical cable targets to HEAF exposures, the WG developed a consensus position and recommendations. The WG conclusions are based on its understanding of relevant data (including operating experience), current state-of-knowledge, and PRA methodology.

This report documents the process, data analysis, and conclusions of the fragility effort. The fragility thresholds documented in this report will be used in conjunction with HEAF hazard modeling results to develop HEAF ZOI estimates. The HEAF hazard estimates and ZOI development are beyond the scope of this report.

KEY FINDINGS

This research characterized electrical cable target fragility from HEAF exposures as follows:

- Electrical failure/damage of thermoplastic (TP) jacketed cables is 15 megajoules per square meter (MJ/m^2).
    - This includes cables in conduits and cable trays
- Electrical failure/damage of thermoset (TS) jacketed cables is 30 MJ/m^2.
    - This includes cables in conduits and cable trays

- Sustained ignition is assumed for cables within the enclosure of origin (e.g., internal cables and components within switchgear and load centers).
- For cables (TP and TS) located outside the enclosure of origin (but within the ZOI), there is no sustained ignition concurrent with the HEAF. The analyst still must consider cable ignition outside the enclosure of origin if within the flame, plume, or radiation region of the post-HEAF fire.
- Cables in raceways located within the scenario ZOI **and** protected by an electric raceway fire barrier system (ERFBS) are considered protected. They are not damaged or ignited, and do not contribute to the fire load under the conditions described in this report.
- The recommended values for bus duct fragility include the following:
    - Aluminum enclosed bus ducts: 15 MJ/m^2
    - Steel enclosed bus ducts: 30 MJ/m^2

WHY THIS MATTERS

This report provides a consensus position to assist researchers, analysts, and stakeholders to evaluate the HEAF hazard and the adequacy of current methods. The conclusions provided will support advances in the method, tools, and data to assess the HEAF hazard in nuclear facilities.

HOW TO APPLY RESULTS

Engineers and scientists advancing hazard and fire PRA methods should focus on Sections 4 and 5 of this report.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Users of this report may be interested in periodic stakeholder engagement opportunities with EPRI and/or NRC on this topic. For more information, please see the NRC website at https://www.nrc.gov/about-nrc/regulatory/research/fire-research/heaf-research.html.

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ACRONYMS

ASTM	ASTM International
AWG	American Wire Gauge
CFR	Code of Federal Regulations
EMT	electrical metallic tubing
EPRI	Electric Power Research Institute
ERFBS	electrical raceway fire barrier systems
FDS	Fire Dynamics Simulator
GE	General Electric
HEAF	high energy arcing fault
IMC	intermediate metal conduit
IPBD	isolated phase bus duct
JNRA	Japanese Nuclear Regulation Authority
LV	low voltage
MOU	memorandum of understanding
MV	medium voltage
NEA	Nuclear Energy Agency
NIST	National Institute of Standards and Technology
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NSBD	non-segregated bus duct
OE	operating experience
OECD	Organisation for Economic Co-operation and Development
PIRT	phenomena identification and ranking table
PRA	probabilistic risk assessment
RES	Office of Nuclear Regulatory Research
RIL	research information letter
RMC	rigid metal conduit

SFPE	Society of Fire Protection Engineers
SNL	Sandia National Laboratories
SWGR	switchgear
TE/I	technical evaluator/integrator
THIEF	thermally induced electrical failure
TP	thermoplastic
TS	thermoset
UAT	unit auxiliary transformer
UL	Underwriters Laboratories, Inc.
WG	working group
ZOI	zone of influence

1 INTRODUCTION

Infrequent events such as fires at a nuclear power plant (NPP) can pose a significant risk to safe plant operations when consequences of fires are not mitigated. NPP operators in the United States combat this risk by having robust fire protection programs designed to minimize the likelihood and consequences of fire events. These programs provide reasonable assurance of adequate protection from known fire hazards.

1.1 Background

High energy arcing faults (HEAFs) are hazardous events in which an electrical arc leads to the rapid release of energy in the form of heat, vaporized metal, and mechanical force. The existing methodology for modeling switchgear and load center HEAFs in fire probabilistic risk assessments (PRAs) is documented in Appendix M to NUREG/CR-6850, *Fire PRA Methodology for Nuclear Power Facilities*, issued September 2005 [1]. The methodology for HEAFs in bus ducts and isolated-phase bus ducts are contained in Section 7 of NUREG/CR-6850 Supplement 1, *Fire Probabilistic Risk Assessment Methods Enhancements* [2]. Both reports provide zone of influence (ZOI) estimates based on well-documented United States operating experience (OE).

Under a memorandum of understanding (MOU), the U.S. Nuclear Regulatory Commission (NRC) Office of Research (RES) and the Electric Power Research Institute (EPRI) have collaborated to form a joint working group (WG) to advance the state of practice in fire PRA modeling associated with HEAF hazards. The WG is chartered to update the methods, tools, and data to support realistic estimates of HEAF risk in industry fire PRAs based on experimental data, operating experience, and engineering judgment.

To develop the updated methodology for NPP operators, several intermediate steps are necessary to determine the ZOI and fire PRA guidance, including the following:

- Survey the U.S. nuclear plants to determine the presence of aluminum and fault clearing times. EPRI 3002020692, *Survey and Analysis of U.S. Nuclear Industry Relative to High Energy Arcing Faults in the Presence of Aluminum*, issued May 2021 [3], documents insights from this effort.
- Conduct physical testing including small-, medium-, and full-scale tests. Small-scale testing characterized the morphology and oxidation states of aluminum particles. Medium-scale “open box” experiments characterized the spectral emission of the arc and conductivity of the arc ejective. Full-scale experiments provided data on enclosure breach time and pressure effects and serve as a benchmark against the HEAF hazard models developed using the National Institute of Standards and Technology’s (NIST’s) Fire Dynamics Simulator (FDS), which is a computational fluid dynamics model commonly used in the fire protection community for predicting the consequences of fire.

- Fragility determination is a two-part effort (including both testing and analysis) geared towards determining the conditions when targets external to the HEAF are likely to be damaged.
- Development and validation of a FDS HEAF hazard model, which allows for the calculation of incident energy from the HEAF across a wide variety of configurations (e.g., fault duration, arc voltage, arcing fault current, equipment geometry, and electrode composition) is another key aspect of the overall approach.
- Modeling HEAFs in the fire PRA is the final step of the overall process which combines multiple inputs and methodologies. This task includes an evaluation of U.S. operating experience, updated fire ignition frequencies, and manual non-suppression probabilities. The fire PRA modeling offers the structure to assess the potential outcomes of a HEAF given the ignition source and location within the electrical distribution system, while integrating its impacts in the overall plant response.

1.2 Overview of HEAF Target Fragility

Due to the simplicity of the model in NUREG/CR-6850 and NUREG/CR-6850, Supplement 1, there are no defined fragilities for targets exposed to HEAF. As such, the current HEAF guidance assumes that any system, structure, and component within the ZOI are equally damaged from a HEAF event.

For thermal fires, Table H-1 of NUREG/CR-6850 documents the specific radiant heating criteria and temperature criteria, based on either thermoplastic (TP) or thermoset (TS) cable types. Ignition and damage criteria are often assumed to be the same. These values are applicable to thermal fires that typically have a slower fire growth rate.

HEAFs present a much shorter, higher energy source term, the effects of which are not as well characterized as other fire phenomena. To address this gap, the response of common targets to short duration, high-energy exposures is evaluated in physical testing to support the development of target damage thresholds (fragility). Quantitative fragility thresholds are necessary to determine HEAF ZOI distances. The target fragility threshold can be coupled with the hazard modeling results to develop a scenario-specific ZOI.

1.3 Objective

The objective of this report is to document the data, process, insights, and conclusions that the joint NRC/EPRI WG developed related to HEAF target fragility. Target fragility includes functional failure modes, commonly referred to as target damage and target ignition. Target fragility is used in conjunction with HEAF hazard estimates to determine the HEAF ZOI.

1.4 Scope

The scope of the target fragility task is to develop a consensus on the fire PRA target damage threshold for HEAF exposures. The WG evaluated damage both in terms of performing its electrical function and ignition. The primary targets assessed are electrical cables (control, power, and instrumentation) with both TP and TS jacketed insulation. Electrical cables are the most common target assessed in fire PRA for its impact on plant response and combustible loading. In addition, the WG developed recommended guidance for treating non-segregated phase bus ducts and non-cable protective features, such as rated electric raceway fire barrier systems (ERFBS) and electrical raceway protection.

2
METHOD OF INVESTIGATION

2.1 Approach

The NRC developed a target fragility plan and shared the plan with EPRI for feedback and improvement. Appendix A reproduces that plan. Figure 2-1 outlines the general approach taken by the WG. This approach consists of a sequence of activities discussed below to support the fragility determination.

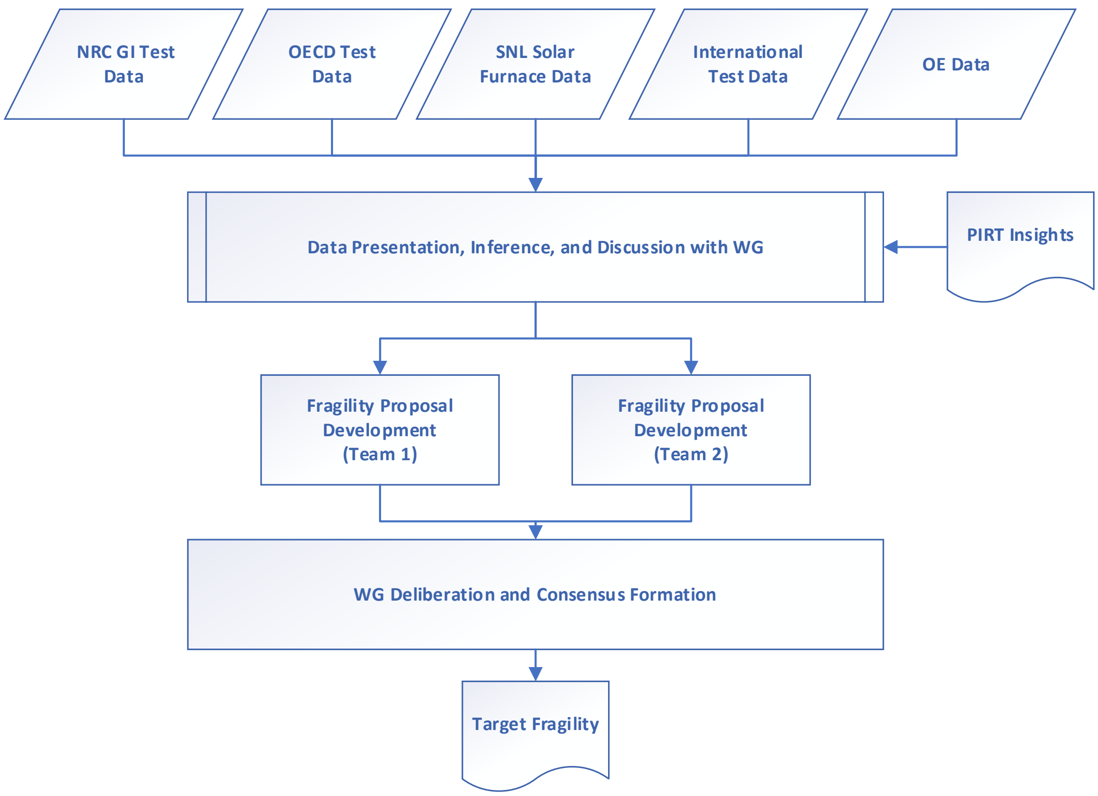


Figure 2-1
Target fragility flowchart

The approach follows a logical progression of tasks, including (1) identify and compile data sources, (2) present the data to the WG through summary reports, (3) propose and develop an agreed-upon approach for reaching a consensus, (4) assign individual WG member roles to perform the activities, (5) develop proposals, (6) deliberate and refine the proposals until the final consensus position on target fragility is achieved.

2.1.1 Data Compilation and Processing

This step involves compiling and processing the various data streams to support clear and consistent information exchange among the WG members. This included quantitative data (e.g., flux and incident energy measurements) and qualitative data (e.g., photo and video graphic information) from tests and operating experience. The data streams identified include the following:

- NRC-sponsored testing including:
  - Medium voltage switchgear [4]
  - Low voltage switchgear [5]
  - Open box [6]
- Organisation for Economic Co-operation and Development (OECD) testing
  - 26 tests of low and medium voltage switchgear and a bus duct [7]
- NRC-sponsored solar furnace testing performed at Sandia National Laboratories (SNL)
  - Small-scale testing of cable samples to solar thermal exposures [8]
- International testing
  - Japanese Nuclear Regulation Authority (JNRA) testing performed on medium voltage switchgear and low voltage distribution panels [9-10]
- Operating experience
  - Review and assessment of U.S. HEAF operating experience

2.1.2 Data Presentation

For each of these data sources, a brief summary report was prepared and provided by the WG. Each document summarized the data set, focusing on the damage to targets, measurements made, and any qualitative information that could be useful in the WG's evaluation. Section 3 summarizes the data sets and observations made by the technical evaluator/integrator (TE/I) team.

2.1.3 Approach Proposal and Selection

Several options were considered for developing a WG consensus on the target fragility. Approaches varied from ad hoc to a more structured elicitation. Given the schedule for performing this work, the group agreed to start with a mixed approach, whereby key benefits and structure of an informed expert elicitation were used as guidance for developing the consensus.

Benefits of this approach were that WG members were assigned individual roles with specific responsibilities and timeliness goals. Within individual roles, there was also a balance between the two supporting organizations. This is thought to provide objective insights to the proposal developments and evaluations. One potential relative limitation to the quasi-structured approach is that there is a potential for a longer time and resource investment compared to ad hoc approaches when a solution is found quickly.

When this plan was prepared, not all data streams had been compiled and presented to the WG. As such, it was unclear how much effort might be required to reach a consensus. Thus, going into the target fragility determination process, the group remained open to abandoning the quasi-structured approach if it became apparent that a consensus approach could be reached sooner, perhaps after the data were presented.

The quasi-structured approach divided the WG into the following roles:

- Proponents: These experts develop, present, and defend a proposal.
- TE/I team: These experts do not have a vested interest in the development of any proposal and objectively evaluate the proposals, views, and available data to inform their decision. In addition to evaluation, these experts also are responsible for developing the composite representation of the technical community. That is, the TE/I team is responsible for developing the WG consensus. This consensus could be the result from selecting the more technically robust proposal, refining a proposal, combining proposals, or some other combination or method to develop a result that represents the informed technical community's position.
- Resource experts: These subject matter experts have intimate knowledge of the data sets, experimentation, instrumentation, physics, modeling, or other discipline related to target fragility of specific devices, HEAF testing, or phenomena. The resource experts support the WG.

2.1.4 Role Selection and Proposal Development

Once the quasi-structured approach was selected, the team members were assigned individual roles, as presented in Table 2-1. While not all WG members were assigned to specific roles, those not assigned still participated to provide insights or input to support discussions or as part of a peer review. For this effort, the proponents were configured as two groups of members, developing two proposals for the TE/I team.

Table 2-1
Role assignments

Role	Personnel	Affiliation
Project Manager	Nicholas Melly Marko Randelovic	NRC EPRI
TE/I	Kevin McGrattan Ashley Lindeman	NIST (NRC) EPRI
Proponent (1)	Chris Lafleur Gabriel Taylor Kenny Hamburger	SNL (NRC) NRC NRC
Proponent (2)	Jason Floyd Dane Lovelace Ken Fleischer	Jensen Hughes (EPRI) Jensen Hughes (EPRI) Consultant (EPRI)
Resource Experts	Tony Putorti Austin Glover Tom Short	NIST (NRC) SNL (NRC) EPRI

2.1.5 Proposal Defense and Consensus Formation

This step involved the presentation of the individual proposals to the WG, which received the written documents before a full-day working meeting. During the first meeting, the TE/I team led the meeting to ensure that each proposal was adequately understood. This included understanding the assumptions and limitations of each proposal. Other WG members were welcome to ask questions and provide additional insights or information to support or question the individual proposals, assumptions, or limitations.

Shortly after the first meeting, the TE/I team caucused to reach agreement on the path forward. Based on the results of this meeting, several paths forward could be pursued, including, but not limited to (1) selecting a proposal that best fits the need, (2) combining proposals to use key attributes of each, or (3) selecting a proposal and requesting specific revisions. After the first proposal, each team revised its writeups to address comments from the TE/I team and from general group discussion. Proposals were revised and sent out before the follow-up interactions. The objective of the follow-up meetings was to reach a WG consensus, although such an outcome was not a priori requirement (i.e., no consensus was a possible outcome as well). While the final proposals documented in Appendix B are slightly different than the original submittals (e.g., addressed comments from working group review and more extensive analysis of sustained ignition), there were no dissentions to the consensus documented in this report.

2.1.6 Target Fragility Approach

The approach ensured that the application is transparent and consistent with how the hazard estimates were developed. In addition to ensuring consistency, it also included guidance on the application of the fragility threshold, limitations, or assumptions. The WG followed the general approach outlined above to determine the electrical cable fragility. This involved several months of effort and was the primary objective of this work.

In addition to cable failure, the WG identified a number of recommendations for other components and protective features that could benefit from the target fragility assessment. Appendix A, Section A.2 lists these additional items. The approach taken to address these additional items differed from the general approach described above, primarily due to issues of resources, time, lack of experimental data, and ease of completion. For those instances, individual WG members took a lead on an item and developed a comprehensive proposal for review, revision, and adoption by the WG. These instances typically required the use of test data, understanding of physical phenomena, technical analysis, and engineering judgment to develop and support a technical consensus position. When a consensus was reached, the position of the WG was documented. Section 5 gives more information on these items.

In addition to providing an approach that met the objectives of this effort, the qualitative insights helped develop the ZOI and guidance used to support subsequent efforts.

2.2 Meetings

The WG held weekly meetings starting in early 2021 to work on target damage estimates. The WG first agreed to the approach presented in Section 2.1 and the plan given in Appendix A. The first few weeks implementing the plan consisted of presenting the available datasets and pertinent information that the WG could use for its assessments. In addition to test data, the insights from the international phenomena identification and ranking table (PIRT) exercise on HEAF [11] were presented to the group. Following the data presentation meetings, the group split into two subgroups to develop proposals.

The first meeting of the WG following the submission of the initial proposals for deliberation and consensus formation took place on April 20, 2021. The purpose of this meeting was for the TE/I team to fully understand the initial proposals and for the proponents to provide feedback and critiques on each proposal. The TE/I team received the initial proposals a few days before the meeting.

The meeting included a refresher on the roles of the specific WG members (proponents, TE/I team, and resource experts). Then each TE/I member presented an understanding of the original proposals, along with items for clarification or improvement. In general, the two proposals presented cable damage thresholds that were very similar. However, the characterization of ignition and sustained ignition differed between the two proposals, and most of the meeting was spent discussing the differences and identifying areas for improved clarification.

By the end of this meeting, the entire WG reached consensus on the cable damage threshold for TP and TS field-routed cable. Because of differences between the two proposals with respect to ignition, a consensus was not reached for the ignition threshold during the April 20th meeting. Following this meeting, the individual teams revised their proposals, based on the feedback from the WG.

The second meeting was held on April 27, 2021, during which it received revisions to the proposals for feedback before final submission. In general, the WG made numerous clarifications to both proposals, while extending the discussion on the approach for sustained ignition. The TE/I team received the final proposals before the meeting on May 3, 2021. During this meeting, the TE/I team provided its general opinions on the proposals. The EPRI proposal included new information on sustained ignition; therefore, the WG members not involved in the development of that proposal were asked to submit comments and feedback a few days after the meeting. The May 3rd meeting concluded by requiring the TE/I team to develop the proposed consensus opinion on the treatment of target damage and ignition thresholds.

On May 12th, the TE/I team shared its draft consensus document with the WG members. Weekly meetings held in May resulted in the WG consensus documented in Section 4.

Between June and September 2021, the WG developed consensus positions on ERFBS, cable raceway protection (conduits and tray covers/bottoms), and bus duct failure.

3 REVIEW OF OPERATING EXPERIENCE, AND TEST DATA

This section briefly summarizes past industry operating experience and experimental data to establish damage thresholds for TP and TS jacketed electrical cables. The summary is intended to give a brief understanding of the datasets. The reader should refer to the source documents for more information.

3.1 Operating Experience

HEAF operating experience in the United States was reviewed to support the characterization of target damage. The reviewers developed a summary table that they provided to the WG members as input. The summary table included a brief description of the event, along with information on damage to the component of origin, damage outside the component of origin, and items not damaged. This exercise considered 21 HEAF events, divided into four categories:

- Medium voltage switchgear (MV SWGR)
- Load centers (also referred to as LV SWGR)
- Non-segregated bus duct (NSBD)
- Isolated phase bus duct (IPBD)

For the operating experience involving switchgear, there is no evidence of significant thermal or functional damage to cables beyond the region impacted by subsequent enclosure fires ignited by the HEAF. In three of the NSBD events, a failure of one bus duct resulted in the failure of a second nearby bus duct (in two cases from the same unit auxiliary transformer (UAT)).

3.2 SNL Solar Furnace Testing

The NRC contracted with SNL to perform a limited series of small-scale high heat flux radiant exposures documented in *HEAF Cable Fragility Testing at the Solar Furnace at the National Solar Thermal Test Facility* [8]. These tests were performed at the solar furnace at the National Solar Thermal Test Facility at SNL in Albuquerque, New Mexico. The solar furnace concentrates sunlight to generate intense thermal environments reaching 6 megawatts per square meter (MW/m^2) on a spot roughly 5 centimeters (cm) (2 inches) in diameter. Figure 3-1 and Figure 3-2 show the components of the solar furnace that reflect the sun and focus the sunlight onto the test article. A heliostat uses flat mirrors with a total reflective surface area of 55 m^2 (592 ft^2) to reflect the sunlight through an attenuator onto a large reflective parabolic dish. The parabolic dish concentrates the sunlight with 228 individually aligned mirrors.

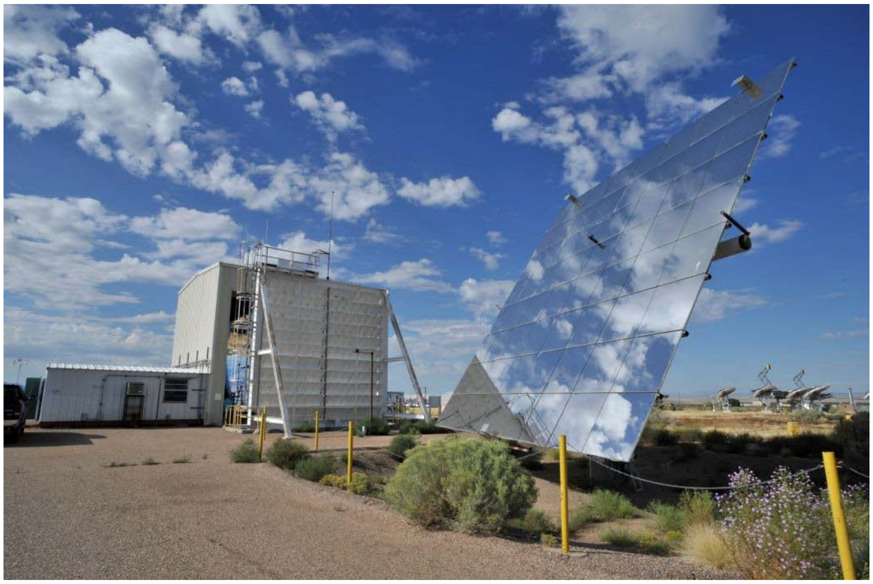


Figure 3-1
Helistat at the solar furnace

Figure 3-2
Parabolic dish at the solar furnace

This testing series was divided into two different phases, with a third phase subsequently added between the two phases to explore specific ignition phenomena. Several different cable designs were used. The cable samples were oriented in the vertical and mechanically secured to the sample holder. Tests varied in the exposure magnitude, duration, and profile and in the measurements taken, sub-jacket temperature, or electrical response. Previous evaluations of cable damage to thermal exposures used the temperature below the cable jacket, but above the conductor insulation (i.e., sub-jacket temperature) to correlate temperature to electrical failure [12]. For this experimental series, these measurements were taken for some of the tests to compare thermal fires and high-intensity, short-duration HEAF exposures.

High-speed video along with pre- and post-test photographs were taken for each experiment. The videos helped determine ignition start and stop times, along with allowing a visual understanding of how the cable responded during the exposure.

The original goal of the program was to assess the conditions for sustained ignition of cables, but the results indicated that ignition within the relatively small exposed area was not sustained beyond the exposure period. As a result, the focus shifted to examining the post-test condition of TP and TS jacketed cables as an indicator of functional damage.

All experiments began with a constant heat flux exposure. In some experiments, the heat flux was ramped down to zero following the initial constant exposure phase, while in others, the profile followed a gradual, staged ramp down to approximate the decay in electrical energy during an actual HEAF event and the residual heat dissipation of the enclosure and surrounding objects.

Figure 3-3 and Figure 3-4 display the experimental results for initial heat fluxes greater than 1 MW/m². Each experiment is characterized by the initial heat flux and the total fluence (time integration of the heat flux profile). The red diamonds indicate damage to the cable jacket but no visible conductor insulation. Black squares indicate visible damage to the conductor insulation but no visible conductor metal. Blue triangles indicate visible conductor metal.

There is no strong correlation relating the observed cable damage to the initial heat flux. However, there is clear evidence linking the damage to the total fluence, suggesting that this parameter is an appropriate metric for characterizing cable damage due to a HEAF.

A key indicator of cable damage is the breaching of the outer protective jacket and exposure of the underlying insulated conductors. The jackets tend to be black and the conductor insulation is multi-colored, making it relatively easy to determine that the jacket is breached. According to Figure 3-3, for TP cables, the fluence at which this occurs is approximately 15 megajoules per meter squared (MJ/m²) and Figure 3-4 for TS cables the value is approximately 30 MJ/m².

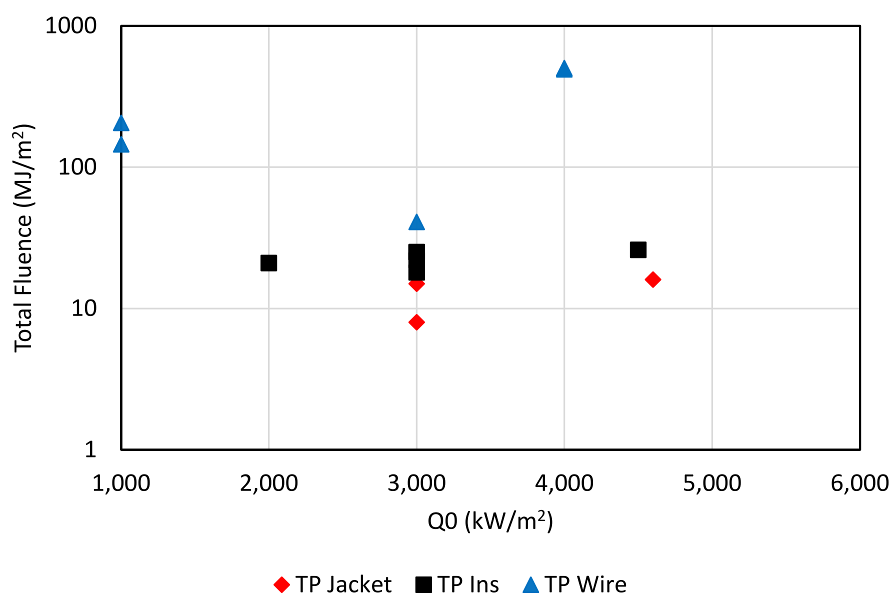


Figure 3-3
Thermoplastic cable results from SNL solar furnace testing

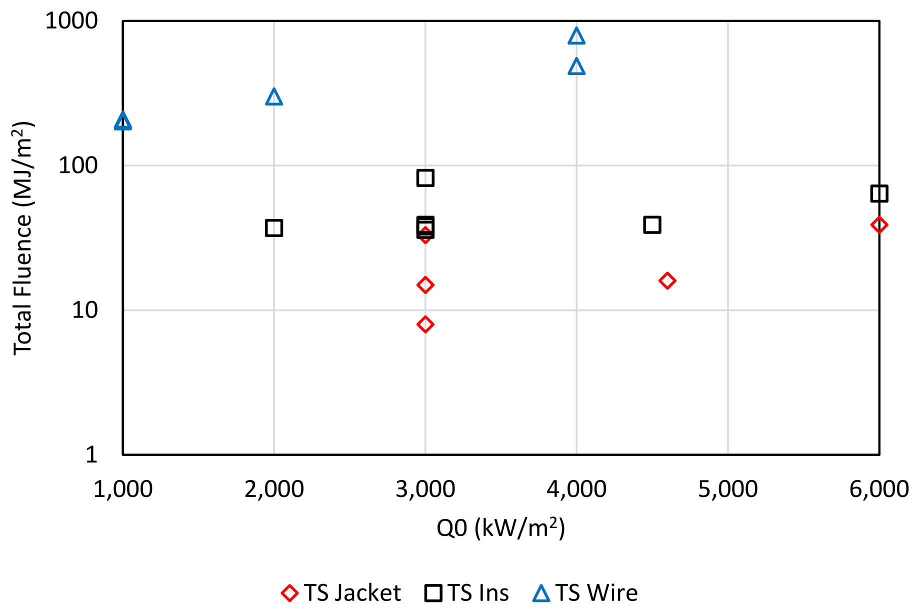


Figure 3-4
Thermoset cable results from SNL solar furnace testing

In the SNL experiments, only a small segment (approximately 5 cm) of a single or a group of three cables was exposed to the radiant heat flux. Ignition was observed in many of the experiments. In two instances, Tests T1-27 and T1-28, a flame was briefly observed (not lasting longer than 1 second), after the exposing heat flux was ramped down to zero. Aside from these two instances, no ignition was observed after the heat flux was removed.

3.3 OECD Phase I Testing

Twenty-six full-scale experiments were conducted in an OECD Nuclear Energy Agency (NEA) project, *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*, issued in 2017 [7]. The experiments were performed at KEMA Laboratories in Chalfont, PA, on equipment rated from 480 volts up to 10,000 volts at various fault current levels and durations. The experiments were performed under an oxygen consumption calorimeter to measure the heat release rate of any ensuing fire. Inconel plate thermometers and ASTM copper slugs measured the heat flux.

For the purpose of this effort, the data pertinent to the WG were shared. The data included photographs of cable samples after the experiment and thermal data near the cable samples. Most of the switchgear experiments included a cable tray installed 0.3 m above the enclosure. In general, significant cable damage was only seen when there was also a significant, sustained, ensuing enclosure fire.

3.4 JNRA Testing

Japan has been actively researching HEAFs following the Onagawa event in 2011 [13]. As part of its research and collaboration with the NRC, the data were made available to the public as International Agreement Reports [9-10]. Reports have been published or are in the publication process, and the data contained in those reports that support determination of cable fragility were shared with the WG. This was done to study basic arc electrical properties and thermal effects (e.g., using infrared cameras to study the arc position). TP cable coupons were present at or near locations where exposure was measured, and the exposures can be compared against cable damage for assessing fragility. These experiments yielded only light damage to the cable jackets (outside of the enclosure) for the given exposure conditions. No JNRA experiment resulted in ignition of cables outside of the test enclosure.

3.5 NRC Generic Issue Testing

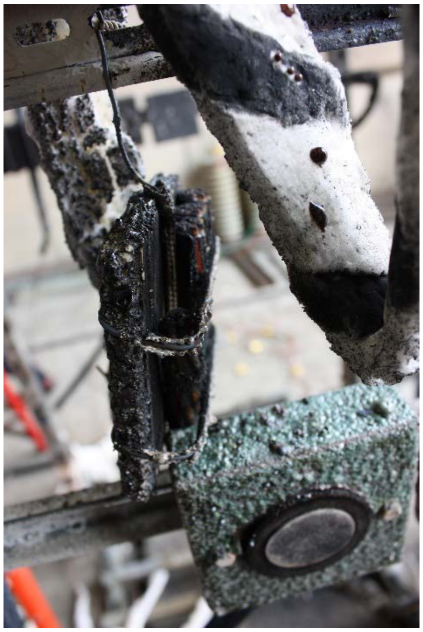
As part of the NRC response to the pre-generic issue related to HEAFs involving aluminum [14], the NRC performed a limited number of experiments on medium voltage and low voltage switchgear in 2018. During these experiments, passive cable sample coupons measuring 10 cm by 10 cm were located at various distances external to the electrical enclosure test device. Active measurement devices were also included near these locations to measure heat flux profiles or incident energy. Photographic evidence and measurement data were provided to the WG to support its efforts. The results of this testing are presented in Research Information Letter (RIL) 2021-10, *Report on High Energy Arcing Fault Testing, Experimental Results from Medium Voltage Electrical Enclosures* [4].

No experiment resulted in a post-HEAF sustained fire involving the cable coupons. In all but one experiment, only charring of the cable jacket was observed, but in Test 2-24, the cables in the lower portion of Rack 2 (0.9 m from the enclosure face) saw significant jacket damage and exposure of cable insulation. Figure 3-5 shows photographs of cables from Rack 2 and Rack 3 (1.5 m from the enclosure face).

During Test 2-24, all the instrumentation on Rack 2 and some of the instrumentation on Rack 3 failed. There was no direct measurement of the total fluence at Rack 2. However, measurements made nearby (Rack 3 at 1.8 m) were extrapolated to Rack 2, yielding an estimated total fluence of 14 MJ/m^2 rounded up to 15 MJ/m^2 to account for uncertainty in the extrapolation.

Rack 2

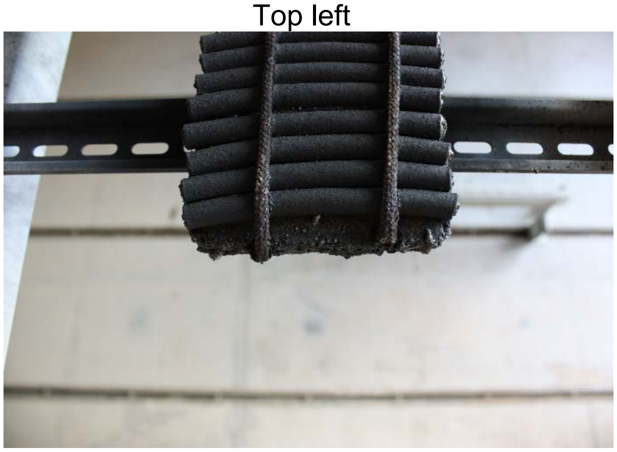
Lower left



Lower right

Rack 3

Top left



Top right

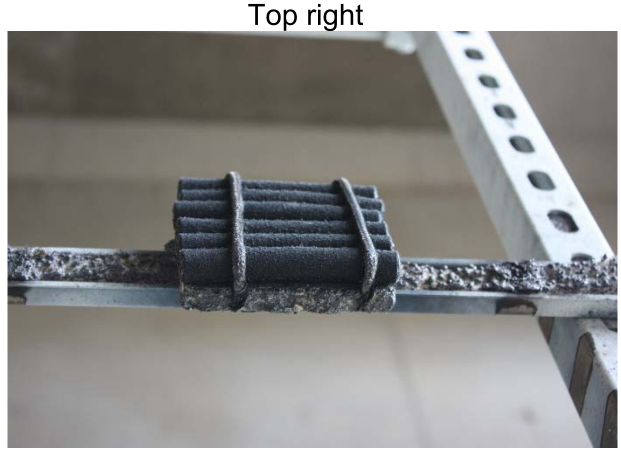


Figure 3-5
Test 2-24 cable photographs

3.6 Phenomena Identification and Ranking Table Insights

In 2018, the NRC published a PIRT report [11] on HEAF. This effort used a facilitated expert elicitation process to identify key phenomena associated with HEAFs and then rank the current state of knowledge and importance for specific HEAF scenarios. The results related to target fragility were communicated to the WG to support the work documented in this report.

4
WORKING GROUP CONSENSUS ON CABLE FAILURE

This section documents the WG consensus on the target fragility of electrical cables. The TE/I team developed this position based on the proposals received by the proponents and the discussion and feedback received from the WG. The final team proposals are included in Appendix B.1 and B.2 of this report.

4.1 Introduction

The ZOI for a HEAF scenario is the volume surrounding the source of the arc where damage to equipment can occur. Figure 4-1 shows this schematically, where the excess energy generated by an arc fault within a switchgear enclosure breaches one or more external panels. This section of the report defines the exposure conditions leading to damage and sustained ignition of electrical cables.

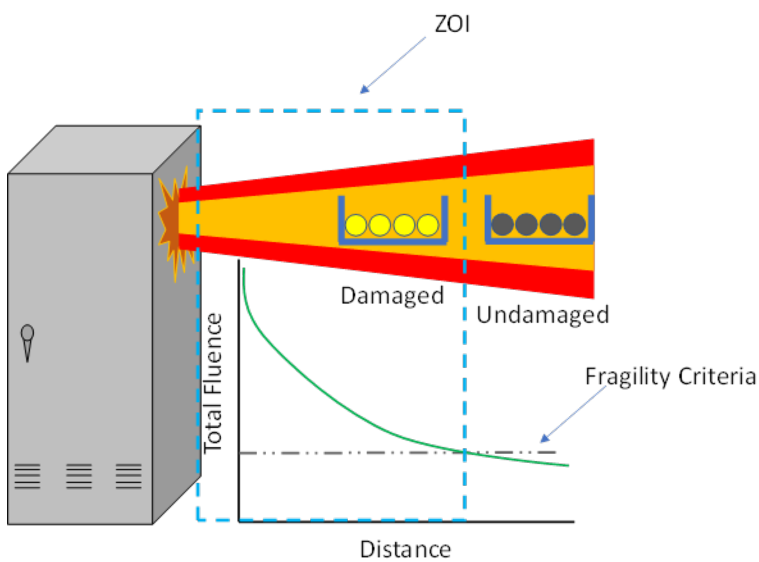


Figure 4-1
Depiction of fragility and ZOI for a HEAF event in a switchgear

Electrical failure and ignition thresholds for electrical cables exposed to fire are well established [1, 12, 15], but these damage criteria do not necessarily extend to HEAF events because the thermal exposure magnitude and duration differ by orders of magnitude. Whereas the maximum possible heat flux from a fire of ordinary combustibles is approximately 150 kilowatts per meter squared (kW/m^2) and its duration can extend for tens of minutes or even hours, the heat flux from a HEAF is up to two orders of magnitude greater and its duration is typically a few seconds. The very different magnitudes of exposure and duration result in differing modes of cable response, thus requiring a separate effort to develop damage criteria.

This document considers the existing HEAF operating experience and experimental data to establish damage thresholds for TP and TS jacketed electrical cables. These damage thresholds take into account both loss of electrical functionality and sustained ignition; that is, the outbreak of a spreading fire.

4.2 Analysis

Development of the fragility of TP and TS cables considered five data sets. Of those five, only two sets of data provide sufficient quantified results with which to establish thresholds for electrical functionality damage, which is assumed to be a fluence intense enough to breach the outer cable jacket and expose underlying conductor insulation. The observations from the SNL experiments indicate that this threshold is 15 MJ/m^2 for TP cables and 30 MJ/m^2 for TS cables. Test 2-24 of the NRC MV SWGR experiments [4] supports the threshold of 15 MJ/m^2 for TP cables. These limits are based on the observed physical damage to cable specimens, not on the direct measurement of electric current.

None of the operating experience or existing experimental data involves a HEAF that was able to ignite and sustain a spreading fire to cable tray targets during the arcing jet. Of course, this does not mean it is not possible, but merely that one has not yet been observed in operating experience or in the laboratory. For the energetic phase of the HEAF, the analyst should use the electrical failure thresholds for TS and TP to determine the ZOI, but does not need to postulate sustained cable tray ignition for these targets.

The evidence cited above does suggest that a fire ignited by the HEAF within the electrical enclosure of origin is capable of growing and igniting cables located just above the enclosure. Thus, under certain conditions, the energy of a HEAF can cause an internal ensuing enclosure fire capable of external fire spread. These conditions mainly concern geometry; that is, cables within the enclosure are exposed for an extended period of time to the residual heat of the hot steel enclosure walls. Simply put, these cables are heated within an enclosure long enough for the residual energy of the HEAF to overcome the thermal inertia of the plastic and metal cable components, maintaining temperatures above those necessary for pyrolysis to occur. The ensuing fire characteristic are outside the scope of this report and will be documented in a future publication.

4.3 Conclusion

In summary, the WG recommends the following thresholds for cable damage:

- The threshold for electrical failure/damage of thermoplastic (TP) jacketed cables is 15 MJ/m^2.
- The threshold for electrical failure/damage of thermoset (TS) jacketed cables is 30 MJ/m^2.
- Sustained ignition is assumed for cables within the enclosure of origin (e.g., internal cables and components within switchgear and load centers).
- For cables outside of the enclosure of origin, but within the postulated HEAF ZOI, no sustained ignition is assumed.
  - For the post-HEAF fire, the analyst still must consider cable ignition if it is within the flame, plume, or radiation region.

5
PROTECTIVE FEATURES AND NON-CABLE DAMAGE LIMITS

Existing PRA methodologies provide recommendations for using various protective features to limit damage or ignition of protected electrical cables. This section revisits those practices and uses the current state of knowledge to ensure the guidance is adequate or to make changes where needed. The WG reviewed the following items:

- ERFBS
- Electrical raceway protection
- Bus duct damage limits

The approach for developing the recommendations presented in this section differs from that given in Sections 3 and 4 of this report. For this section, the WG identified specific configurations that required evaluation and then identified a champion for the topic to develop a technical basis. The draft technical basis documents for each topic were presented to the WG members for critique and feedback. Based on these discussions, the evaluations were revised and returned to the WG for additional feedback or endorsement. This review and critique loop continued until the WG reached a consensus. The results presented in Sections 5.1 through 5.3, represent the consensus positions of the WG for the specific topics.

5.1 Electrical Raceway Fire Barrier Systems

ERFBS commonly referred to as “fire wraps,” are a non-load-bearing partition type envelope system installed around electrical components and cabling that are rated by test laboratories in hours of fire resistance and are used to maintain safe-shutdown functions free of fire damage [16]. ERFBSs are used in NPPs to provide separation between redundant safety-related components and safe shutdown functions. ERFBS come in numerous designs and configurations; however, they all encase the component they are protecting to reduce the thermal exposure to the protected component during elevated fire conditions.

5.1.1 Current Practice

Section M.4.2, “High Energy Zone of Influence” of NUREG/CR-6850 presents guidance on the use of ERFBS in HEAF scenarios, summarized as follows:

- Cables that drop into an electrical enclosure and are protected by an ERFBS are assumed damaged but are not ignited, and they do not contribute to the fire load.
- Cables in the first overhead cable tray that is within 1.5 m (5 ft) vertical distance of the top of the enclosure and are protected by an ERFBS are considered protected (i.e., assumed damaged, not ignited).

5.1.2 Technical Considerations

The following discussion presents the technical information and state of knowledge to support the proposed treatment of ERFBS. ERFBS performance during HEAF exposures involves two primary concerns: thermal response and mechanical response.

Understanding ERFBS testing

NRC Generic Letter 86-10, Supplement 1, *Fire Endurance Test Acceptance Criteria for Fire Barrier Systems Used to Separate Redundant Safe Shutdown Trains Within the Same Fire Area* [17], specifies guidance to evaluate the adequacy of fire endurance tests and fire barrier systems. This document identifies the standard time-temperature fire endurance test curve defined in ASTM E-119, *Standard Test Methods for Fire Tests of Building Construction and Materials* [18], and the following acceptance criteria (in part):

- The fire barrier design has withstood the fire endurance test without the passage of flame or the ignition of cotton waste on the unexposed side for a period of time equivalent to the fire-resistance rating required of the barrier.
- Analysis of temperature levels recorded on the unexposed side of the fire barrier demonstrates that the maximum temperature rise does not exceed 139°C (250°F) above ambient temperature.
- The fire barrier remains intact and does not allow water to be projected beyond the unexposed surface during the hose stream test.

Thermal Response

Research has shown that the thermal exposure provided by a standard time-temperature test can be approximated as a blackbody source. This approximation closely matches the heat flux measurements taken at the wall and floor furnace locations, as presented in the *Society of Fire Protection Engineers (SFPE) Handbook* [19]. Using this approximation, the heat flux profile for a standard time-temperature test is derived (see Figure 5-1). The energy fluence can be calculated by integrating the heat flux profile, as shown in Figure 5-2.

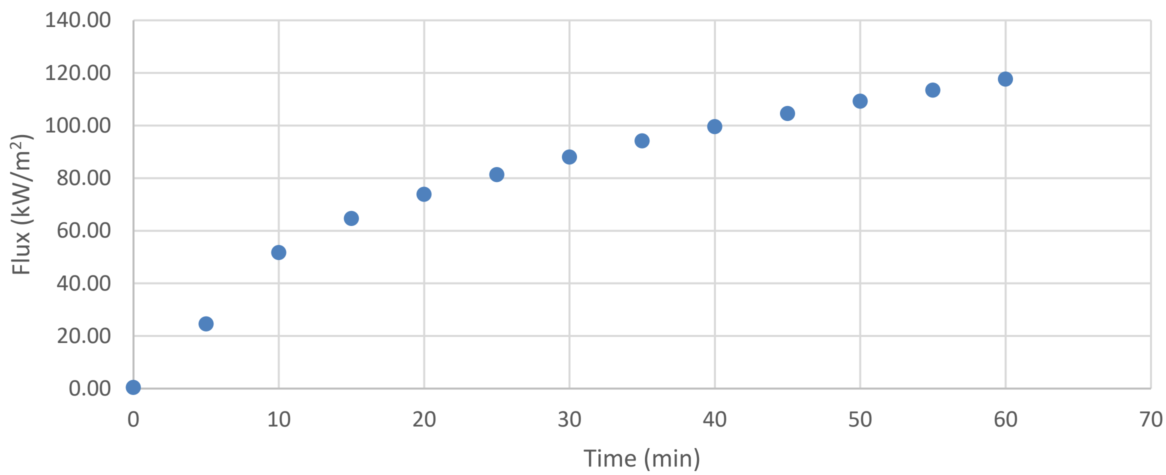


Figure 5-1
Heat flux profile approximated as black body from standard time-temperature curve

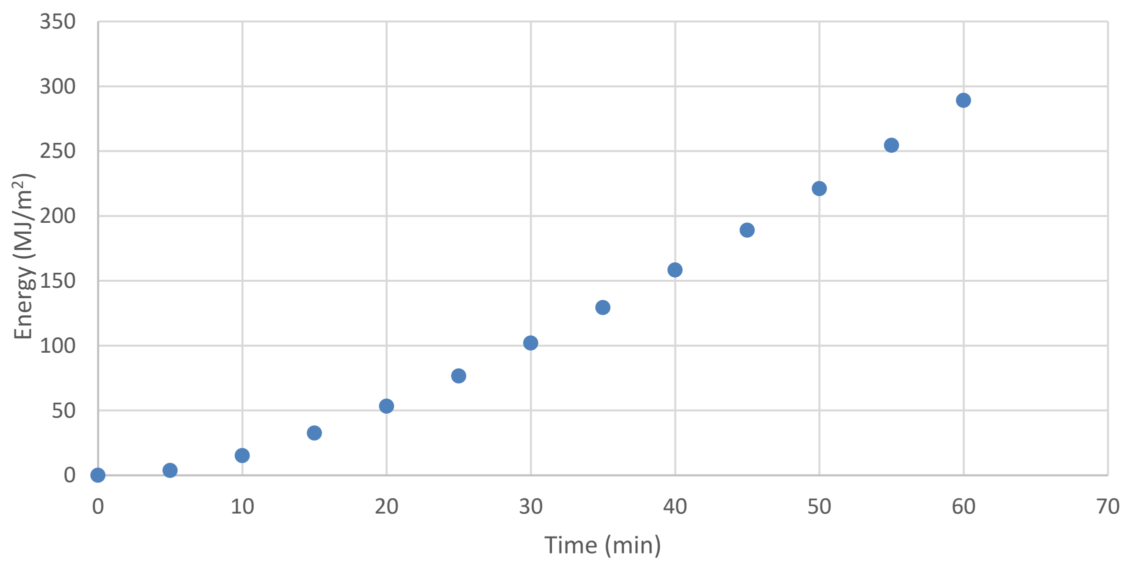


Figure 5-2
Energy fluence over time

While regulatory guidance and regulations (Appendix R to Title 10 of the Code of Federal Regulations [CFR] Part 50) identifies both 1-hour and 3-hour barriers, the 1-hr case is used for evaluation here as the minimum level of protection and forms the basis for the subsequent recommendation. At 1-hour, the standard time-temperature curve exposes the test assembly to approximately 290 MJ/m^2. From Section 4, unprotected cables are assumed damaged at 15 MJ/m^2 or 30 MJ/m^2 for TP and TS jacketed cables, respectively. Therefore, from the thermal perspective, a fully rated ERFBS per GL 86-10 Supplement 1, can be exposed to nearly 10 times the amount of energy needed to damage an unprotected TS cable while maintaining the protected cable(s) to less than a 139°C temperature rise. The generic failure threshold for TP cables exposed to a classical fire are assumed to fail at 205°C; thus, a 139°C temperature rise with an ambient starting temperature of 24°C is 165°C, or 40°C below the TP cable damage threshold. For reference, the generic failure threshold for TS cables is 330°C.

The analysis with the standard time-temperature curve for rated ERFBS has demonstrated that they can be exposed to nearly 290 MJ/m^2 and maintain the protected (cold) side temperature to less than the expected failure threshold for cables. Several additional factors add margin to this evaluation, including the following:

- Time scale:
  - Short-duration HEAF event versus longer (tens of minutes to hours) fire endurance test results in less heat absorption and transfer into the ERFBS.
- Heating profile:
  - A fire endurance test exposes ERFBS on all surfaces to the thermal insult, while the HEAF exposures are unidirectional. This geometry difference requires more thermal energy from the HEAF's unidirectional exposure to elevate the test assembly to an equivalent thermal state.

Mechanical Response

During a HEAF event, metal particulate and vapor, along with a pressure transient (wave), is observed. The metal particulate consists of molten metal droplets a few millimeters in diameter down to metal vapor particulate in the micrometer and nanometer scales. From testing performed in 2018, the peak internal pressure rise within the tested medium voltage electrical enclosure was approximately 27.6 kilopascals (kPa) (4 psi) above ambient. External pressure measurements have been attempted in various testing programs, with limited usable data. The general position is that localized pressure gradients do not appear to be a damaging concern; however, volumetric over pressurization can cause failure of structural components such as electrical enclosure doors and panels or doors or dampers of small volumetric rooms, etc. Given this, it is unlikely that the pressure wave has sufficient intensity to damage ERFBS.

As part of the ERFBS endurance testing, a hose stream test is applied to the test article. The purpose of the hose stream test is to provide a consistent means of evaluating the ERFBS resistance to impact, erosion, and cooling effects. In the test method, the hose stream is applied immediately after the end of the fire endurance test period; that is, after having been thermally stressed. In a HEAF event, the ERFBS would be exposed to a simultaneous thermal and mechanical stressor. Having the mechanical stress applied concurrent with the thermal stress is expected to result in a less severe exposure compared to the hose stream test, due to the lack of thermal degradation of the barrier.

5.1.3 Conclusion and Recommendations

Based on the information collected, reviewed, and analyzed, the WG collectively agreed that electrical cables protected by ERFBS are assumed undamaged from the effects of a HEAF exposure.

The recommended fire PRA guidance related to crediting the performance of ERFBS in HEAF scenarios is as follows:

- Cables protected by ERFBS that enter the postulated HEAF initiating electrical enclosure are assumed damaged, but not ignited, and they do not contribute to the fire load (no change from current guidance).
- Cables in raceways located within the scenario ZOI and protected by an ERFBS are assumed to survive the HEAF blast and mechanical force. They are neither damaged, nor ignited, and do not contribute to the fire load.
- Credit for ERFBS assumes a minimum 1-hour fire rating and a barrier that is properly designed, tested, configured, installed, inspected, and maintained.

5.2 Electrical Raceway Protection

Certain types of electrical raceway systems may be capable of providing some degree of protection from the thermal and mechanical impacts of a HEAF. The next two subsections analyze electrical raceway conduits and cable trays with top and bottom covers.

5.2.1 Electrical Raceway Conduit

An electrical raceway conduit is a tubular raceway used to protect and route electrical wiring in a building or structure. Electrical raceway conduit may be made of metal, plastic, fiber, or fired clay. Most conduits are rigid, but a flexible conduit is used for some purposes. Using electrical conduit is one of several methods to route and protect electrical cables in NPPs. Typically, these conduits are metal and can have a polymeric coating. From a fire hazards perspective, conduits can provide a certain level of thermal protection (due to the thermal mass of the conduit) from exposure fires.

Three primary types of electrical raceway conduits are of interest for the protection of electrical cables in NPPs. The three types are rigid metal conduit (RMC), intermediate metal conduit (IMC), and electrical metallic tubing (EMT).

The conduit wall thickness will vary depending on the type of conduit and the diameter. The wall thickness for RMC varies from approximately 2.6 millimeters (mm) (0.104 in.) to approximately 6.8 mm (0.266 in.) [20]. The wall thicknesses of IMC and EMT vary from 2 mm (0.078 in.) to about 3.8 mm (0.15 in.) [21] and 1.07 mm (0.042 in.) to slightly over 2.11 mm (0.083 in.) [22], respectively.

5.2.1.1 Current Practice

Section M.4.2, "High Energy Zone Influence" of NUREG/CR-6850 presents guidance on the use of conduits in HEAF scenarios, as summarized below:

- For cables that drop into the top of the panel: If cables are protected (i.e., not exposed) by conduit or fire wrap, they are assumed damaged, but not ignited, and they do not contribute to the fire load.
- Conduit within 1.5 m (5 ft) vertical distance of the top of the cabinet are considered protected (e.g., assumed damage, not ignited).

5.2.1.2 Technical Considerations

The following discussion presents the technical information and state-of-knowledge to support the proposed treatment of electrical cables in conduits for fire PRAs. Electrical raceway conduit performance during HEAF exposures involve two primary concerns: thermal response and mechanical response.

Understanding Electrical Raceway Conduit Testing

In the mid-2000s, the NRC conducted a series of experiments with the primary project objective to characterize the various modes of electrical failure (e.g., hot shorts, shorts to ground) within bundles of power, control, and instrument cables. A secondary objective of the research project was to develop a simple model to predict Thermally Induced Electrical Failure (THIEF) when a given interior region of the cable reaches an empirically determined threshold temperature. The results of this effort are documented in the three volumes of NUREG/CR-6931, *Cable Response to Live Fire (CAROLFIRE)* [12].

The CAROLFIRE program included a series of 78 small-scale radiant heating tests and 18 intermediate-scale open burn tests. The small-scale tests were performed in an SNL facility called Penlight and involved exposure of two to seven pieces of cable to grey-body radiant heating, always including at least one instrumented cable for thermal response in addition to the cables monitored for electrical performance. Tests were conducted with the Penlight apparatus configured for air drop, conduit, and cable tray testing. Researchers conducted 20 of the 78 Penlight tests using the conduit configuration. The intermediate-scale tests involved exposure of cables, generally in bundles of 6 to 12 cables each, under various routing configurations and at various locations within a relatively open test structure. The fires were initiated by a propene (also known as propylene) gas diffusion burner. The fire typically ignited, at a minimum, those cables located directly above the fire source. The intermediate-scale involved exposure to cables just above the upper extent of the gas burner's flame zone, in the fire plume above the flame zone, and outside the plume but within a hot gas layer.

Thermal Response

Electrical raceway conduits can potentially reduce the likelihood of cable damage and ignition when exposed to a given heat flux. When a HEAF event occurs, the conduit would provide protection for the cables until the heat is transmitted through the conduit and the cables reach failure temperatures or the conduit melts. The following provides simple calculations intending to illustrate some basic physics to support the WG's objective of assessing the potential for crediting cable conduits providing a level of protection to electrical cable. These scoping level calculations were used to determine if a more detailed evaluation was viable but should not be used to calculate a fragility figure of merit.

Suppose a single unprotected electrical cable routed near an electrical cabinet that experiences a HEAF is exposed to some incident energy flux, q''_{cab}, at its nearest point to the cabinet. If all of the energy impacting the cable is assumed to heat it, its temperature increase, ΔT_{cab}, can be estimated from Equation 5-1:

$$\boldsymbol{q''_{\mathrm{cab}}\, D_{\mathrm{cab}}\, L = \rho_{\mathrm{cab}}\, \pi \left(\frac{D_{\mathrm{cab}}}{2}\right)^2 L\, c_{\mathrm{cab}}\, \Delta T_{\mathrm{cab}}} \qquad \textbf{Eq. 5-1}$$

Where:

q''_{cab} = incident energy impacting cable (kJ/m^2)
D_{cab} = cable diameter (0.0183 m)
L = length of exposed cable segment (1 m)
ρ_{cab} = bulk cable density (2,000 kg/m^3)
c_{cab} = bulk cable specific heat (1.5 kJ/kg/K)

The values in parentheses are average values representative of the properties of a 7 conductor, 9 American Wire Gauge (AWG) electrical cable.

Using a similar argument, if the cable is protected within a steel conduit, its temperature increase, $\Delta T_{\mathrm{cab+con}}$, can be estimated from Equation 5-2:

$$\boldsymbol{q''_{\mathrm{con}}\, D_{\mathrm{con}}\, L = \left(\rho_{\mathrm{con}}\, \pi D_{\mathrm{con}} \delta_{\mathrm{con}} L\, c_{\mathrm{con}} + \rho_{\mathrm{cab}}\, \pi \left(\frac{D_{\mathrm{cab}}}{2}\right)^2 L\, c_{\mathrm{cab}}\right) \Delta T_{\mathrm{cab+con}}} \qquad \textbf{Eq. 5-2}$$

Where:

q''_{con} = incident energy impacting conduit (kJ/m^2)
D_{con} = conduit outer diameter (0.0334 m)
ρ_{con} = conduit (steel) density (7800 kg/m^3)
δ_{con} = conduit thickness (0.0032 m)
c_{con} = conduit (steel) specific heat (0.5 kJ/kg/K)

The values in parentheses are representative of a metric designator 27 mm (1 in) RMC steel conduit. This size conduit is typical in NPPs.

If q''_{cab} is the failure threshold (i.e., fragility) of the single unprotected cable, the equivalent failure threshold of the cable within the conduit can be estimated from Equation 5-3 by setting ΔT_{cab} equal to $\Delta T_{\mathrm{cab+con}}$ and solving for q''_{con}:

$$\boldsymbol{q''_{\mathrm{con}} = q''_{\mathrm{cab}} \left(\frac{\rho_{\mathrm{con}}\, D_{\mathrm{con}}\, \delta_{\mathrm{con}}\, c_{\mathrm{con}} + \rho_{\mathrm{cab}} \left(\frac{D_{\mathrm{cab}}}{2}\right)^2 c_{\mathrm{cab}}}{D_{\mathrm{con}} \left(\rho_{\mathrm{cab}} \frac{D_{\mathrm{cab}}}{4}\, c_{\mathrm{cab}}\right)}\right)} \qquad \textbf{Eq. 5-3}$$

The bracketed expression on the right-hand side of this equation is approximately 1.5 for the parameter values chosen. Figure 5-2 shows the ratios of $q''_{\mathrm{con}}/q''_{\mathrm{cab}}$ for RMC, IMC, and EMT for a range of conduit diameters.

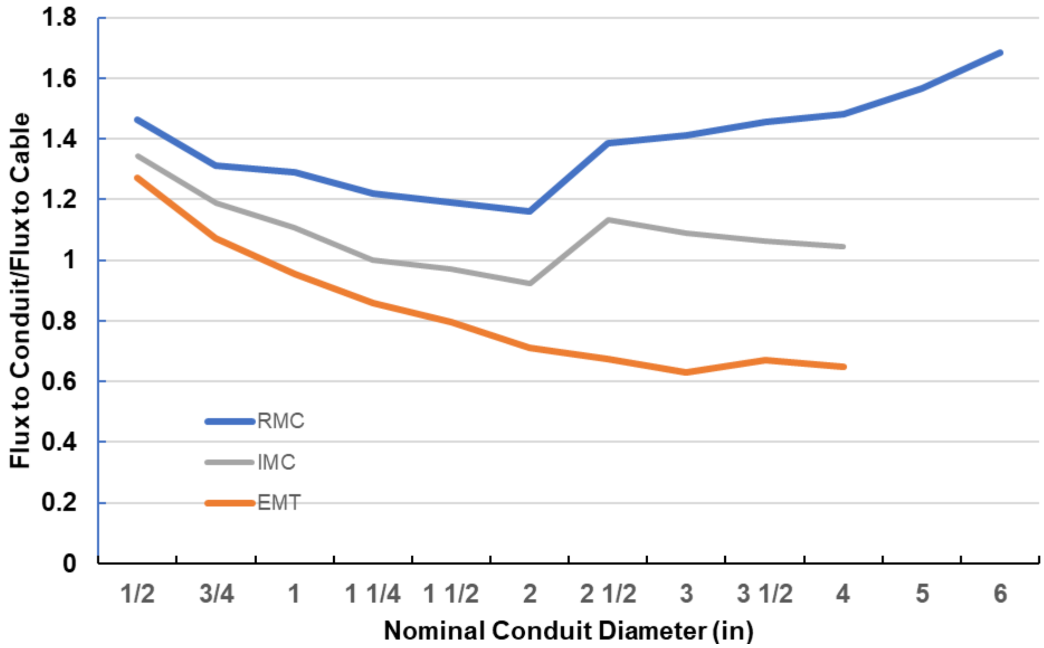


Figure 5-3
Ratios of q"con/q"cab for RMC, IMC, EMT

While the calculations show that RMC can provide some protection for the cables from the HEAF, especially at the larger diameters, the IMC and EMT provide significantly less protection. At larger diameters, the EMT ratio drops below 1, indicating that the thin-walled EMT could potentially result in reduced protection. The thin-walled EMT conduit adds exposed surface area that captures the energy from the HEAF, but it adds little additional heat capacity to the overall system since it is a thin construction. The amount of incident energy absorbed by the system gets larger, but the thermal mass for energy storage does not increase proportionately. Therefore, the flux ratio drops below 1. This scenario is similar to the heat transfer problem of adding insulation to a pipe. As insulation is added, it increases the diameter, resulting in more surface area for heat exchange. There is a critical thickness of insulation where the increased area outweighs the benefit of reduced conduction and is dependent on conductivity. A similar scenario explains the IMC value below 1. This concept was validated through some exploratory calculations using NIST's Fire Dynamics Simulator (FDS) [23].

The impact of the metal conduit on the cables after the HEAF event is also a concern. If a conduit is exposed over the duration of a HEAF and heated until it is glowing red, it is unclear what can happen to the cable inside. The cable would be exposed to an additional heat flux over an extended period of time as the metal cools. This phenomenon can potentially lead to failure of the cable after the HEAF event.

While the modeling has shown that metal conduits can provide some protection from a HEAF, there are many variables, and it is not possible to draw firm conclusions about their effectiveness. While cables in conduits will not contribute to a heat release rate in terms of a hot gas layer, there is not enough information to determine any recommended changes to the current cable failure criteria of 15 MJ/m^2 and 30 MJ/m^2.

Mechanical Response

During a HEAF, metal particulate and vapor along with a pressure transient (wave) are observed. The metal particulate consists of molten metal droplets a few millimeters in diameter down to metal vapor particulate in the micrometer and nanometer scales. From experiments performed in 2018 [4], the peak internal pressure rise within the tested medium voltage electrical enclosure was approximately 27.6 kPa (4 psig). Various testing programs have attempted external pressure measurements, with limited usable data. The general belief is that localized pressure gradients do not appear to be a damaging concern; however, volumetric over pressurization can cause failure of structural components, such as electrical enclosure doors and panels or small room doors or dampers. It is likely that any overpressure from a HEAF can cause some movement of the conduit without causing failure of the conduit or the cables.

5.2.1.3 Conclusions and Recommendation

Based on the information collected, reviewed, and analyzed, the WG concluded that electrical raceway conduits do not significantly increase the protection of an electrical cable in the event of a HEAF. However, the WG determined that the guidance in NUREG/CR-6850 could be extended, and the conclusions in Section 4.3 of this report (for TP and TS cables) should be extended to included cables within a conduit.

The revised guidance for conduits is summarized as follows:

- Electrical failure/damage of TP jacketed cables in conduits is 15 MJ/m^2.
- Electrical failure/damage of TS jacketed cables in conduits is 30 MJ/m^2.
- For cables outside of the enclosure of origin, but within the postulated HEAF ZOI, no sustained ignition is assumed during or after the HEAF.

5.2.2 Electrical Raceway Cable Tray Covers

Cable tray covers are relatively thin metal sheets that are used as bottoms and tops of cable trays. These bottoms and tops protect the electrical cables in the trays from dust, dirt, and mechanical damage. Cable tray covers are often used in NPPs to reduce the cable’s thermal exposure during fires.

5.2.2.1 Current Practice

NUREG/CR-6850 [1] does not provide any guidance on the use of cable tray bottoms and tops in HEAF scenarios. However, it does provide limited guidance in Section Q.2.2, “Cable Tray Barriers and Fire Stops,” on the use of cable tray bottoms and tops to limit the spread of fire from one cable tray to another, as summarized below for cable tray bottoms and tops:

- Solid tray bottom covers, solid tray top covers with no vents, and solid tray bottom covers with vented top covers prevented propagation of a fire from the first tray to the second tray.
- Barriers seem to substantially delay cable damage for qualified cable. However, the barriers did not delay cable damage for nonqualified cable.

5.2.2.2 Technical Considerations

The following discussion presents the technical information and state of knowledge to support the proposed treatment of cable tray bottoms and tops. The performance of cable tray bottoms and tops during HEAF exposures involve two primary concerns: thermal response and mechanical response.

Understanding Cable Tray Bottom and Top Testing

Limited test data are available for analyzing the performance of cable tray bottoms and tops. NUREG/CR-6850 references 13 experiments conducted by SNL on covered cable trays exposed to fire [24]. These experiments demonstrated that tray covers prevented the propagation of a fire from a lower tray to one above.

Thermal Response

The cable tray bottom thickness of 0.002 m is approximately that of 14-gauge steel that is commonly used for cable tray covers and is similar to a wall thickness of small diameter (1/2") conduit.

Fundamentally, a covered tray is analogous to a cable in a conduit – the overall system consists of cables protected by a metal barrier. Depending on the specific cable tray geometry and cover thicknesses a range of performance would be possible as seen for conduits in Figure 5-3. Given the uncertainties and the system's fundamental characteristics the working group concludes that the cable covers should behave in a similar manner to conduits and that the same conclusion of no benefit applies. The analyst should use the fragility values for cables: 15 MJ/m^2 (thermoplastic) and 30 MJ/m^2 (thermoset).

Mechanical Response

During a HEAF, metal particulate and vapor along with a pressure transient (wave), are observed. The metal particulate consists of molten metal droplets a few millimeters in diameter down to metal vapor particulate in the micrometer and nanometer scale. From testing performed in 2018 [10], the peak internal pressure rise within the tested medium voltage electrical enclosure was approximately 27.6 kPa (4 psig). External pressure measurements have been attempted in various testing programs, with limited usable data. The general belief is that localized pressure gradients do not appear to be a damaging concern; however, volumetric over pressurization can cause failure of structural components such as electrical enclosure doors and panels or small room doors or dampers. While that pressure wave can have sufficient intensity to cause deflection of a cable tray bottom, it is not likely to cause its failure.

5.2.2.3 Conclusion and Recommendation

Based on the information collected, reviewed, and analyzed, the WG concluded that cable tray bottoms and tops do not significantly increase the protection of an electrical cable from damage in the event of a HEAF. Analysts should use the TP (15 MJ/m^2) and TS (30 MJ/m^2) fragility criteria for cables (Section 4). This includes cable trays with covers (e.g., top covers, bottom covers or both). Similar to the guidance in NUREG/CR-6850 (and consistent with the fragility testing), there is no sustained ignition of the cables in cable trays with tray bottoms or tops.

The guidance for cable trays is summarized as follows:

- Electrical failure/damage of TP jacketed cables is 15 MJ/m².
- Electrical failure/damage of TS jacketed cables is 30 MJ/m².
- For cables outside of the enclosure of origin, but within the postulated HEAF ZOI, no sustained ignition is assumed.
  - For the post-HEAF fire, the analyst still must consider cable ignition using the ignition guidance in FAQ 16-0011 [25].

5.3 Bus Duct Damage Limits

This section develops the fragility of a bus duct exposed to a HEAF. The bus duct fragility is developed assuming that the failure mechanism is burn through of the bus duct. When the walls of the duct fail, hot gases and particles can enter the bus duct. This can have an effect on the electrical properties of the bus bars (increased resistance due to temperature), the bus bar coating, and the dielectric properties of the gas surrounding the bus bars. Without further testing, the fragility of the bus bars is unknown, for both the insulated and uninsulated configurations. A review of operating experience[1] revealed three events in which, once a HEAF breached a non-segregated bus duct (NSBD), the internal bus bars of a target bus duct enclosure faulted and tripped the protective relays.

Crediting any insulating material covering the bus bars, such as Noryl insulation, is not assumed to provide any significant additional protection from the bus duct burn through (based on a number of insulation failures identified from an OE review). Additionally, the potential inflow of hot gases and aerosols due to the HEAF could result in the decreased dielectric strength of the gas inside the bus duct.

Therefore, without further testing or modeling, given a breached bus duct, it is difficult to discern the functionality of bus bars narrowly outside the ZOI. Bus bars are generally close to the bus duct enclosure (e.g., less than 1 feet). Given the state of knowledge, the burn through of the bus duct should result in bus bar failure.

During the working group deliberations three different methods were proposed to evaluate the fragility of bus ducts. These methods include:

1. A conservative/bounding method assuming a lumped mass of bus duct cover exposed to a HEAF on one side and adiabatic conditions on the back side (Section 5.3.1).
2. A simple time dependent method assuming a lumped mass of bus duct cover exposed to a HEAF on one side and ambient conditions (i.e., the interior of the bus duct) on the back side (Section 5.3.2).
3. FDS to model a bus duct exposed to a jet of hot gas containing aerosols (Section 5.3.3).

[1] In all OE reports reviewed where a NSBD breach occurred; bus bar failures occurred in target bus ducts. One of these events, the Diablo Canyon HEAF, is described in detail in NUREG/CR-6850 Supplement 1 [2], with the other two NSBD target failures being similar.

5.3.1 Method 1: Bounding Lumped Mass Approach

This approach looks to determine the minimum amount of energy needed to fail the bus duct; that is, how much energy does it takes to raise the temperature of the bus duct to where it fails due to burn through.

The first question to consider is: What failure temperature should be used for a bus duct cover? As metals increase in temperature, their yield strength will decrease. The covers of a bus duct are only supporting their own weight as the bus bars themselves are supported by other structures along their length. This suggests that the bus duct covers should be able to withstand relatively large temperature increases before failure due to occurrence of tearing. Additionally, HEAF events are short-duration events. To heat a bus duct cover, several hundreds of degrees over a brief period of time will require substantial net heat fluxes. Even though metals have high thermal conductivities, net heat fluxes on the order of MW/m^2 will impose temperature gradients of tens to hundreds of degrees. Melting could be occurring on the exposed surface while the inner surface remains cool enough to avoid failure.

The bounding method considered two paths to failure:

Path 1: Tearing without melting, in which the duct heats to a temperature below the melting point, assumed to be 500°C for aluminum and 1300°C for steel, compared to the respective melting points of 660°C and 1500°C.

Path 2: A mix of melting and tearing in which the heat of liquefaction, 376 kJ/kg for aluminum and 250 kJ/kg for steel, is added to the energy needed to raise to the temperatures in Path 1.

This approach is just a simple calculation of the energy needed to raise the bus duct wall to its failure point as shown in Equation 5-4:

$$\boldsymbol{E} = \boldsymbol{\rho}\Delta\boldsymbol{x}(\bar{\boldsymbol{c}}\Delta\boldsymbol{T} + \Delta\boldsymbol{h}_{\boldsymbol{l}}) \qquad \textbf{Eq. 5-4}$$

where E is the energy in kJ/m^2, ρ is the density in kg/m^3, Δx is the thickness in m, $\bar{c}$ is the average specific heat over the temperature rise in kJ/(kg·K), ΔT is the bus duct temperature rise in K, and Δh_l is the heat of liquefaction.

Figure 5-4 shows the specific heat for steel [26] and aluminum [27]. The average values over the range of interest are 0.697 kJ/(kg·K) for steel and 1.01 kJ/(kg·K) for aluminum. The spike seen in the steel data is an endothermic change in the crystalline structure of carbon steel.

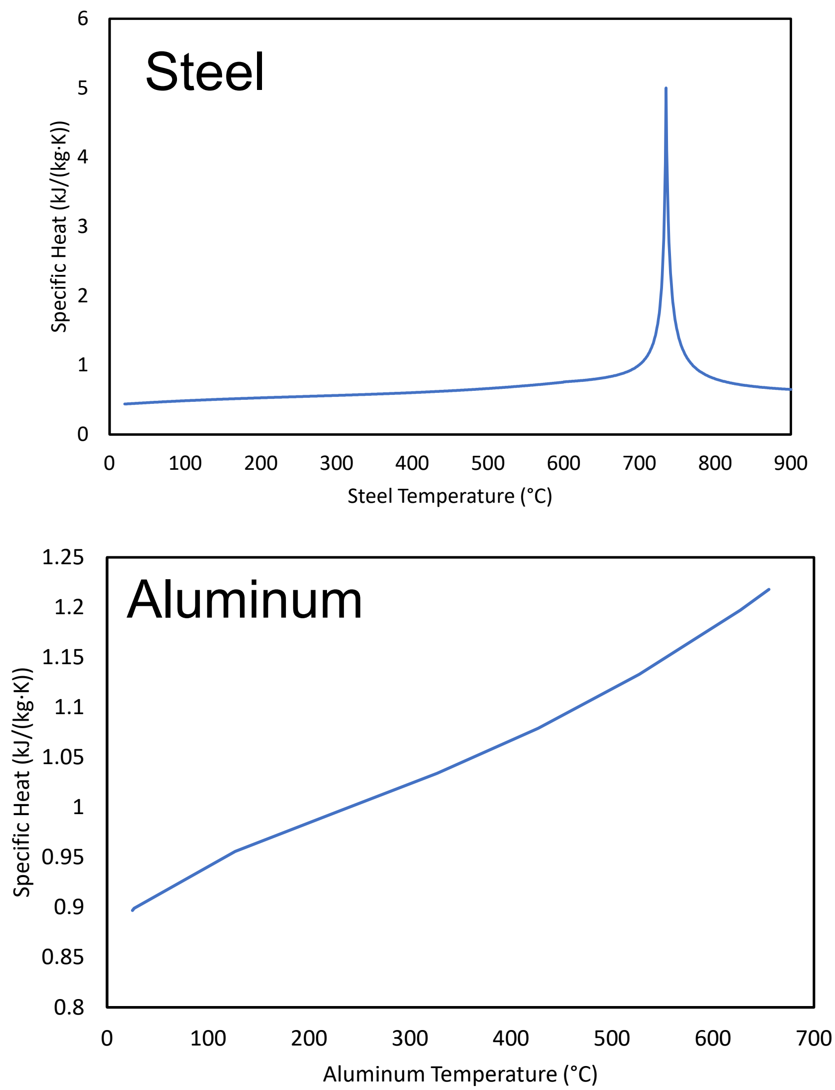


Figure 5-4
Specific heat of steel [26] (top) and aluminum [27] (bottom)

Table 5-1 shows the results of applying Equation 5-4 to a 3 mm thick duct wall (11 gauge) with densities of 7,800 kg/m^3 for steel and 2,700 kg/m^3 for aluminum.

Table 5-1
Results of applying Equation 5-4 to a 3 mm thick bus duct

Metal	Net Input Energy Required (MJ/m^2)	
	Critical Temperature (Path 1)	Melt (Path 2)
Steel	21.1	27.0
Aluminum	3.9	7.0

The values in Table 5-1 represent the energy that must be absorbed by the duct wall. Because HEAF events are of short duration, achieving such high amounts of heat transfer would mean exposure temperatures at which the exposure is primarily radiative. Given an incident amount of radiation, the amount actually absorbed by the surface is determined by the emissivity of the surface. For a metal bus duct that has been in use, both the steel and the aluminum duct will have an oxide layer. A typical oxidized steel emissivity is 0.8 to 0.9 (average of 0.85), and for aluminum is 0.4 [28]. An estimate of the incident flux needed to reach the net input energy in Table 5-1 can be obtained by dividing the values by the emissivity, as shown in Table 5-2.

Table 5-2
Results after correcting Table 5-1 for emissivity

Metal	Incident Energy Required (MJ/m^2)	
	Critical Temperature (Path 1)	Melt (Path 2)
Steel	24.8	31.8
Aluminum	9.8	17.5

5.3.2 Method 2: Time Dependent Lumped Mass Approach

As the bus duct heats up, the unexposed face will radiate and convect energy to the inside of the bus duct. Overcoming that heat loss will increase the incident energy required. The simple lumped mass time dependent approach shown in Equation 5-5 can be used to determine this.

$$\frac{dT}{dt} = \frac{\epsilon\sigma\left(T_H^4 - T^4\right) + h_H(T_H - T) - \epsilon\sigma F\left(T_H^4 - T^4\right) + h_D(T - T_D)}{\rho\Delta x c(T)} \qquad \textbf{Eq. 5-5}$$

Where T_H indicates the HEAF exposure, D indicates the duct interior, h is a heat transfer coefficient in kW/(m^2·K), σ is the Stefan-Boltzman constant, and F is a view factor that accounts for some heating of the top and bottom duct surfaces which limits radiative losses.

Equation 5-5 applies up to the point where melting begins. Once melting begins, there is no more temperature rise and the duct decreases in thickness. At this point Equation 5-6 would apply.

$$\frac{dx}{dt} = \frac{\epsilon\sigma\left(T_H^4 - T^4\right) + h_H(T_H - T) - \epsilon\sigma F\left(T_H^4 - T^4\right) + h_D(T - T_D)}{\rho h_l} \qquad \textbf{Eq. 5-6}$$

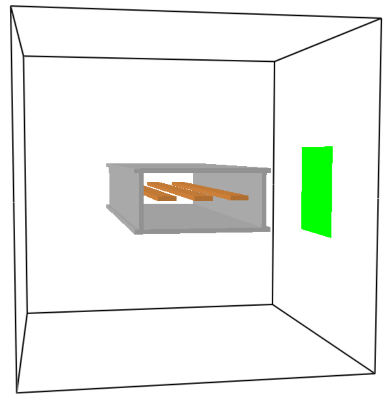
Equations 5-5 and 5-6 were evaluated to determine the incident energy required for Path 1 and Path 2 as a function of the HEAF duration. This was done by iterating T_H until the duct just reached the failure temperature for Path 1 or until the duct just melted for Path 2 at the end of the HEAF. It was assumed that the external HEAF exposure was a jet of hot outflow from an adjacent bus duct with a HEAF and that the internal bus duct temperature remained ambient (a reasonable simplifying assumption, given the short duration). The value of h_H was assumed to be 0.05 kW/(m^2·K), representing strong forced convection, and the value of h_D was assumed to be 0.01 kW/(m^2·K), representing natural convection. F was taken as 0.95 based on the Method 3 FDS simulations, which showed little significant heating of the remaining bus duct perimeter over the HEAF duration. Table 5-6 shows results using the same bus duct thickness and emissivity for Method 1. There is a slight dependence on the HEAF duration, but overall, the results are similar to those for Method 1.

Table 5-3
Results applying Equations 5-5 and 5-6 to a 3 mm thick bus duct

HEAF Duration (s)	Incident Energy Required (MJ/m^2)			
	Steel		Aluminum	
	Path 1 Critical Temperature	Path 2 Melt	Path 1 Critical Temperature	Path 2 Melt
4	24.3	31.3	8.9	16.2
6	24.7	32.1	8.8	16.1
8	25.2	32.7	8.7	16.1
10	25.6	33.5	8.7	16.0

5.3.3 Method 3: FDS Simulations

The final method used FDS to simulate the heating of a bus duct. A simple model was created to evaluate a section of bus duct exposed to a jet of hot gas representing an adjacent bus duct where a HEAF event has caused an outflow of heated gas. The failure of the bus duct wall used a phase change model in FDS. The FDS input file used a 2.5 cm (1 in) resolution. The HEAF exposure was a jet of hot gas directed at the bus duct with a velocity of 20 m/s. The jet was air with 0.1 kg/kg of aluminum oxide (Al_2O_3). Simulations were run with different jet temperatures. The wall of the bus duct was instrumented to measure duct thickness and gauge heat flux (the heat flux as would be measured experimentally using a heat flux gauge or plate thermometer). The integrated heat flux for the first wall cell to reach zero thickness was used to determine the



exposure needed to fail the duct.

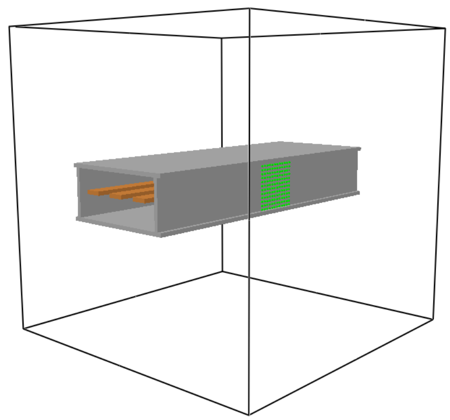


Figure 5-5 shows the FDS geometry, and Figure 5-6 shows a snapshot of results for a steel duct with a 5,000 K jet just after burn through.

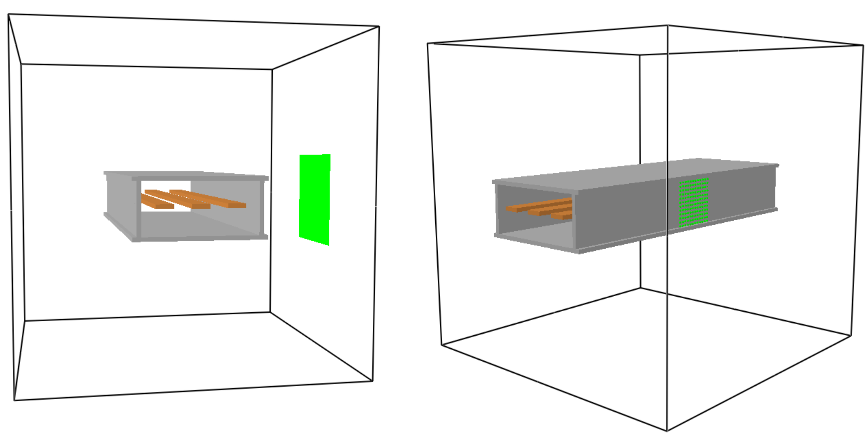


Figure 5-5
FDS model of a bus duct exposed to a HEAF. Left shows heat source (green rectangle) and right shows instrumentation (green dots).

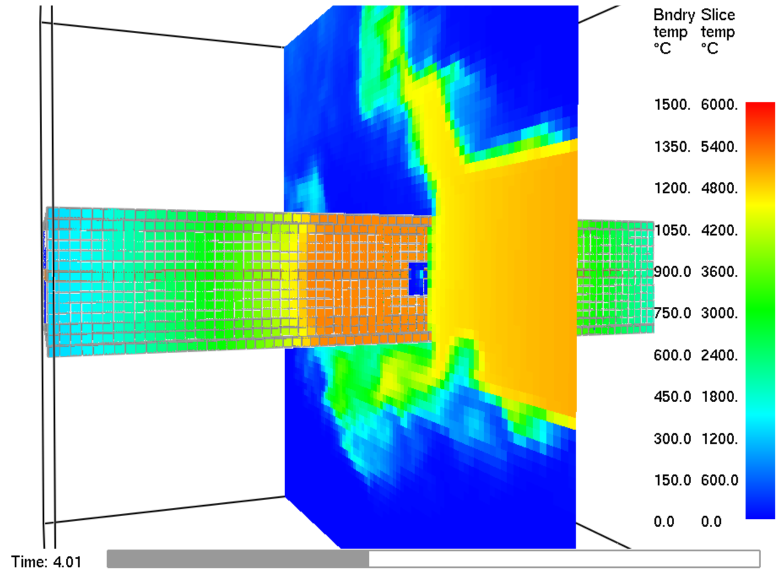


Figure 5-6
FDS model of a steel bus duct exposed to a 5,000 K jet just after burn through

FDS simulations were run for both steel and aluminum bus ducts. Exposure temperature, burn through temperature, and emissivity were varied. Table 5-4 shows the results.

Table 5-4
Results of FDS simulations of a 3 mm bus duct exposed to a HEAF

Metal	HEAF Temperature (K)	Emissivity	Critical Temperature (K)	Failure Time (s)	Incident Energy (MJ/m^2)
Steel	4000	0.85	1300	8.9	35.1
	5000	0.85	1300	3.8	33.5
	6000	0.85	1300	2.1	34.5
	5000	0.80	1300	4.0	35.6
	5000	0.90	1300	3.6	31.6
	5000	0.85	1100	3.3	29.0
	5000	0.85	1500	4.3	37.9
Aluminum	4000	0.40	500	4.5	17.4
	4500	0.40	500	3.0	17.4
	5000	0.40	500	2.1	17.5
	4500	0.30	500	3.8	23.1
	4500	0.50	450	2.4	14.0
	4500	0.40	450	2.8	16.3
	4500	0.40	550	3.1	18.6

Results are similar to Method 1 and Method 2. The total energy is similar, and there is also little dependence on the time to failure. Changing the emissivity by a small amount results in a proportional change to the required incident energy. This is the expected result, based on Equation 5-6. Using the average specific heat from Method 1, a 200 K change in temperature for steel is a shift of approximately 3 MJ/m^2, and a 50 K change for aluminum is 1.7 MJ/m^2. This is approximately the change seen in the FDS results.

5.3.4 Recommended Fragility

Overall, the three methods are in good agreement. For a steel duct the incident energy ranges from 25 MJ/m^2 for reaching the critical temperature to 33 MJ/m^2 for burn through. For aluminum the values range from 9 to 17 MJ/m^2. FDS simulations of the 2018 medium voltage switchgear tests showed good agreement in the first observed failure of the switchgear when compared to testing suggesting that the FDS burn through time reasonably captures the exposure needed.

The recommended values for bus duct fragility are as follows:

- 15 MJ/m^2 for aluminum bus ducts
- 30 MJ/m^2 for steel bus ducts

These values are respectively equivalent to the TP and TS fragility criteria developed in Section 4.

6
SUMMARY AND CONCLUSIONS

This report documents the WG's effort to develop consensus positions on fire PRA target damage thresholds for HEAF exposures. These positions were developed through either a planned approach, as described in Section 2, or an analytical approach for protective features and non-cable damage limits (see Section 5). Regardless of the approach, the WG used all available information and subject matter expertise in developing the consensus positions. This included relevant test data, PIRT insights, operating experience, calculations, simulations, and engineering judgment. The thresholds developed use target incident energy (MJ/m^2) as a metric for defining failure. This supports its use in the subsequent development of HEAF ZOI estimates, in which outputs from hazard modeling of HEAF will be compared to these failure thresholds to develop the ZOI. The hazard modeling and ZOI development will be the subject(s) of future report(s).

Based on the work and discussions from the WG, the conclusions in Table 6-1 were drawn for quantitative thresholds for target failure.

Table 6-1
Summary of target fragility thresholds

Target Type	Threshold (MJ/m^2)
TP jacketed cables (including cables in conduit and cable trays)	15
TS jacketed cables (including cables in conduit and cable trays)	30
Aluminum enclosed bus ducts	15
Steel enclosed bus ducts	30

The WG evaluated cables routed in conduit and cables routed in raceway with solid bottoms and top covers. Based on the data and simulations, the WG concluded that both conduits and cable tray covers do not significantly increase the protection of an electric cable from damage in the event of a HEAF. Cables in conduits and cables in trays with a cover should use the TP (15 MJ/m^2) and TS (30 MJ/m^2) fragility criteria.

In addition to these target fragilities, the working group evaluated specific protective features such as ERFBS. For ERFBS, the WG recommended the following treatment for targets in HEAF scenarios:

- Cables protected by ERFBS that enter the postulated HEAF initiating electrical enclosure are assumed damaged, but not ignited, and they do not contribute to the fire load (no change from current guidance [1]).
- Cables in raceways located within the scenario ZOI and protected by ERFBS are considered protected. They are neither damaged nor ignited, and they do not contribute to the fire load.
- Credit for ERFBS assumes a minimum 1-hour fire rating and a barrier that is properly designed, tested, configured, installed, inspected, and maintained.

7
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A
TARGET FRAGILITY PLAN

The U.S. Nuclear Regulatory Commission (NRC) developed a target fragility plan and shared with the Electric Power Research Institute (EPRI) for feedback and improvement. This plan is reproduced in Section A.1.

A.1 Overview

A.1.1 Project Background and Description

The NRC/EPRI working group on HEAF has been tasked with improving the methodology for assessing the HEAF hazards in nuclear power plants (NPPs). A part of this effort includes updating the zone of influence (ZOI) used to determine target sets assumed damaged in a fire PRA scenario. Damage includes ignition and loss of electrical function. To gain a better understanding of this hazard, the NRC performed HEAF testing to understand how the energy source behaves as the event progresses. Additional testing on target damage (electrical cables) was performed at Sandia National Laboratories. Target damage, also referred to as "target fragility" is used in conjunction with hazard modeling for a specific HEAF scenario to determine the ZOI (i.e., geometric limits) of equipment damage. The equipment within the ZOI is assumed damaged.

A.1.2 Project Scope

The scope of the target fragility sub-task is to develop a consensus on fire PRA target damage caused by a HEAF. Damage includes ignition and functional failures. Past practices have assumed that these two failure modes occur concurrently [1]. The primary targets assessed are electrical cables (control, power, and instrumentation). Electrical cables are the most common target assessed in fire PRA for its impact on plant response and combustible loading. Fragility of other targets or target configurations may be determined based on available time and resources.

A.1.3 Objective

The objective of this task is to provide best estimates of target fragility (target damage) thresholds for HEAF exposures to electrical cables.

A.1.4 High-Level Requirements

The target fragility approach should include the following:

- Ability to have target fragility threshold coherent with HEAF hazard modeling outputs (e.g., incident energy, heat flux)
- Ability to rely on data, science, and documented subject matter expert judgment to support target fragility thresholds
- Ability to provide a consensus approach for treatment of target fragility

A.1.5 Deliverables

The deliverables for this subtask include fire PRA target fragility thresholds for electrical cables.

A.1.6 Affected Parties

The target fragility will be used by the WG to support updating the ZOI used in fire PRA. Stakeholders are also affected, and for transparency, the technical basis to support ZOI development will also be documented and made available.

A.1.7 Specific Exclusions from Scope

This effort does not include developing the zone of influence. The ZOI development is related, but a follow-on effort that will combine the HEAF scenario hazard modeling and target fragility aspects to develop scenario specific ZOI consistent with the updated fire PRA methodology for HEAF.

This effort does not involve development of PRA application guidance. However, insights from this effort may support development/refinement of that guidance.

A.1.8 Implementation Plan

In order to develop the target fragility, the following actions are anticipated.

- The working group should be split into groups with specific roles:
  - Proponents:
    - Experts who develop, present and defend a proposal
  - Evaluator:
    - Technical experts without a vested interest in the development of any proposal
    - Objectively evaluate the views of others in developing the proposals
  - Integrator:
    - Technical lead responsible for developing the composite representation of the technical community
    - This can be the same individual(s) that serve as evaluators
    - Responsible for monitoring, directing, and documenting the outcomes of the effort

- Resource experts:
  - Experts with intimate knowledge of the subject matter or impacted subject matter
  - Examples: fire modelers, test engineers/scientist, materials experts, electrical experts

- Data compilation and processing:
  - In this step the various data streams will be compiled and processed to support clear and consistent information exchange with the WG.
  - This will include quantitative data such as flux and incident energy measurements and qualitative data such as photo and video graphic information from tests and operating experience.
- Data presentation, inference and discussion with WG, including insights from the international PIRT:
  - In this step the data from the various sources will be presented to the WG
  - Feedback may require re-processing data for consistency, gained insights, or to include information not initially prepared.
  - Data will be presented sequentially as it is prepared for the WG.
  - Insights from the international PIRT will also be presented early on for consideration during the data review to support focus on key parameters.
- Proposal development:
  - In this step, the working group members will work on developing models, methods, or proposals on target fragility determination.
  - It is anticipated that the proposals will be developed by individual WG members or a subset of WG members.
- WG deliberation and consensus formation:
  - In this step the individual proposals will be presented to the WG.
  - Outcomes include selection of a proposal "as is", selection of a proposal with changes, or combining multiple proposals into a WG consensus method.
  - All approaches to reach a consensus should be pursued. However, if consensus cannot be reached after significant efforts, the viable expert opinions should be documented along with specific concerns with proposals.
- Target fragility approach:
  - This step provides documentation of the overall effort

A.2 List of Other Targets for Fragility

The WG developed the following list of targets that may benefit from characterization of its fragility associated with a HEAF exposure. Several of these items are addressed in the main body of this report. Items not addressed in this report have been deferred by the WG until hazard modeling results are available.

Table A-1
List of potential HEAF targets

Items in This Report	Items Addressed in Subsequent Report(s) if Necessary
• Cable raceway types ○ Trays with covers (see Section 5.2.1) ○ Conduits (see Section 5.2.2)	• Cable raceway types ○ Cable bus ducts or cable risers ○ Junction boxes
• Electric raceway fire barrier systems (ERFBS), also known as "fire wraps" (see Section 5.1)	• Electrical equipment ○ Switchgear ○ Load centers ○ Motor control centers (MCCs) ○ Other electrical cabinets ○ Transformers ○ Motor-generator sets
• Bus ducts (see Section 5.3)	• Instrument air lines (e.g., soldered piping)

B
TEAM PROPOSALS

This appendix contains the final proposals provided by each team.

B.1 Proposal from Team 1

B.1.1 Objective

The objective of this effort is to characterize the failure threshold of fire probabilistic risk assessment (PRA) targets exposed to the energy and effluent of a high energy arcing fault (HEAF). The specific targets that have been prioritized are electrical cables commonly found in nuclear power plants near equipment that can support a HEAF (switchgear and bus ducts). The resulting target fragility requires consistency with hazard model outputs to support development of HEAF PRA scenario zones of influence (ZOI). Determining the ZOI is outside the scope of the target fragility effort documented here.

B.1.2 Approach

The team followed a simple approach:

1. Understanding the question (objective of effort)
2. Understanding the available data streams
3. Determining criteria to characterize target failure
4. Analyzing the data to support the characterization of a failure threshold
5. Evaluating methods to streamline the process and ensure consistency with fire PRA application
6. Ensuring the team members agree to the proposal and thoroughly discussing any differing views to achieve team consensus (if possible)
7. Documenting the effort in the proposal

B.1.3 Summary of Results

The team concluded that a simple incident energy threshold was the most appropriate approach for characterizing the electrical cable target fragility. Two thresholds are differentiated by the cable jacket material type: thermoset (TS) and thermoplastic (TP).

The team did explore the possibility of expanding its judgment to include sustained ignition but concluded that the limited data and test-to-field variations could not support such a determination. The team recommends that the working group (WG) consider the attributes of the sustained ignition concern as part of the development of the PRA guidance for modeling the ensuing fire and propagation as communicated in this proposal recommendation (Section B.1.7).

B.1.3.1 Structure of Proposal

The proposal is broken down into the following sections:

- Evaluation of specific failure mode thresholds:
  a.) Damage (Section B.1.4)
  b.) Ignition (Section B.1.5)
- Summary and conclusions (Section B.1.6)
- Recommendations (Section B.1.7)

B.1.4 Failure Mode 1: Damage

B.1.4.1 Understanding the Question

The team understands the question to be: What is the threshold at which an electrical cable is no longer capable of performing its function? Loss of function is considered loss of the cable's insulation integrity to maintain electrical isolation of the individual conductors (i.e., loss of insulation resistance sufficient to effect circuit function). The exposure condition is assumed to be from a HEAF.

B.1.4.2 Understanding the Available Data Streams

The team reviewed the following data:

- Japanese Nuclear Regulation Authority (JNRA) data provided in "Fragility Evaluation: JNRA Low Voltage General Electric (GE) Distribution Panel and Medium Voltage GE Switchgear Tests":
  - Used flame-retardant polyvinyl chloride (PVC) (CV-2) or heat-resistant PVC (CCV), both TP.
  - Cable photos do not show damage to the level that would be considered a loss of cable functionality. In one test, maximum incident energy was approximately 5.5 MJ/m^2 at target. This would suggest the threshold is above 5.5 MJ/m^2.
  - Data were not analyzed in Section B.1.4.7 due to exposure levels (incident energy) lower than required to cause damage.
- U.S. NRC data presented in "Fragility Evaluation: 2018 Medium Voltage GE Switchgear Tests":
  - Used 3/C and 7/C PVC jacketed cable coupons, both TP.
  - Cable photos show varying levels of damage.
  - Test 2-24 required estimating incident energy at several exposure locations due to measurement equipment damage from the experiment.
  - The lowest energy at which damage beyond just jacket damage was observed was 5.9 MJ/m^2. This would suggest that the damage threshold is greater than 5.9 MJ/m^2.
  - Section B.1.4.7 describes the data analysis.

- Organisation for Economic Co-operation and Development (OECD) data presented in "Fragility Evaluation: 2014-2016 test series":
  - Cables located in the cable tray above the enclosure or offset above the enclosure with plate thermometers attached to the underside of the ladder back style cable tray provide some usable data.
  - Most of the experiments resulted in an arc plume that was not directed at the cable samples.
  - Some experiments resulted in ensuing fires that caused significant damage to the cables, leading to difficulty in distinguishing the HEAF damage from the ensuing fire damage.
  - Several tests (12, 13, and 23) provide some insights to the proximity of the threshold.
- Operating experience (OE) presented in "Electric Power Research Institute (EPRI) Fragility Insights from OPEX":
  - This document presents a compilation of event and damage descriptions.
  - For fragility, this information is difficult to use due to the lack of incident energy, electrical energy, or geometrical configuration data.
  - This is good information to calibrate the ZOI estimates, and application guidance developed in subsequent tasks.
  - This data set was not used in this effort.
- Sandia National Laboratories (SNL) solar furnace data presented in *HEAF Cable Fragility Testing at the Solar Furnace at the National Solar Thermal Test Facility* [8]:
  - SNL tested both TP and TS cables.
  - Photographic evidence and incident energy are estimates.
  - Most data require a qualitative assessment of damage.
  - The experimental approach excluded some damage mechanisms (mechanical impact or erosion). TP data provide a direct comparison between NRC and SNL data sets.
  - SNL provides the most robust data set to support the development of electrical damage criteria.

B.1.4.3 Determining Criteria to Characterize Target Damage

Many different metrics that could be used to evaluate post-test damage to the cable samples. The tests reviewed included many different primary flux levels, durations, and exposure profile shapes. After discussion, the team concluded that total incident energy (MJ/m^2) is the best criterion for developing an electrical failure threshold. The total energy of exposure is an efficient way to normalize the data when dealing with the differences of the other variables.

While there is likely a minimum heat flux at which damage would not occur regardless of duration, the team members determined that insufficient data were available to support their judgment, and they did not view such a threshold as having a sufficient impact on the results, given that the PRA guidance document limits the duration to 15 seconds (worst case). In addition, the lower flux limit is likely not applicable to HEAF-type exposures and more applicable to traditional hydrocarbon fires. As such, for the electrical damage failure mode, the team will report the target fragility level (damage criteria) as the total incident energy (MJ/m^2).

B.1.4.4 Analyzing the Data to Support the Characterization of a Damage Threshold

The target fragility associated with the loss of function for an electrical cable has been split into two different categories, based on the composition of the cable's jacket material; namely: TS and TP. The team concluded that these thresholds to be applied to power, control and instrumentation cable found in open ladder-back cable tray or cable air drop configurations. The team recommends the following incident energy thresholds for each category of cable:

- TS cables will fail electrically after exposure to 32 MJ/m^2.
- TP cables will fail electrically after exposure to 15 MJ/m^2.

B.1.4.5 Assumptions

- The target will fail electrically if the jacket is damaged to the point of exposing the inner shielding and/or insulated wires, or both:
  - This assumption is made because the SNL testing, while severe, did not include the degradation mechanism of the erosion of damaged polymer material and potential for hot molten metal projectiles to cause localized damage to the exposed electrical insulation. The lack of erosion effects likely resulted in the development and maintained a char layer that effectively serves as a thermal shield.
- Different heat flux profiles and target configurations (single cable, three-cable bundle) were used in the Phase 1 test program at the solar furnace. In addition, for TP cable samples, the NRC full-scale data were evaluated, which included cable coupons containing six to eight cable segments per coupon. It was assumed that these test differences between cable configurations (single versus three-cable bundle) did not significantly affect the results in terms of jacket damage to the target cable. That is, from a material degradation sense, the number of cables exposed does not affect the loss of cable function (i.e., damage).
- According to the staff at the solar furnace, the calibration equipment used to specify the heat flux (the high-heat flux gauge and the radiometer) has up to a 10-percent error This proposal makes no attempt to adjust the data to account for measurement uncertainty.

B.1.4.6 Basis

- The analysis was based on the visual inspection of post-test cable samples from the Phase 1 testing at the solar furnace in January-February 2021 and the photographic evaluation of the cable coupon samples from the 2018 NRC full-scale testing. The damage of the cables was subjectively categorized with the following definitions:
  - Jacket damage: Surface damage to the jacket was observed but was overall the jacket was still intact, such that no inner components of the cable were exposed.

- Insulation exposure: The jacket was sufficiently damaged so that there was clear exposure of the inner shielding and/or insulated wires of the cable. This also includes damage characteristics on the jacket, such as pinholes or deep cracks.
- Wire exposure: The jacket and insulation of the wires were damaged sufficiently to expose the copper wire.

- For TS, there were 14 usable data points from the solar furnace testing [8] to inspect post-test damage of the cable samples. A test was considered unusable when the duration and total incident energy were much larger than what would be expected from a HEAF event or from full-scale testing (Tests 1-08 through 1-16). These higher energy tests typically resulted in significant damage to all cable components making it difficult to characterize the damage from an electrical function standpoint. Table B-1 presents this data set.
- For TP, there were 13 usable data points from the solar furnace testing and 14 usable data points from the NRC full-scale testing to inspect post-test damage of the cable samples. The discussion on unusable data from previous bullet applies to this as well. Table B-2 presents these data.
- Note that Tests 1-08 through 1-16 were used to investigate electrical damage and thermal response at much longer time scales than a HEAF event. These tests resulted in total energy exposures between approximately 150 and 800 MJ/m^2. The damage from these cable targets was exploratory and not used in this assessment.

Table B-1
TS test parameters from Solar Furnace Phase 1 Testing [8]

Test Number	Nominal Primary Flux (MW/m^2)	Nominal Primary Duration (s)	Profile	Calculated Total Energy (MJ/m^2)	Damage
T1-2	3	2	Dynamic	14	Jacket damage
T1-23	3	2	Simple	7	Jacket damage
T1-25	5	2	Simple	15	Jacket damage
T1-27	6	4	Simple	38	Jacket damage
T1-29	3	8	Dynamic	32	Jacket damage
T1-28	6	8	Simple	63	Jacket damage
T1-31	5	6.3	Dynamic	37	Jacket damage
T1-3	3	10	Dynamic	37	Insulation exposure
T1-17	0.05	N/A	Simple	33	Insulation exposure
T1-20	0.05	N/A	Simple	85	Insulation exposure
T1-21	3	25	Simple	82	Insulation exposure
T1-30	3	10	Dynamic	35	Insulation exposure
T1-36	2	15.5	Dynamic	36	Insulation exposure
T1-37	3	10	Dynamic	39	Insulation exposure

Table B-2
TP test parameters from Solar Furnace Phase 1 Testing [8]

Test Number (Sample ID)	Nominal Primary Flux (MW/m^2)	Nominal Primary Duration (s)	Profile	Calculated Total Energy (MJ/m^2)	Damage
T1-5	3	2	Dynamic	14	Jacket damage
T1-19	0.05	N/A	Simple	52	Jacket damage
T1-22	3	2	Simple	7	Jacket damage
T1-24	5	2	Simple	15	Jacket damage
T1-7	3	4	Long Ramp	24	Insulation exposure
T1-18	0.05	N/A	Simple	89	Insulation exposure
T1-26	6	4	Simple	36	Insulation exposure
T1-32	3	6	Dynamic	24	Insulation exposure
T1-33	3	4	Dynamic	17	Insulation exposure
T1-34	5	2.5	Dynamic	25	Insulation exposure
T1-35	2	7	Dynamic	21	Insulation exposure
T1-38	3	4	Dynamic	21	Insulation exposure
T1-6	3	10	Dynamic	40	Wire exposure
2-21 (1-13)	0.4	4	Test	5.9	Insulation exposure
2-21 (1-23)	1.2	4	Test	7.8	Insulation exposure
2-21 (1-24)	0.4	4	Test	7.8	Insulation exposure
2-21 (1-37)	0.2	4	Test	1.2	Jacket damage
2-21 (1-38)	0.2	4	Test	1.2	Jacket damage
2-24 (1-1)	0.2	4	Test	1.5	Jacket damage
2-24 (1-13)	2.4 (est.)	4	Test	9.4 (est.)	Insulation exposure
2-24 (1-14)	2.4 (est.)	4	Test	9.4 (est.)	Insulation exposure
2-24 (1-23)	3.2 (est.)	4	Test	12.7 (est.)	Insulation exposure
2-24 (1-24)	3.2 (est.)	4	Test	12.7 (est.)	Wire exposure
2-24 (1-37)	0.2	4	Test	1.2	Jacket damage
2-24 (1-38)	0.2	4	Test	1.2	Jacket damage
2-24 (1-47)	0.4	4	Test	1.5	Jacket damage
2-24 (1-48)	0.4	4	Test	1.5	Jacket damage

B.1.4.7 Determining the Damage Threshold

TP data are presented first, as they are the largest data set and provide a convenient comparison between test series. Figure B-1 presents the available dataset categorized by damage state and plotted by flux and incident energy. Figure B-2 presents the available TP data in a box plot split by test series (NRC or SNL) and damage characterization (IE – insulation exposure, WE – wire exposure). Note that jacket damage (JD) is not included as it was considered it to be a "catch-all" category and the qualitative characterization of the lower limit is difficult to characterize. Thus, any estimate of data quartiles for the JD case was viewed to have little meaning and has been excluded from the box plot. It should also be noted that the WE damage state was limited to one data point for each test series. In addition, several data points in the NRC data set are estimates due to the fact that the active measurement system (TC wire), while protected, was damaged during the event and incident energy could not be reported. From this graph there is an apparent systemic difference between the two data sets. The NRC data appears to show damage at a lower incident energy level than the corresponding SNL data of the same damage state. Possible reasons for this difference are discussed next.

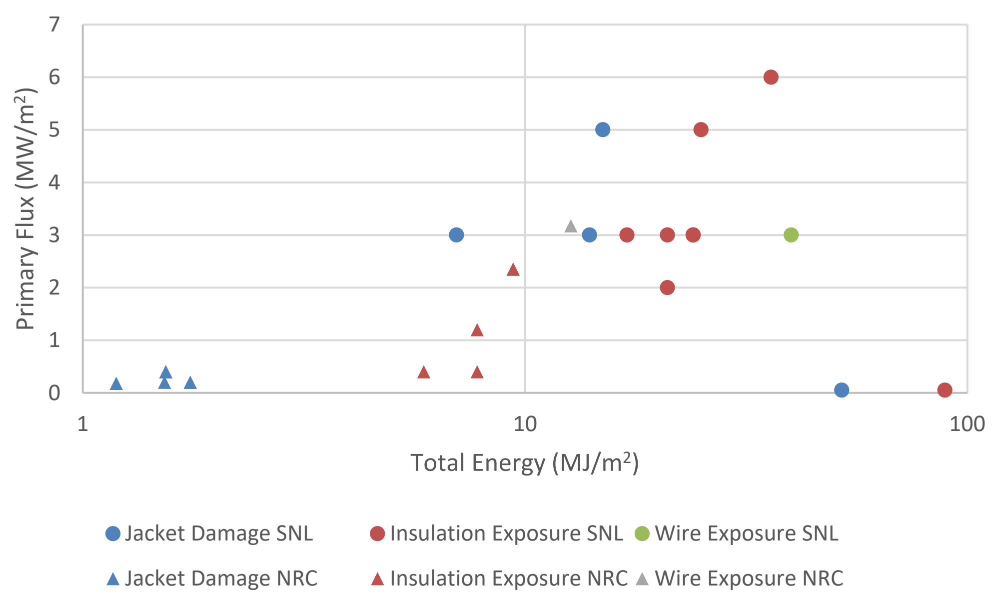


Figure B-1
Thermoplastic dataset by flux and incident energy (note $\log_{10}$ scale for total incident energy)

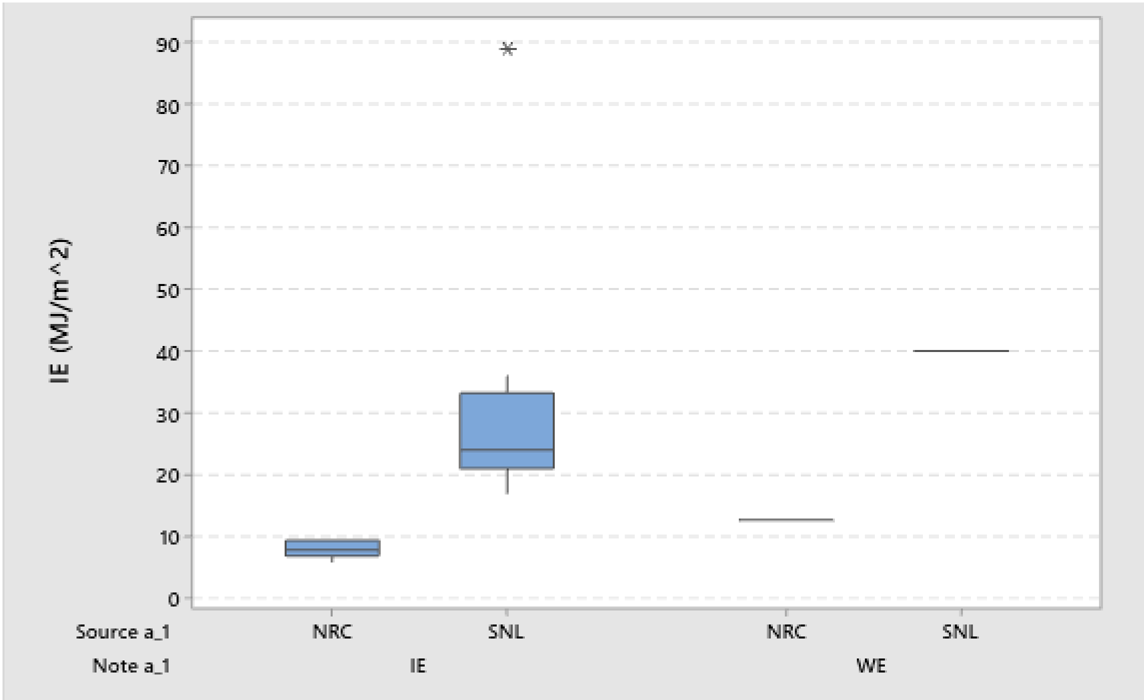


Figure B-2
Box plot presenting thermoplastic data

Exposure conditions could contribute to the differences presented in Figure B-2. The SNL tests were a purely radiant exposure using solar energy as the source of thermal stress. In the NRC tests, the cable coupons were exposed to radiant and convective heating, along with mechanical forces, such as momentum-driven flows from the arc plume (jet) and particulate erosion from the molten metal particles within the HEAF plume (jet). Visual comparisons of cable samples between the two-test series indicated that the SNL samples appear to exhibit a larger char layer than that observed from the NRC testing. Figure B-3 is a photograph of the lower left TP cable sample (1-23) from Test 2-21, which received approximately 7.8 MJ/m^2 of energy. Figure B-4 is a photograph of the TP cable sample used in SNL Test 1-34 which received approximately 25 MJ/m^2 of energy. Both example photos are from the upper region of the box plot for their respective test series and the insulation exposure category. As can be seen in the SNL example, the char layer is more substantial than that observed in the NRC test. While both cases involve localized melting, the char layer is, for all practical purposes, nonexistent in the NRC test compared to the SNL test, where it is easily identified. The development of the char layer in the SNL tests likely has a primary effect on the heat transfer characteristics within the cable sample. That is, the char layer is acting as a thermal shield and limiting the heat transfer inward to the cable. One likely cause for the lack of the char layer on the NRC cable is the effect of particulate erosion at the surface of the cable. The HEAF plume (jet) being a momentum-driven flow consisting of hot molten metal particulate from the electrode and enclosure effectively acts as an erosion mechanism that removes the char layer and minimizes the thermal shielding effect.

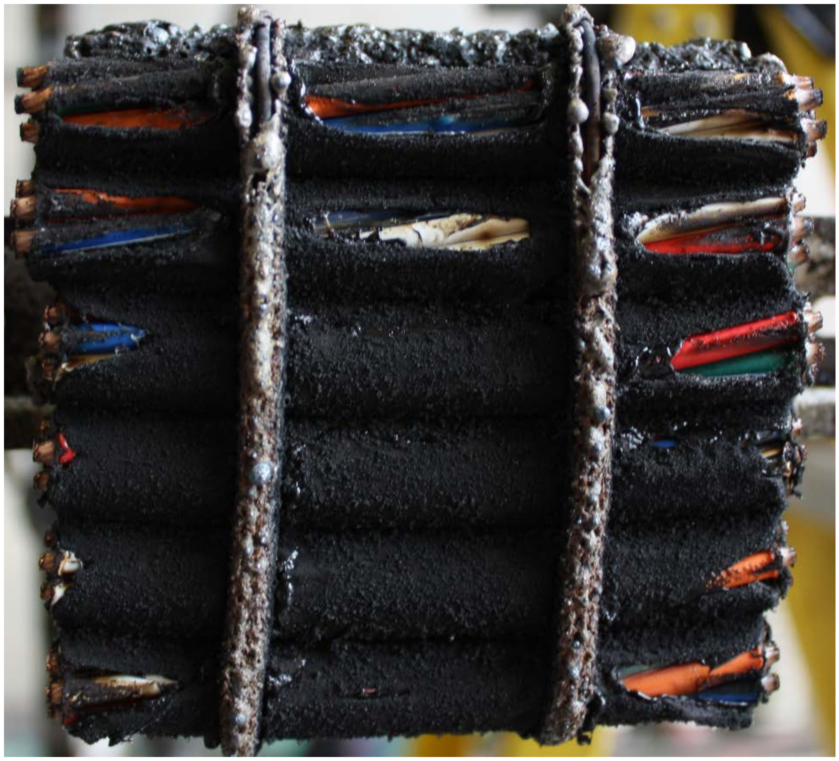


Figure B-3
Photo of NRC Test 2-21 Rack 2 sample 1-23 (7.8 MJ/m^2), sample classified as "insulation exposure"

Figure B-4
Photo of SNL Test 1-34 (25 MJ/m^2), sample classified as "insulation exposure"

The most damaged cable sample from the NRC testing occurred on rack #2 sample 1-24 located at approximately 3 ft (0.9 m) from the exterior of the electrical enclosure. This sample was located at the bottom cable coupon location on the right side of the instrumentation rack. The top half appears to have received more damage than the bottom and, as such, the top half of the cable coupon is shown in Figure B-5. A red circle has been added to the photo to identify a location where the conductors appear to be visible. This cable construction consists of the stranded conductor enveloped by a clear insulation, which is surrounded by a colored insulation jacket. Because of the clear nature of the insulation, it is not apparent from the photo if this observation of the conductor includes insulative media or is void of such insulation. The teams concluded that this data point was close to electrical failure, if not failed. However, caution should be used with the 12.7 MJ/m^2 value, as it is an estimate and not a direct measurement made during the test.

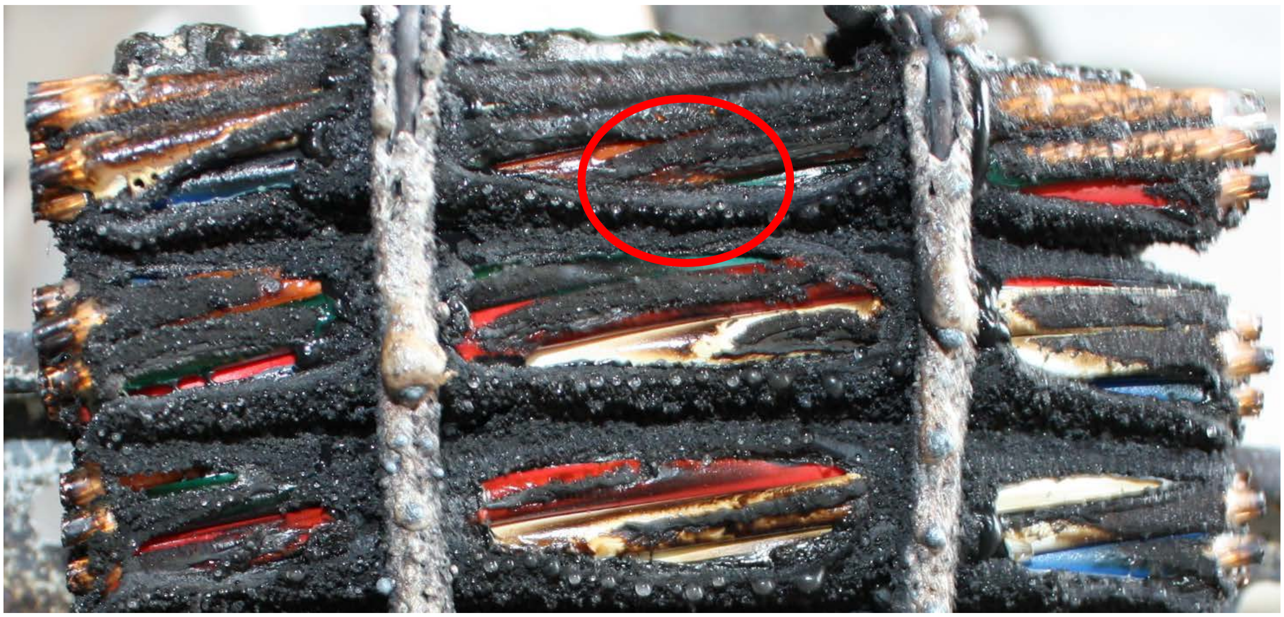


Figure B-5
Photo of Test 2-24 sample 1-24 bottom right (12.7 MJ/m^2 estimated), sample classified as "wire exposure"

Based on the data reviewed by the team, the consensus was that the damage threshold for a TP cable is slightly above the 12.7 MJ/m^2 observed in Test 2-24. This is based on the need for multiple adjacent insulated conductors to sustain damage to their insulation in close proximity to each other. The photograph above shows evidence of conductor insulation remaining in this orientation. The team concluded that using the upper bound of the jacket damage estimate from the SNL data set could reasonably predict the damage threshold for thermoplastic materials. Because the data set is not resolved sufficiently to determine the exact transition point between jacket damage and insulation exposure for the SNL data set, there is a gap between 15 MJ/m^2 (maximum recorded energy for jacket damage) and 17 MJ/m^2 (minimum recorded energy for insulation exposure) for the SNL dataset. To ensure coverage, the team concluded that using the maximum jacket damage energy of 15 MJ/m^2 adequately covers the unknown data gap and provides reasonable compensation for the bias between the SNL and NRC data sets. This approach correlates cable damage to when the jacket is no longer present in the SNL tests.

This is a compromise between two factors: 1) the need for insulation damage to occur for actual cable damage, and 2) the NRC full-scale data shows damage at lower incident thresholds (see Figure B-2). As such, the team agreed that 15 MJ/m^2 is a reasonable estimate for the target fragility threshold for TP cable.

For the TS case, given that a similar data set for TS material is not available from the NRC data, the logic developed for the TP case is again used. Figure B-6 shows the damage state of the samples as a function of the total energy (x-axis) and nominal primary heat flux (y-axis). As shown, the data line up nicely in terms of an energy exposure threshold. The minimum energy exposure that resulted in insulation exposure is 33 MJ/m^2. Alternatively, the maximum energy exposure below the insulation exposure damage level that resulted in only jacket damage (that is less than the 33 MJ/m^2 value) is 32 MJ/m^2. As with the TP case, using the maximum incident energy below insulation exposure from the SNL tests for TS cable correlates cable damage to when the jacket is no longer present in the SNL tests. However, unlike the TP case, there is no direct comparison between full-scale NRC data and the small-scale SNL solar furnace data set. As such, the team had to assume similar behaviors (shifts in data characterizations) exist for the TS case. With this assumption, the two factors identified in the TP case suggest that using the highest incident energy value of jacket damage below insulation exposure events for the SNL tests is a reasonable approximation for estimating cable damage. As such, the team agreed that 32 MJ/m^2 is a reasonable estimate for the target fragility threshold for TS cable.

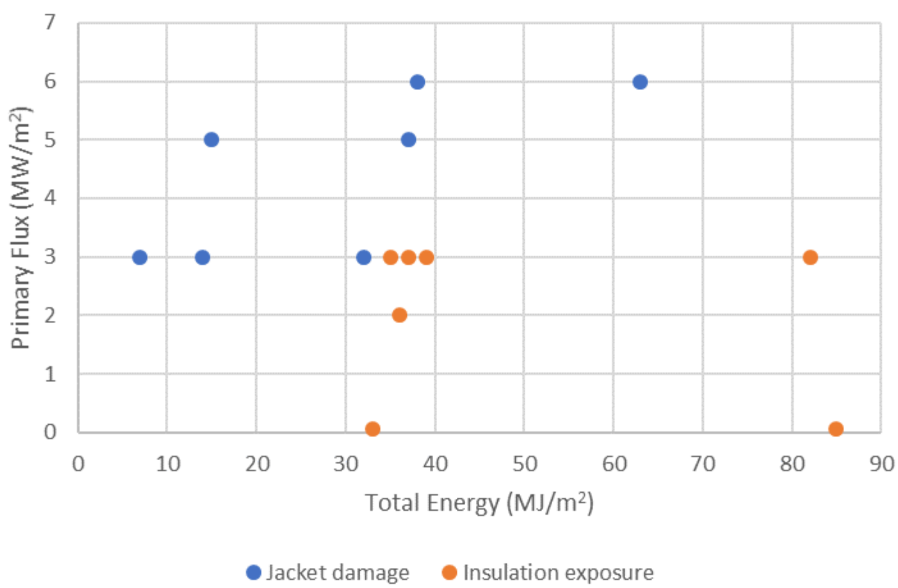


Figure B-6
Thermoset damage as a function of heat flux and total energy

B.1.4.8 Evaluating Methods to Streamline the Process and Ensure Consistency with Fire Probabilistic Risk Assessment Application

Subsequent sections of this report discuss the methods to streamline the process and ensure consistency with fire PRA application as it relates to cable ignition.

B.1.4.9 Ensuring the Team Members Agreed to the Proposal and Thoroughly Discussing Any Differing View to Achieve Team Consensus (If Possible)

The team met several times to discuss the proposal and attempt to identify improvements or alternatives. After several revisions and refinements to the initial proposal, the team agreed with the proposed approach.

B.1.5 Failure Mode 2: Ignition

B.1.5.1 Understanding the Question

The team understands the question to be: What is the minimum threshold that an electrical cable ignites from exposure to a HEAF event and sustains ignition. This question does not address the fire propagation from within the electrical enclosure or the propagation from other nearby combustible materials.

B.1.5.2 Understanding the Available Data Streams

Data streams identified in Section B.1.4.2 were reviewed for pertinent information. This information is summarized as follows:

- SNL literature related to ignition modeling by Martin [29] and data application to that model were reviewed in detail:
  - Martin developed plots for specific materials that distinguish between regions of ignition and no ignition, based on the fluence (incident energy) and flux (rate of energy).
  - Note that ignition is broken into two different regions, persistent ignition, and transient ignition.
  - The upper right branch (“Persistent ignition” vs “Transient ignition”) worked well for a specific allative cellulosic material. Differing materials resulted in the shift of the upper right branch. The lower branch (“No ignition” vs “Transient ignition”) appears to be independent of material.
  - Section B.1.5.4 describes the data analysis.

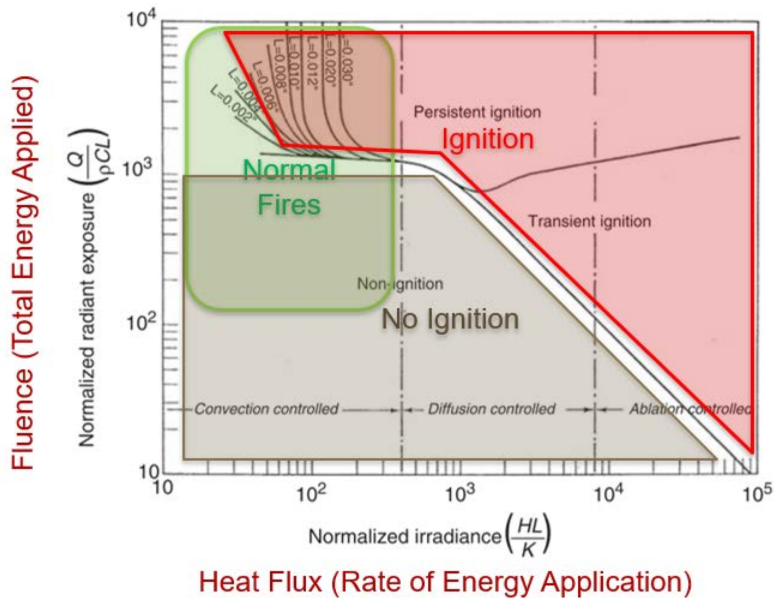


Figure B-7
Summary plot of ignition data for blackened cellulose by Stan Martin

- NRC video from the 2018 test series:
  - Video evidence from SNL and the National Institute of Standards and Technology (NIST) taken during the 2018 medium voltage switchgear tests was reviewed in detail.
  - SNL video is of high fidelity and high frame rate but is limited by the location, frame selection, and length of video.
  - NIST video is of lower quality, due to the proximity and lower frame rate, but does capture most cable samples in the frame.

The discussion below identifies specific results usable for this exercise.

B.1.5.3 Determining Criteria to Characterize Target Fragility

The information provided by SNL suggests that the threshold for ignition should be based on a fluence (energy) and irradiance (flux) relationship. This relationship is characterized in Figure B-8 with the solar furnace test data [8] plotted against the cellulose ignition model.

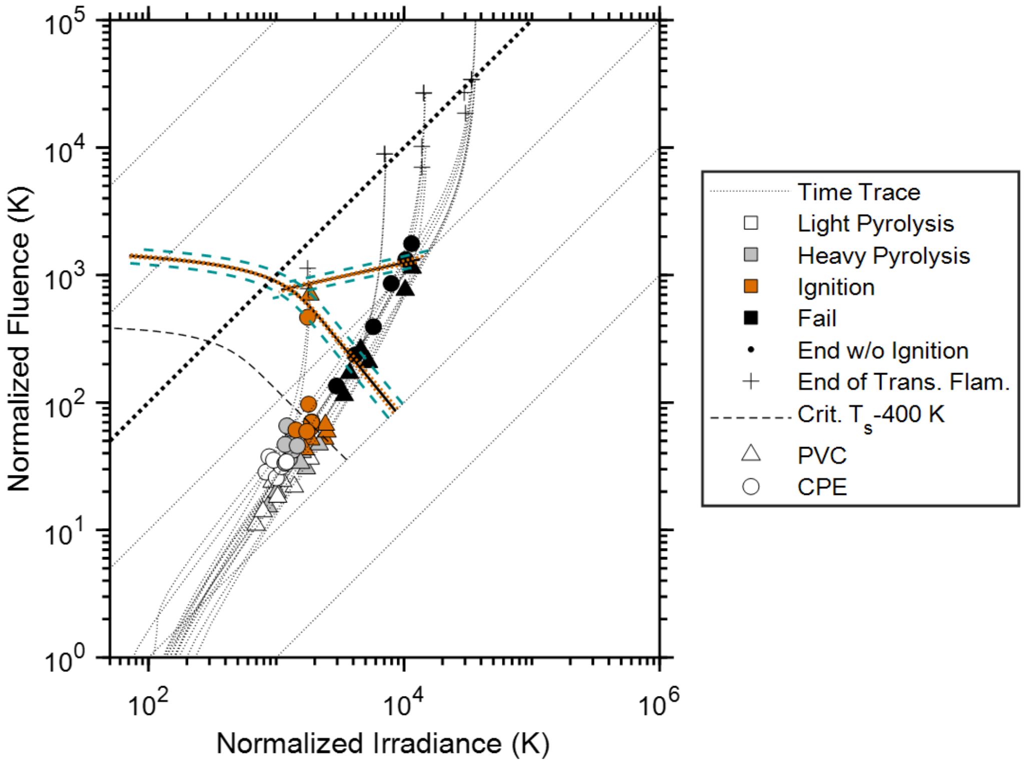


Figure B-8
Chlorinated polyethylene (CPE) and PVC ignition model data

B.1.5.4 Analyzing the Data to Support the Characterization of the Ignition Threshold

The tight grouping (see Figure B-8) in terms of when the cables ignited was promising; however, the lack of data points that span the entire ignition curve limits the application of such a model specific to the cable ignition concern.

The video evidence from the 2018 testing was reviewed. The review focused on the test racks at 3 ft (0.9 m) and 6 ft (1.8 m), as they were the locations with the highest exposure. The video observations are summarized as follows:

- **Test 2-19:** Maximum measured incident energy near cables (1.26 MJ/m^2):
  - There was no observable ignition of cable samples.
- **Test 2-21:** Maximum measured incident energy near cables (Rack 2: 7.8 MJ/m^2; Rack 3: 3.4 MJ/m^2):
  - Rack 2 lower cable coupon appears to display limited ignition at 7 seconds as viewed from the GoPro1 camera file. The file terminates at approximately 7.4 seconds.
  - Rack 3 lower cable coupon may be ignited at 24 seconds as viewed from the NIST shed high-definition (HD) camera. The video resolution makes it difficult to determine what is burning at this time frame, but there are flames in the vicinity of the lower cable samples. None of the SNL video files lasted long enough beyond the end of the test to have a clear (non-smoke obscured) view of the cable samples.

- **Test 2-22:** Maximum measured incident energy near cables (Rack 2: 2.12 MJ/m^2; Rack 3: 0.7 MJ/m^2):
  - Rack 2: SNL interior full video indicates that the lower cable samples may have ignited briefly, but the angle of view and other combustion in the vicinity of the cable samples make for a difficult judgment of the actual cable ignition.
  - Rack 3: GoPro1 provides clear evidence that cables on Rack 3 did not ignite immediately after the HEAF test exposure.
- **Test 2-24:** Maximum measured incident energy near cables (Rack 2: 12.7 MJ/m^2 est.; Rack 3: 4.7 MJ/m^2):
  - There was no observable ignition of cable samples.

B.1.5.5 Assumptions

Field applications consist of electrified cables. Electrical damage results from the loss of insulation integrity, causing leakage currents that have the potential to cascade into larger fault currents, resulting in localized overheating, and act as an ignition pilot source. The number of electrified cables within a raceway increases the population of pilot ignition sources to promote ignition of volatized materials to support combustion.

B.1.5.6 Basis

There is evidence that ignition can occur at lower thresholds than identified for damage, and this is likely due to sufficiently high heat fluxes to cause ignition but insufficient incident energy (soak time) to thermally penetrate the cable polymer and raise the material's temperature to sustain a combustion reaction. For these cases, the exposure region is likely in the transient ignition regime presented by Martin (see Figure B-7). While this could present a sufficient hazard with the right configuration, material type, and location with respect to the HEAF hazard, the current state of knowledge cannot accurately predict ignition.

Prediction of cable ignition criteria, even for non-HEAF fire hazards, has been limited. The approach used for non-HEAF events has been to assume ignition occurs concurrently with damage. For many tests documented in CAROLFIRE [12] that exposed electrical cables to various radiant heat fluxes, cable ignition occurred at or shortly after electrical failure at least in part due to sparking from the failing energized cables.

B.1.5.7 Evaluating Methods to Streamline the Process

No methods to streamline the process were identified.

B.1.5.8 Ensuring the Team Members Agree to the Proposal and Thoroughly Discussing Any Differing View to Achieve Team Consensus (If Possible)

The team met several times to discuss the proposal and attempt to identify improvements or alternatives. After several revisions and refinements to the initial proposal, the team agreed with the proposed approach.

B.1.6 Summary and Conclusions

The team has reviewed a substantial amount of data and information in developing this proposal. The team concluded that a simple total incident energy approach or application of existing models cannot address the dynamics related to the ignition of electrical cables from a HEAF exposure. From review of the test data, models, and understanding of the OE, the team concludes that sustained ignition of the electrical cables would require a sustained thermal heat source, such as a cabinet fire or ensuing fire. A direct HEAF-only exposure, while severe, is short in duration and unlikely to elevate the bulk cable temperature to a state that would support sustained pyrolysis and combustion. As such, the team recommends that the WG develop PRA guidance to cover the ignition and spread of electrical cables.

B.1.7 Recommendations

The team recommends that the WG evaluate the integration of the ZOI from a HEAF with the ZOI resulting from an ensuing fire. Targets may not be damaged by the HEAF exposure, but could potentially be damaged by a fire emanating from the electrical enclosure as a result of the HEAF. This effort should focus on ensuring consistency between the thermal fire ZOI and any guidance for ensuing enclosure fires from the HEAF. Existing HEAF fire propagation guidance along with the heat release rate (HRR) guidance in NUREG-2178 Vol. 1/ EPRI 3002005578 [30], should be reviewed with respect to the measurements made with the calorimetry hood used in some of the Phase 1 OECD HEAF tests [7].

B.2 Proposal from Team 2

B.2.1 Introduction

This proposal develops a proposed set of fragilities for electrical cables exposed to HEAF events of various durations. This work is being done under the memorandum of understanding (MOU) between EPRI and the U.S. NRC.

The ZOI for a scenario is the distance from the ignition source below which target damage can occur. For an ordinary fire scenario, the ZOI is a maximum distance determined by fire growth. Some targets within the ZOI may not see damage if the fire is mitigated (e.g., suppressed). For a HEAF event, where the event duration is defined as part of the scenario, the ZOI is an encompassing region of damage. This is depicted in Figure B-9 which depicts a switchgear that has been breached by a HEAF with the resulting exposure as a function of distance from the enclosure. The fragility is the condition required to damage the cable, and the ZOI is the distance where the fragility is no longer exceeded. The first step in assessing the ZOI, therefore, is to understand the target fragility.

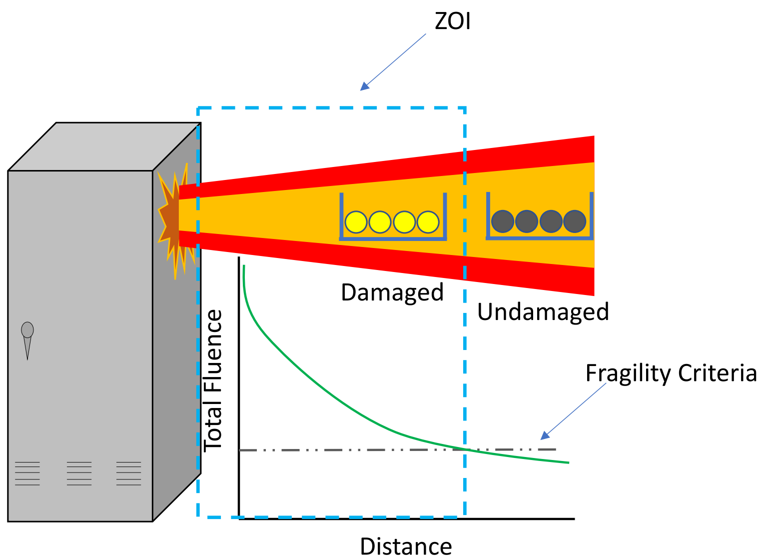


Figure B-9
Depiction of fragility and ZOI for a HEAF in a switchgear

Fragilities for electrical cables exposed to fire are well established [1, 12, 15]. The maximum possible heat flux from a fire of ordinary combustibles is approximately 150 kW/m^2. This would represent a cold target immersed within the continuous flame volume of a large fire. Exposures from HEAF events can exceed that by an order of magnitude or more; however, the duration of HEAF events (10 seconds or less) is significantly less than the potential duration of most fires considered in a fire PRA (minutes to hours). The very different magnitudes of exposure and duration could result in differing modes of cable response than those seen in a fire. This requires an effort to develop fragility criteria specific to HEAF scenarios.

The remainder of this report examines existing HEAF operating experience and HEAF test data for insights on the fragility of TP and TS jacketed electrical cables to a HEAF scenario. It proposes and develops a set of a fragility criteria, including the sustained ignition threshold determination which is presented in Section B.2.4.

B.2.2 Review of Operating Experience and Prior Testing

This section reviews fragility insights from operational experience (OE) (Section B.2.2.1), Sandia National Laboratories (SNL) fragility testing (Section B.2.2.2) the 2014-2016 OECD tests (Section B.2.2.3), the JNRA tests (Section B.2.2.4), and the 2018 medium voltage switchgear tests (Section B.2.2.5).

B.2.2.1 Operating Experience with HEAF Events

OE includes 21 HEAF events [31]. In general, if an event involved cable damage, the damaged cables were also exposed to the post-HEAF ensuing fire. In these cases, based on available information, it is not readily possible to assess what fraction of the cable damage resulted from the HEAF versus the exposure from the ensuing fire. In three non-segregated bus duct (NSBD) events, a failure of one NSBD resulted in the failure of a second NSBD that was running nearby (in two cases from the same unit auxiliary transformer (UAT)). No cables were involved, but the NSBD targets were an adjacent nearby (few feet) NSBD. The OE is divided into four main categories:

- Table B-3: Medium voltage switchgear (MV SWGR)
- Table B-4: Low voltage switchgear (LV SWGR)
- Table B-5: Non-segregated bus duct (NSBD)Table B-6: Isolated phase bus duct (IPBD)

Table B-3
HEAF OE involving medium voltage switchgear

FEDB ID	HEAF Event Description
106	Post-event fire with damage to cables likely due to the fire.
732	Evidence of breach on top of switchgear cabinet.
947	Post event fire. Integrated control system (ICS) cable failure 46 minutes after the HEAF event indicating failure due to ensuing fire, not HEAF.
74	Post-event fire with damage to feeder cables primarily due to fire; other cables (reactor coolant pump and condensate pump) in the vicinity that had heat damage on conduits but passed electrical testing.
112	Fire limited to switchgear.
50910	Post-event fire. Damage to the 4kV bus was limited to the incoming line compartment along with the feeder cables. Heat but no electrical failure of cables above and 3 to 5 feet (0.9 to 1.5 m) away.

Table B-4
HEAF OPEX involving low voltage switchgear

FEDB ID	HEAF Event Description
434	Post-event fire with heat damage to overhead cable trays.
50935	Plant repaired cables “damaged” by the fire, including cables in cable trays above the load center; extent of cable damage is unclear, but extensive soot damage noted.

Table B-5
HEAF OPEX involving non-segregated bus duct

FEDB ID	HEAF Event Description
100	A 4 kV NSBD (fed from the station auxiliary transformer (SAT)) located immediately above the faulted 12 kV NSBD (fed from the UAT) was damaged by the fault and a large amount of slag was present under the bus duct.
575	The event resulted in an adjacent NSBD of a different system voltage to also fail (from same UAT). An arc fault ignited transient combustibles in the vicinity of the fault.
51291	Resulted in adjacent NSBD of a different system voltage (but from the same UAT) to also fail (located directly below).
678	Cables located in a cable tray adjacent to the bus experienced insulation failure as a result of this event; however, per the LER, it appears to be the result of the ensuing fire.
162	Molten debris was on top of switchgear below the faulted NSBD.
922	Post-event fire involving transient materials below the duct that were ignited by aluminum slag. From the LER, no other equipment was damaged during this event.
50909	Damage was limited to the faulted section of the bus duct.
51764	In this outdoor event, there was no collateral damage to the bus duct below or to other equipment.
10584	The NSBD was outdoors, with no observed damage beyond the bus. Cables routed in a ladder cable tray immediately adjacent to the faulted NSBD were not damaged.
50926	The event identifies damage to the bus, cables, and switchgear. However, the extent of the damage is not clear.

Table B-6
HEAF OPEX involving iso-phase bus duct

FEDB ID	HEAF Event Description
929	Post-event fires of an oil fire at the "B" main power transformer, a hydrogen fire underneath the main generator, and a third small oil fire in the generator housing damaged the following: • Main generator: neutral bushing and current transformers, external housing, and the exciter end seal oil piping, generator moisture detection piping • "B" MPT: bushings and connections to the IPBD • "A" IPBD • Neutral grounding transformer • Radio frequency monitor • Miscellaneous cabling and piping in the vicinity (no further information)
51199	Post-event fire damaged cable insulation and the oil collection pan fire was initiated.

The review of operating events in Tables B-3 through B-6 indicates that the footprint of cable damage is primarily determined by the post-HEAF fire for switchgear. Damage to cables outside of the fire impacted region is not evident in OE.

B.2.2.2 SNL Fragility Tests

SNL performed a series of tests using its solar furnace test facility to evaluate the fragility of electrical cables [8]. The solar furnace test facility concentrates sunlight into an approximately 5 cm disc and allows for heat fluxes in an approximate range from 50 kW/m^2 to 6 MW/m^2. Testing involved a range of fluxes, fluences, and time-dependent flux profiles with both thermoplastic (TP) and thermoset (TS) cables tested. The original goal of the testing program was to assess the conditions for sustained ignition of cables. Test results showed that ignition was not sustained during the testing. Section B.2.4 further discusses cable ignition threshold determination. As a result, testing shifted focus to examining the post-test condition of TP and TS cables. There are some potential concerns with the ability to directly apply the results of SNL testing to determining cable fragility.

Figure B-10 provides an overview of the SNL cable fragility test approach.

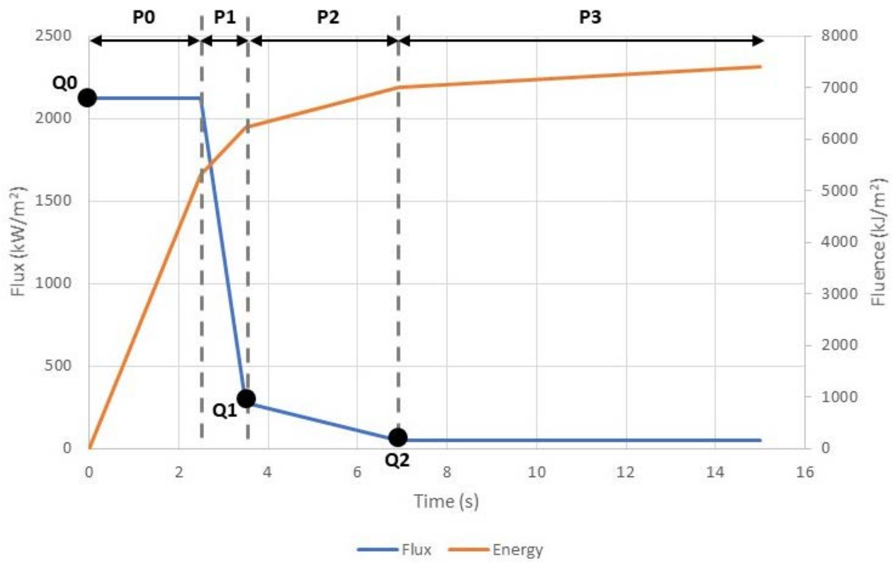


Figure B-10
Simulated HEAF primary and feedback flux profile

Figure B-10 presents a typical flux profile used at the solar furnace. Exposure consisted of one, two, or three parts, with the three-part exposure shown in Figure B-10. All tests began with a constant flux exposure labeled as Q0 in Figure B-10. Some initial tests went from Q0 to zero flux as quickly as the solar furnace can change the flux. Some tests went from Q0 to zero flux over a longer duration (P1). P1 was selected to emulate the decay rate seen in the 2018 MV SWGR tests. This profile is referred to as the "simple" profile. Some tests went from Q0 to an intermediate Q1 value to a constant Q2 value of 50 kW/m^2. The value of Q1 and the times for P1 and P2 were selected to approximate the decay seen in the 2018 MV switchgear tests. The 50 kW/m^2 flux represents the combination of some heating from the still hot enclosure plus heat feedback from a postulated sustained flame on a cable tray. This profile presented in Figure B-10 is called the "dynamic" profile.

B.2.2.2.1 Solar Furnace Test Limitations

The exposure area is very small, approximately 5 cm (2 in). In testing, the largest exposures are seen in cables that experience an arc jet resulting from the breaching of the enclosure where the arc occurs. The arc jet is tens of centimeters in diameter. The small length of cable exposed in the SNL tests allows for a larger fraction of heat removal via conduction along the copper wires in the cables than would occur if a prototypical length of cable were heated.

The solar furnace exposure is unidirectional. In a HEAF event, the cables that see the highest fluxes are those that see any resulting breach in the enclosure. Once breached, the pressure of the arc results in a jet out of the breached enclosure panel. Both infrared video and FDS modeling show that this jet is thousands of Kelvin (K) in temperature with velocities of tens of meters per second. The jet is optically thick and contains liquid and solid particles consisting of metal and oxidized metal from the enclosure and the electrode. The solar furnace does not include the convective heat transfer or particulates. An air drop cable enveloped by the jet would be exposed around its entire circumference. Cables in a ladder cable tray enveloped by the jet would be exposed anywhere from one-half their circumference to their entire circumference, depending on the cable tray fill.

B.2.2.2.2 Solar Furnace Test Assessment

Due to the limitations noted above in how well test conditions replicate a real-world event, it is unclear whether the SNL exposures and resulting damage can be directly applied in terms of a fragility model. Instead, the data were examined in terms of general insights on cable fragility. Figure B-11 plots all the SNL test results with heat fluxes of 1 MW/m^2 and above. Each test is plotted as a point on a graph of Q0 vs. exposure (time integration of the flux):

- The symbol fill indicates the cable type where:
  - Solid points are TP cables
  - Hollow points are TS cables
- The color indicates the amount of damage observed post-test where:
  - Red is damage to the jacket but no visible insulation
  - Black is damage to visible insulation but no visible conductors
  - Blue is damage to visible conductors

Electrical failure of a cable would be expected somewhere between the time when insulation is exposed and the time when a conductor is exposed; that is, at some point after the jacket is breached, there will be sufficient damage to wire insulation that the insulation no longer provides adequate electrical resistance. It is noted that points do not indicate the heat flux profile. As discussed after Figure B-10, some tests involved constant fluxes and other tests involved a step profile of Q0 followed by one or two ramps with a plateau at the end of each ramp.

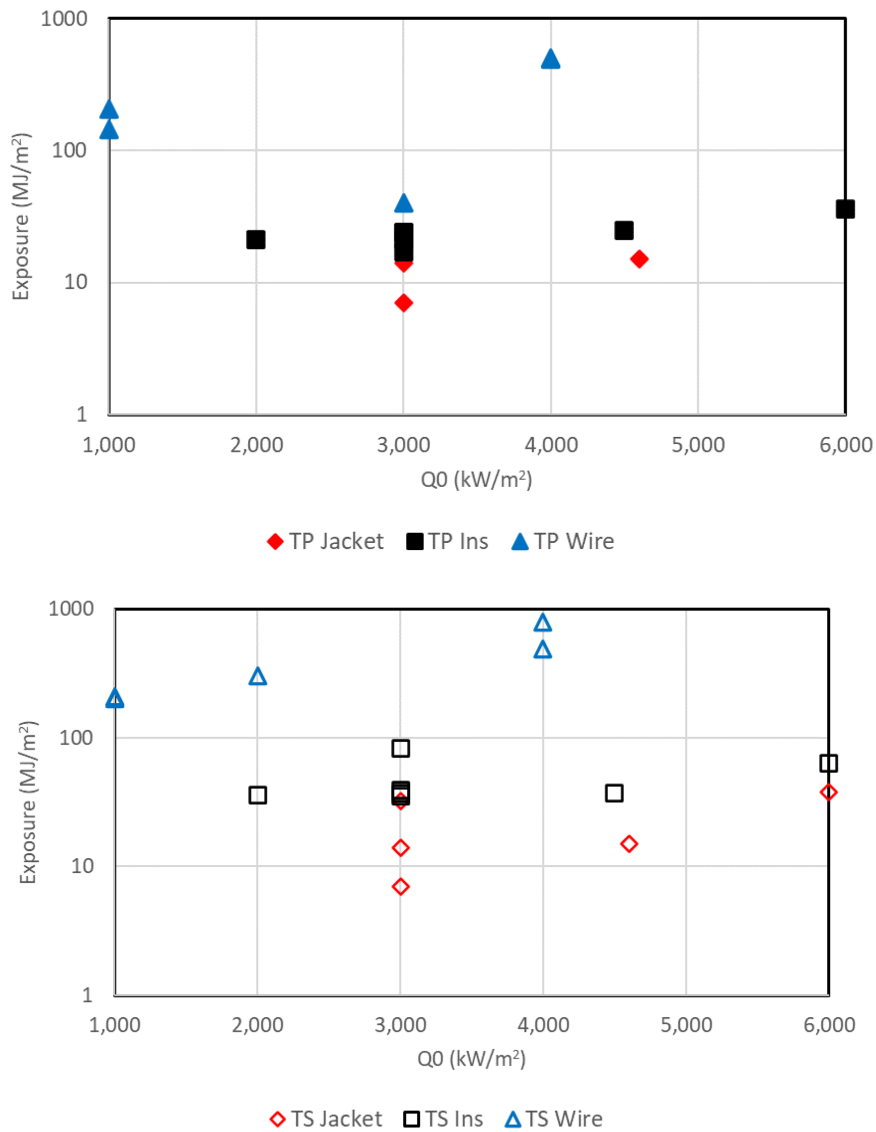


Figure B-11
Results of SNL solar furnace testing for TP (top) and TS (bottom) cables

The following observations are made:

- There is no clear indication of dependence on Q0. Most tests resulted in only jacket or insulation damage. The points for those tests do not show any trend with Q0. The plot suggests a trend in the exposed wire data; however, there is considerable uncertainty as to when the wire was exposed. All that is known is that, at the end of the test, it was exposed, and actual exposure of the wire would have occurred at an earlier time. Given the larger gap in exposure between insulation and wire exposure tests, the apparent trend of increasing fluence with Q0 may entirely be an artifact of the test matrix (i.e., if somewhat lower exposures had been used for the tests where the exposed wire was seen, then wire damage would have been seen but without an apparent trend).

- There is a trend for exposure. There is a clear progression in exposure seen as damage levels go from jacket to insulation to wire. This suggests the use of exposure as the sole metric for cable fragility during the HEAF event.
- For TP cables, the ranges of exposure for the various levels of damage are as follows:
  - Jacket damage only: 8 to 52 MJ/m^2 for all data and 15 to 16 MJ/m^2 with outliers removed.
  - Insulation exposure only: 18 to 89 MJ/m^2 for all data and 21 to 25 MJ/m^2 with outliers removed.
  - Exposed wire: 41 to 503 MJ/m^2 for all data and 145 to 493 MJ/m^2 with outliers removed.
- For TS cables the range of exposure for the various levels of damage are as follows:
  - Jacket damage only: 8 to 39 MJ/m^2 for all data and 15 to 33 MJ/m^2 with outliers removed.
  - Insulation exposure only: 33 to 85 MJ/m^2 for all data and 36 to 82 MJ/m^2 with outliers removed.
  - Exposed wire: 202 to 791 MJ/m^2 for all data and 208 to 488 MJ/m^2 with outliers removed.
- In general, there was a significant increase in the exposure value necessary to expose the conductor compared to the exposure value to expose the cable insulation. In part, this was due to an effort to reach this state in some of the tests. This makes it difficult to draw any conclusions on the relative resilience of TP and TS cables using the exposed conductor data. All that is known is that, at the end of the test, the conductor was exposed. For TP, the highest exposure with exposed insulation is 26 MJ/m^2 and the lowest with exposed wire is 42 MJ/m^2. For TS, the values are 85 MJ/m^2 and 202 MJ/m^2. Conclusions on the relative resiliency cannot be made since it is possible that the actual point of exposed wire for TS was at 120 MJ/m^2. Since the exposed conductor data do not support an assessment of the relative resiliency of cable types, this leaves the values for exposed insulation. The mean exposure without outliers is 24 MJ/m^2 for TP and 48 MJ/m^2 for TS, a ratio of 2. From NUREG/CR-6850 Appendix H [1], the threshold fluxes for damage, for 19-minute exposure times, are 6 kW/m^2 for TP and 11 kW/m^2 for TS. This is a ratio of 1.8 and is similar to the ratio from the SNL data. This suggests that for a HEAF, TS cables have twice the resiliency (e.g., can withstand twice the exposure) of TP cables.
- In tests that measured electrical functionality was measured, no failures occurred unless conductors were exposed. This was approximately one-third of the tests. While it is recognized that the short length of cable exposed may limit the possibility for electrical failure, these results suggest that the fragility threshold lies in or above the upper region of exposure values, resulting in exposed insulation but no exposed conductors.

B.2.2.3 OECD Tests

The OECD tests [7] were a series of 26 HEAF tests taking place from 2014 to 2016 that included 26 tests of 10 types of switchgear and a bus duct. Most tests of switchgear placed a cable tray 0.3 m above the top of the switchgear. Tests were performed under an oxygen consumption calorimeter in order to measure the heat release rate of any ensuing fire. Inconel plate thermometers and ASTM copper slugs were used to measure the heat flux. Table B-7 contains observations on cable fragility made from the tests:

Table B-7
OECD Test Data Summary

Test No.	Voltage	Current	Equipment	Duration	Description (Energy/Damage)
1	480 V	34 kA	Class “M” switchgear	2 s	Maximum fluence of 32 kJ/m^2 front (0.9 m) and 35 kJ/m^2 top (0.3 m). Minimal impact to cable tray.
2	480 V	34 kA	Class “M” switchgear	4 s	Maximum fluence of 76 kJ/m^2 front (0.9 m) and 26 kJ/m^2 top (0.3 m). No impact to cable tray.
3	480 V	34 kA	Class “M” switchgear	8 s	Maximum fluence of 130 kJ/m^2 front (0.9 m) and 97 kJ/m^2 top (0.3 m). Post-test fire of ~100 kW for 15 minutes. Some damage to cables in tray but no sustained tray ignition.
4 – 7	480 V	50 kA	Westinghouse DS Switchgear	-	Arc not sustained.
8	7.2 kV	23 kA	Mitsubishi 1 and 3	2.2 s	Maximum fluence of 1.0 MJ/m^2 rear (0.9 m) and 143 kJ/m^2 top (0.3 m). 50 kW sustained fire. No impact to cable tray beyond soot deposition.
9	7.2 kV	23 kA	Mitsubishi 1 and 3	2.8 s	Maximum fluence of 1.8 MJ/m^2 rear (0.9 m) and 210 kJ/m^2 top (0.3 m). 50 kW sustained fire. Some damage to cable tray from ensuing fire but no sustained ignition.
10	7.2 kV	24 kA	Mitsubishi 1 and 3	2.1 s	Maximum fluence of 860 kJ/m^2 front (0.9 m) and 0 kJ/m^2 top (0.3 m). 50 kW sustained fire. No impact to cable tray beyond soot deposition.
11	7.2 kV	25 kA	Mitsubishi 1 and 3	2.1 s	Maximum fluence of 46 kJ/m^2 rear (0.9 m) and 88 kJ/m^2 top (0.3 m). No sustained fire. Significant cable damage directly over breach point in enclosure top; however, tray was improperly secured and was dislodged during test, which may have limited damage.

Table B-7 (continued)
OECD Test Data Summary

Test No.	Voltage	Current	Equipment	Duration	Description (Energy/Damage)
12	7.2 kV	24 kA	IRSN cabinet	2.1 s	Maximum fluence of 3.2 MJ/m^2 front (0.9 m) and 260 kJ/m^2 top (0.3 m); however, multiple tray gauges failed. No sustained ensuing fire. Minor cable damage (jacket) and deeper melting at ladders. No sustained cable tray fire.
13	7.2 kV	24 kA	IRSN cabinet	2.6 s	Maximum fluence of 3.7 MJ/m^2 front (0.9 m) and 1.0 MJ/m^2 top (0.3 m); however, multiple tray gauges failed. Ensuing fire self-extinguished in 5 minutes. Minor cable damage (jacket) and deeper melting at ladders. No sustained cable tray fire.
14	7.2 kV	24 kA	IRSN cabinet	2.6 s	Maximum fluence of 2.5 MJ/m^2 front (0.9 m) and 850 kJ/m^2 top (0.3 m); however, multiple tray gauges failed. Ensuing fire self-extinguished in 5 minutes. Minor cable damage (jacket) and deeper melting at ladders. No sustained cable tray fire.
15	10 kV	15 kA	GRS cabinet	3.2 s	Maximum fluence of 260 MJ/m^2 front (0.9 m), 300 kJ/m^2 side (0.9 m) and 410 kJ/m^2 top (0.3 m). Sustained 1 MW fire, including cable tray, which was fully consumed.
16	10 kV	15 kA	GRS cabinet	3.2 s	Maximum fluence of 510 MJ/m^2 front (0.9 m), 380 kJ/m^2 side (0.9 m) and 970 kJ/m^2 top (0.3 m). Sustained 400 kW fire, including cable tray, which was partially consumed.
17	6.9 kV	33 kA	Korea cabinet	3.1 s	Maximum fluence of 350 MJ/m^2 front (0.9 m), 110 kJ/m^2 side (0.9 m) and 130 kJ/m^2 top (0.3 m). Sustained 100 kW fire. Trays not directly over cabinet and no damage seen beyond some deposition seen.
18	6.9 kV	32 kA	Korea cabinet	3.1 s	Maximum fluence of 320 MJ/m^2 front (0.9 m) with failed gauges, 110 kJ/m^2 side (0.9 m) and 220 kJ/m^2 top (0.3 m). Sustained 200 kW fire decaying to 50 kW at 5 minutes. Light charring of trays with no sustained tray fire.

Table B-7 (continued)
OECD Test Data Summary

Test No.	Voltage	Current	Equipment	Duration	Description (Energy/Damage)
19	7.2 kV	24 kA	Mitsubishi 2 and 4	2.6 s	Maximum fluence of 830 kJ/m^2 rear (multiple failures) 220 kJ/m^2 front (0.9 m), 470 kJ/m^2 side (0.9 m) and 250 kJ/m^2 top (0.3 m). Slow decay from 250 kW to 50 kW over 4 minutes. Tray mounts damaged causing shifting of trays away from cabinet. Some charring of cable in one tray.
20	7.2 kV	24 kA	Mitsubishi 2 and 4	2.6 s	Maximum fluence of 700 kJ/m^2 rear, 410 kJ/m^2 front (0.9 m), 190 kJ/m^2 side (0.9 m) and 80 kJ/m^2 top (0.3 m). Slow decay from 250 kW to 50 kW over 6 minutes. Tray mounts damaged causing shifting of trays away from cabinet. No cable tray impacts.
21	7.2 kV	28 kA	Mitsubishi 2 and 4	3.7 s	Maximum fluence of 27 kJ/m^2 rear, 48 kJ/m^2 front (0.9 m), and 160 kJ/m^2 top (0.3 m). Slow decay from 250 kW to 50 kW over 6 minutes. Minor charring of cable jackets. No tray fires.
22	7.2 kV	25 kA	Mitsubishi 2 and 4	4.1 s	Maximum fluence of 640 kJ/m^2 front (0.9 m) and 120 kJ/m^2 top (0.3 m). Ensuing fire with no HRR data. Charring and cracking of cable jackets but no tray fire.
23	480 V	35 kA	Finland cabinet IP-20 fused-disconnect panel	7.1 s	Maximum fluence of 810 kJ/m^2 front (0.9 m), of 680 kJ/m^2 side (0.9 m) with failed gauges, of 1.5 MJ/m^2 front (0.9 m), and >1.3 MJ/m^2 top (0.3 m). 250 kW ensuing fire. Fire spread to cable trays with exposed conductors across width of tray.
24	480 V	40 kA	Westinghouse Type DS	-	Arc not sustained.
25	480 V	40 kA	Westinghouse Type DS	3.0 s	Maximum fluence of 220 kJ/m^2 top (0.3 m) with minimal exposure elsewhere. No ensuing fire. Minimal tray impact (Note: Bus bar modification with bolts – target 10 s).
26	4.2 kV	27 kA	Non-segregated bus duct	4.3 s	Maximum fluence of 980 kJ/m^2 rear. All other locations failed. No cable tray.

The OECD tests, during which trays remained in place during the test, show that damage to trays located above enclosures is primarily due to the ensuing fire. Significant cable damage was only seen when there was also a significant, sustained, ensuing fire.

B.2.2.4 JNRA Tests

The JNRA tests [9-10] are not true prototypical tests. While the tests used prototypical equipment, a portion of each test item's sheet metal enclosure was replaced with expanded metal mesh. This was done to study basic arc electrical properties and thermal effects (e.g., using infrared cameras to study the arc position). The solid enclosure panels replaced with mesh panels significantly impacted the thermal environment of the event, and the measured exposures cannot be considered as prototypical exposures. However, since TP cable coupons were present at or near locations where exposure was measured, the exposures can be compared against cable damage for assessing fragility.

The report uses a six-part scale for cable damage as shown in Table B-8 [9-10]:

Table B-8
Target damage descriptions

Identifier	Damage Description	Types of Damage
1	None	No damage; cable and plastic the same as installed and can be reused. Usually low temperatures. May look slightly brown from minor copper minor deposition. No smoke soot. May be reused.
2	Sooted	No damage to cable or plastic. Soot from smoke from other combustibles or copper covers the cable. The cable jacket color is dull and the letters on the cable are hard to see.
3	Minor damage	Light charring or discoloration of the target and cables, minor charring.
4	Medium damage	Charring of cables; plastic bent slightly.
5	Heavy damage	Deep charring of cable. Cables may be missing; plastic samples may be missing. This usually occurs for targets within 50 to 100 cm of arc. Plastic is bent over metal target mount. Orange steel after cool down indicates high heat.
6	Destroyed	Cable or plastic samples are no longer attached. This usually occurs for targets within 40 cm of the arcs, on long duration arcs. Bright orange steel indicates very high heat.

No information defines deep (e.g., jacket plus insulation, only jacket but no visible insulation). Photographs of cables in the test report are small thumbnail photos at low resolution, making it difficult to assess how badly damaged the cables are. The enclosures tested included low voltage distribution panels (DP tests) and medium voltage switchgear (S tests). The following is an assessment of the data presented in the report for cables outside the enclosures:

- Low voltage (480 or 600 V, 46 kiloampere (kA)) distribution panel:
  - DP 7, DP 7A: Max exposure of 150 kJ/m^2. Little damage seen on cables.
  - DP 8: DAQ system failed, no flux data. Test report states one coupon with 5 heavy damage and six with 4 medium damage. However, none of the photos appear to show exposed insulation.

- DP 9: Repeat of DP 8. Max exposure of 5.5 MJ/m^2. Observations as follows:
  - Test report states three coupons with 5 heavy damage. However, in the photos, it is difficult to discern whether any insulation was exposed:
    - Bundle E6 (peak location) looks like insulation may or may not be exposed through the jacket.
    - Bundle E3 failed a post-test electrical test in one cable with conductor-conductor shorting. It was exposed to only 143 kJ/m^2 or an average flux of 51 kW/m^2. This is less than the total exposure required for TP cable in NUREG/CR-6850 Volume 2 and is a very unexpected result. None of the other 23 cables, almost all at much higher exposures, failed. This result appears to be anomalous and will not be credited.

- Medium voltage (7.1 kV, 26 kA) switchgear:
  - S 7: Maximum exposure of 2.6 MJ/m^2. Test report states one coupon with 5 heavy damage and five with 4 medium damage. However, none of the photos appear to show exposed insulation.
  - S 8: Maximum exposure of 1.7 MJ/m^2. Test report states one coupon with 5 heavy damage and seven with 4 medium damage. However, none of the photos appear to show exposed insulation.
  - S 9: Maximum exposure of 2.6 MJ/m^2. Test report states one coupon with 5 heavy damage and seven with 4 medium damage. However, none of the photos appear to show exposed insulation.
  - S 9: Maximum exposure of 210 kJ/m^2. No significant cable damage.

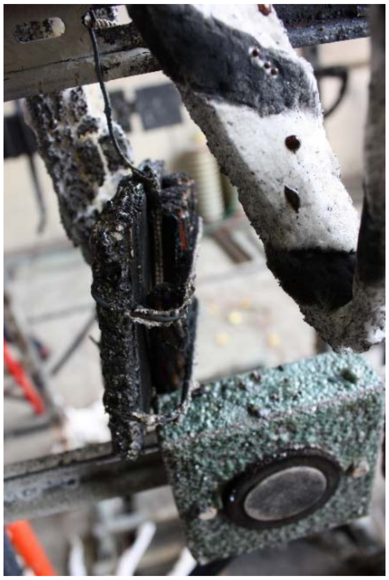
The JNRA tests suggest that there is likely little damage done to the cable samples beyond damage to the cable jackets for the tested fluences. However, due to the poor resolution of the damage photos of the cable targets and lack of clarity with respect that the “target damage descriptions” (Table B-8) give beyond the jacket damage state, conclusions based on the JNRA tests are limited beyond general observations. No JNRA test results showed ignition of cables outside of the test enclosure.

B.2.2.5 2018 Medium Voltage Switchgear Tests

The 2018 medium voltage switchgear (MV SWGR) tests [4] consisted of four tests with each test having five racks of instrumentation and cable coupons (TP). No tests resulted in a post-HEAF sustained fire involving the cable coupons, discussed further in Section B.2.4. In all but Test 2-24, post-test photographs of the cable show only charring of the cable jacket. In Test 2-24, the cables in the lower portion of Rack 2 (0.9 m from the enclosure face) saw significant jacket damage and exposure of cable insulation. Figure B-12 shows photographs of cables from Rack 2 and Rack 3 (1.5 m from the enclosure face).

Rack 2

Lower Left



Lower Right

Rack 3

Top Left

Top Right

Figure B-12
Test 2-24 cable photographs

The photographs for Rack 3 show only charring of the jacket. Rack 3 saw exposures up to 4.7 MJ/m^2. This is close to the maximum fluence seen in the JNRA tests. The lower right photograph for Rack 2 shows that insulation is visible over much of the exposed portion of the circumference in the middle portion of four of the six cables in the coupon. Multiple exposed wires show signs of charring and melting of their insulation. One consideration in examining these photos is that the cables are only 10 cm in length with exposed copper wires at the ends. The jet from the enclosure breach would have enveloped the cable coupon allowing for heat to be conducted from the cable tips into the cables over the 4 s duration of the arc. Therefore, the accrued cable damage is a combination of the external heating of the jacket and insulation by the jet, and the internal heating due to heat conducted from the exposed ends of the conductors. The lower right photo clearly shows exposed conductors at the ends of the cable. This level of damage is likely exacerbated by conduction into the ends through the copper. At the center of the coupon there is likely still some impact from axial conduction. Without an electrical test, it is unknown whether the cables are still functional. For the purpose of defining a fragility criterion, it is assumed the cable coupon was at the threshold of failure for Test 2-24 at 0.9 m (3 ft) from the cabinet.

During Test 2-24, all the instrumentation on Rack 2 and some of the instrumentation on Rack 3 failed. There is no direct measurement of the exposure at Rack 2. In all the 2018 MV switchgear tests, the enclosure was breached at similar times. Test 2-21 was also a 4 s arc like Test 2-24 but at a lower power (lower fault current). In Test 2-21, the minimum, average, and maximum T-CAP exposures at Rack 2 were 5.9, 6.7, and 7.6 MJ/m^2. At Rack 3 the values are 2.1, 2.6, and 3.2 MJ/m^2. The Rack 2 to Rack 3 ratios are respectively 2.7, 2.6, and 2.4, respectively. In the FDS modeling, the ratios for Test 2-21 are 3.5, 2.7, and 2.6. These are similar to the values seen in the test. For Test 2-24, the ratios derived from FDS are 3.5, 2.9, and 2.9. These are slightly higher overall than for Test 2-21. This suggests a reasonable estimate of the Rack 2 exposure for Test 2-24 is three times the Rack 3 exposure, or 14.1 MJ/m^2. As noted above, the bare ends allow the copper conductors to conduct some heat inside the cables in the coupon, making the effective exposure worse than the external exposure to just the jacket. To account for this and the fact that the actual cable functionality was unknown, the estimated Rack 2 effective fluence is rounded up to 15 MJ/m^2. This is the threshold value (basis) to be established for failure of a TP cable.

The cable coupons in the tests were TP cables. Using the SNL results that the average exposure where only insulation damage for TS cables was seen, was twice the value for TP cables would make the threshold value (basis) for TS cables at 30 MJ/m^2. Sustained cable jacket ignition was not observed at these values in OE or testing. Section B.2.4 provides further exploration of the determination of fluence necessary for sustained ignition of TP and TS cable jackets.

B.2.3 Conclusions and Recommendations for Cable Fragility During a HEAF

OE indicates that the footprint of cable damage is primarily determined by the post-HEAF fire for switchgear. Damage to cables outside of the fire impacted region is not evident in OE.

The SNL results suggest that the applicable metric for HEAF cable fragility is the exposure. Both TP and TS cables show the rapid development of insulative char layers that must be eroded to expose the insulation. SNL testing indicates that TS cables have a factor of 2 higher threshold for damage compared to TP cables. This is similar to the relative thresholds for traditional thermal fire exposures to cable.

The JNRA tests appear to show limited damage to cables outside the enclosure beyond charring of the cable jackets. In the 3-second test, DP 9 saw a maximum fluence of 5.5 MJ/m^2 at 0.3 m from the cabinet. This is a factor of 3 less than the 4 s MV switchgear Test 2-24 extrapolated fluence at 0.9 m.

Only one of the 2018 MV switchgear tests, Test 2-24, had significant damage to cable coupons. Since heat flux gauges near the damaged coupons were also damaged in the test, a direct heat flux measurement is not available. Data from Test 2-21 and from FDS simulations of Test 2-21 and Test 2-24 were used to extrapolate the surviving Rack 3 data in Test 2-24 to Rack 2. The extrapolated exposure near the cable coupons results in a damage threshold for TP cables of

15 MJ/m^2. Using the results of the SNL data, the threshold for TS cables is 30 MJ/m^2. This plus the observations from OE suggest the following for estimating the fragility of cables due to a HEAF event:

- Cables above an electrical enclosure—Many HEAF events in OE are accompanied by an ensuing fire involving combustible material inside the enclosure with the HEAF. HEAF events have the highest non-suppression probability of all ignition sources [32]. Given the growth time of electrical cabinet fires [33], if a post-HEAF ensuing electrical enclosure fire is postulated for a scenario, it is likely that the fire will damage cables directly over the top of the enclosure and within the ZOI.
- Cables below bus ducts—OE shows that the shower of molten metal from bus ducts and their electrodes can ignite fires and cause damage to plastic components. It has not been shown to penetrate a second metal barrier. OE also contains examples of cables ignited by debris from hot work.
- Sustained ignition—Neither OE nor testing has shown evidence that HEAF results in sustained ignition of cables outside of the enclosure unless they are also intimate with the post-HEAF ensuing cabinet fire. Sustained ignition is not postulated from the HEAF jet outside of the enclosure; Section B.2.4 provides further basis.
- Exposed cables to the side of an enclosure—OE and testing show that, when a HEAF event breaches the enclosure, it tends to do so in a preferential direction. Exposed cables in the direction of the breach may be exposed to the jet of hot gasses and metal droplets. Cables that do not see the breach do not see significant exposures. Fragility should only be applied to cables located in the jet from the enclosure breach. This paper makes no determination on direction of the arcing jet upon cabinet breach and will need to be considered during the determination of HEAF ZOIs.
- Based upon the review of OE, various small- and large-scale test series, and insights from modeling, the fragility threshold for cables exposed to a HEAF are as follows:
  - Damage:
    - 15 MJ/m^2 for TP cables
    - 30 MJ/m^2 for TS cables
  - Sustained ignition:
    - Not postulated for cables outside of the enclosure, see Section B.2.4
    - Plausible for post-HEAF ensuing enclosure fire

B.2.4 Supplementary Information Related to Evaluation of Sustained Ignition

B.2.4.1 Introduction

This section addresses the issue of sustained ignition of electrical cables exposed to HEAF events of various durations. This assessment identifies exposure conditions in which, immediately after the HEAF, a sustained fire that can grow and spread over cable trays. This is a supplement to the 15 MJ/m^2 damage criterion for thermoplastic (TP) cables and 30 MJ/m^2 for thermoplastic (TS) cables. It should be considered analogous to the relationship between the threshold fire exposures for cable damage in Appendix H of NUREG/CR-6850 Vol. 2 [1] and the threshold fire exposure for bulk cable tray ignition in FAQ 16-0011 [25].

The previously established criteria of 15 MJ/m^2 for TP cables and 30 MJ/m^2 for TS cables address the fire PRA issue of unavoidable damage due to a HEAF event. No action by plant personnel can prevent this damage to cable targets within the ZOI defined by the 15 or 30 MJ/m^2 thresholds. This, however, is only part of the input to a fire PRA. There is also the possibility for the post-HEAF ensuing fire to damage targets outside the immediate ZOI of the HEAF at a later time. This damage can be due to exposure to the fire plume, exposure to radiation from the fire, or exposure to a hot gas layer. Unlike damage directly resulting from the HEAF energy release, damage due to the post-HEAF fire is potentially avoidable. Depending on the time-to-damage, a non-suppression probability will apply. The longer the time-to-damage, the lower the non-suppression probability. Determining this time to damage in a PRA requires defining what is the initial, growing fire present at the end of the HEAF. This growing fire where suppression can be credited will consist of any ensuing fire involving the enclosure that had the HEAF plus any secondary combustibles (e.g., cable trays), outside of the enclosure that also have a sustained growing fire.

The section assesses the exposures due to a HEAF; they result in sustained ignition of electrical cables in the absence of additional exposure due to an ensuing fire that is higher than seen in testing and OE, and beyond that expected from HEAFs in typical switchgear and bus ducts seen in United States nuclear power plants (i.e., ignition that results in a growing, spreading fire over a cable tray). This proposal bases the recommendation for not postulating sustained ignition from the arc jet outside of the enclosure using the basic principles of sustained ignition and a review of OE and test data.

B.2.4.2 Overview of Sustained Ignition

A material exposed to a heat flux will have a flame present when two conditions are met:

1. The pyrolysis rate ($kg/(m^2 \cdot s)$) is high enough to form a flammable mixture in the gas adjacent to the fuel surface.
2. Sufficient energy is available to overcome the activation energy of the combustion process. In the context of a fire involving electrical cables this energy could take the form of a spark, a hot surface, or the gas temperature being above the autoignition temperature.

If either of the above conditions ceases to be present, the flame will extinguish.

When a combustible material is exposed to very high heat fluxes, both conditions can be met quickly. At very high heat fluxes, where there is insufficient time to conduct heat into the surface, the surface of the material can quickly heat, and rapid pyrolysis can occur. Additionally, the high heat fluxes can result in either a high enough surface temperature to cause ignition, or radiative adsorption by the pyrolyzates can result in high enough gas temperatures to cause ignition. If the high heat flux is suddenly removed, it is possible that the flame will not sustain itself. The briefer the exposure time, the less the surface will be able to heat the combustible material in-depth. If insufficient in-depth heating occurs, conductive losses into the material will be larger than the flame feedback, and the surface temperature will cool which will decrease energy available for pyrolysis. If the in-depth temperature profile is cold enough, the heat losses will drop the surface temperature below a pyrolysis rate that sustains a flammable mixture before the bulk material can heat up. This discussion also applies to ignition events related to electrical failure of cables. Electrical failure of a power cable could result in local ignition due to a short; however, unless the bulk material has been sufficiently preheated, that localized ignition would not lead to a growing, spreading fire.

The example of this process is the work by Martin [29] looking at the conditions needed to have sustained ignition of cellulose. The normalized plot shown in Figure B-13 summarizes Martin's work. The x-axis scales the external flux by the ability to conduct heat away from the surface. Points on the x-axis are plotted as:

$$x = \frac{\dot{q}^{"}L}{k}$$

where x is the point plotted in K, $\dot{q}^{"}$ is the incident heat flux in kW/m^2, k is the material conductivity in kW/(m·K), and L is the characteristic thickness of the material in m. The y-axis scales the exposure by the heat capacity of the target. Points on the y-axis are scaled as:

$$y = \frac{q^{"}}{\rho c L}$$

where $q^{"}$ is the incident exposure in kJ/m^2, ρ is the material density in kg/m^3, and c is the material specific heat in kJ/(kg·K).

In the plot, the region labeled "Persistent ignition" is where the heat feedback from the flame is sufficiently large compared to conductive losses that a flame is sustained once the external flux is removed. While electrical cables have some variance in density, specific heat, and conductivity, the range of values is relatively similar for TP and TS cables suggesting the use of a single ignition threshold.

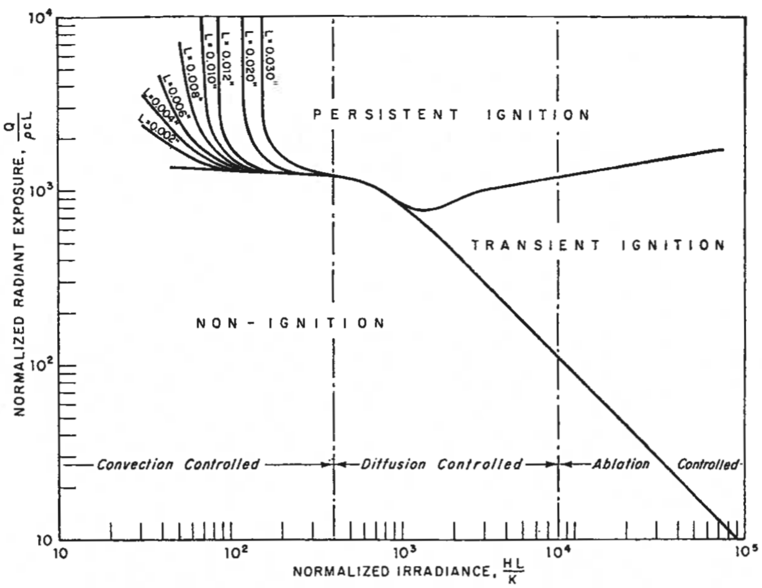


Figure B-13
Ignition threshold for blackened cellulose [29]

The Martin ignition model postulates that ignition is a function of the exposure, the flux, and the bulk properties (specific heat and conductivity) of the combustible. The specific heat and conductivity will have some variance based on the type of plastic, but in general the various cable polymers have similar values as is recognized in the development of the THIEF model in NUREG/CR-6931 [12] which recommends the use of a conductivity of 0.0002 kW/(m·K) and a specific heat of 1.5 kg/(kg·K) for all cable types. This suggests the use of the same value for both TP and TS cables, which is consistent with the approach used for bulk cable tray ignition in FAQ 16-0011 [25].

The specific lines shown in Figure B-13 above apply for blackened cellulose. It is possible that some cable plastics could show somewhat different behavior; however, both cable plastics and cellulose are organic polymer materials, and, on a log-log plot, a cable-specific line is expected to appear as a similar line to blackened cellulose.

The framework of the Martin blackened cellulose plot is used to derive the potential values of persistent ignition for the TP and TS by plotting test data, reviewed in Section B.2.2, and using nominal cable values. The Martin plot [29] tabulated values for the cellulose, and has been extrapolated to cover the range of scaled flux and scaled exposure encompassed by, the test data, as shown in Figure B-14.

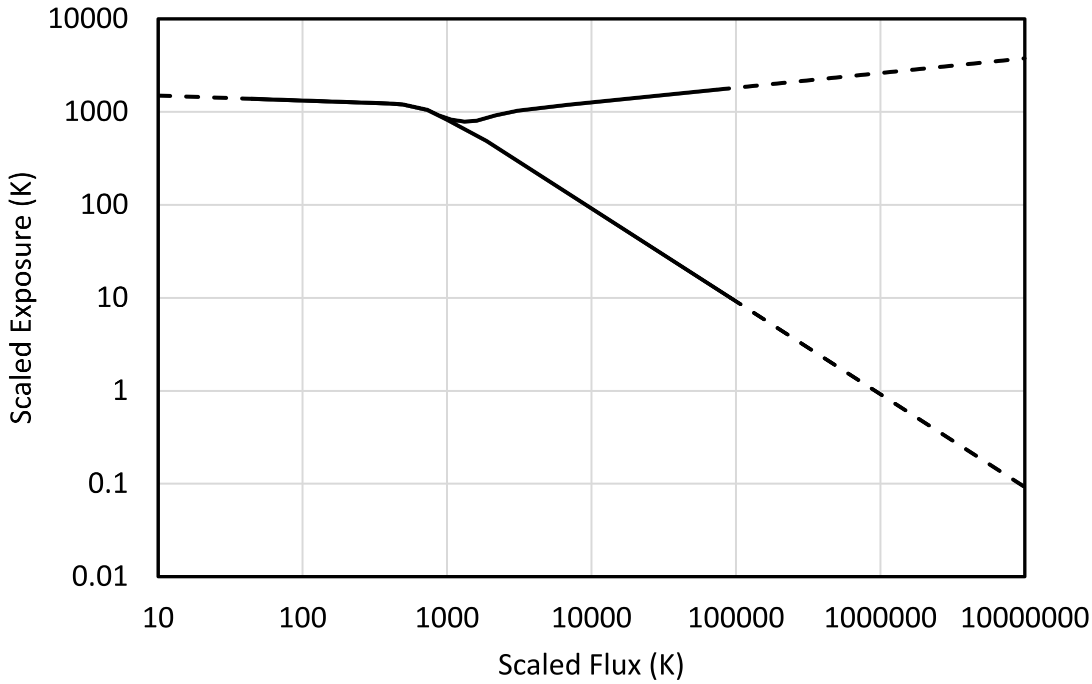


Figure B-14
Extrapolated Martin plot

The various exposures seen in the tests are plotted on the extrapolated Martin plot in Section B.2.4.3.

B.2.4.3 Review of Operating Experience and Prior Testing

This section reviews fragility insights and plot exposures for nominal cable values on the Martin plot when possible from operational experience (OE) (Section B.2.4.3.1), the OECD tests (Section B.2.4.3.2), the JNRA tests (Section B.2.4.3.3), the 2018 MV switchgear tests (Section B.2.4.3.4), and the SNL fragility tests (Section B.2.4.3.5).

B.2.4.3.1 Operating Experience with HEAF Events

There are 21 HEAF events in OE [31]. NUREG/CR-6850 Vol. 2 [1] recommends igniting a growing and propagating fire in the lowest cable tray in any stack of cable trays within 1.5 m (5 ft) of the top and 0.3 m (1 ft) horizontal separation from the edge of an enclosure with a HEAF. This has not been reported in OE. While a number of events involve an ensuing fire in the enclosure, no events in OE indicate the sustained ignition of cable trays immediately after the HEAF. While it is recognized that OE does not include all possible risk-significant events, the lack of bulk cable tray ignition due to the HEAF itself provides reasonable conclusion that the bulk ignition threshold is higher than exposures associated with HEAF events to date.

B.2.4.3.2 OECD Tests

The OECD tests [7] were a series of 26 HEAF tests taking place from 2014 to 2016 that included 26 tests of 10 types of switchgear and a bus duct. Most tests of switchgear placed a cable tray 0.3 m above the top of the switchgear. Over half of the tests involved an ensuing fire in the enclosure. Only a handful of tests, those with the largest post-HEAF ensuing fires, showed substantial damage to cables in the overhead tray. The highest measured exposures over the top of the enclosure during the test series was under 2 MJ/m^2.

Figure B-15 shows the Martin plot for the OECD test. The equations, values of conductivity, and specific heat presented in Section B.2.4.2 along with the bounding range of cable diameters (1 cm and 3 cm) and the average density of 2210 kg/m^3 that was calculated from all of the cables tested in NUREG/CR-6931 [12] and NUREG/CR-7010 [34] are used to scale the flux and exposure. Figure B-15 uses the values calculated in Table B-9 based on summary data in Table B-7 (summarized below):

- Q" is the maximum exposure [MJ/m^2] from Table B-7.
- t is the duration (s) from Table B-7.
- Scaled flux and fluence are calculated for cables 1 cm and 3 cm in diameter.

Table B-9
OECD test data scaled for external flux and exposure

Q" (MJ/m^2)	t (s)	Scaled Flux 1 cm Cable (K)	Scaled Exposure 1 cm Cable (K)	Scaled Flux 3 cm Cable (K)	Scaled Exposure 3 cm Cable (K)
0.04	2.0	875	1.1	2625	0.4
0.03	4.0	325	0.8	975	0.3
0.10	8.0	606	2.9	1819	1.0
0.14	2.2	3250	4.3	9750	1.4
0.21	2.8	3750	6.3	11250	2.1
0.00	2.1	24	0.0	71	0.0
0.09	2.1	2095	2.7	6286	0.9
0.36	2.1	8571	10.9	25714	3.6
1.00	2.6	19231	30.2	57692	10.1
0.85	2.6	16346	25.7	49038	8.6
0.41	3.2	6406	12.4	19219	4.1
0.97	3.2	15156	29.3	45469	9.8
0.13	3.1	2097	3.9	6290	1.3
0.22	3.1	3548	6.6	10645	2.2
0.25	2.6	4808	7.6	14423	2.5
0.08	2.6	1538	2.4	4615	0.8
0.16	3.7	2162	4.8	6486	1.6
0.12	4.1	1463	3.6	4390	1.2
1.30	7.1	9155	39.3	27465	13.1
0.22	3.0	3667	6.6	11000	2.2
0.98	4.3	11395	29.6	34186	9.9

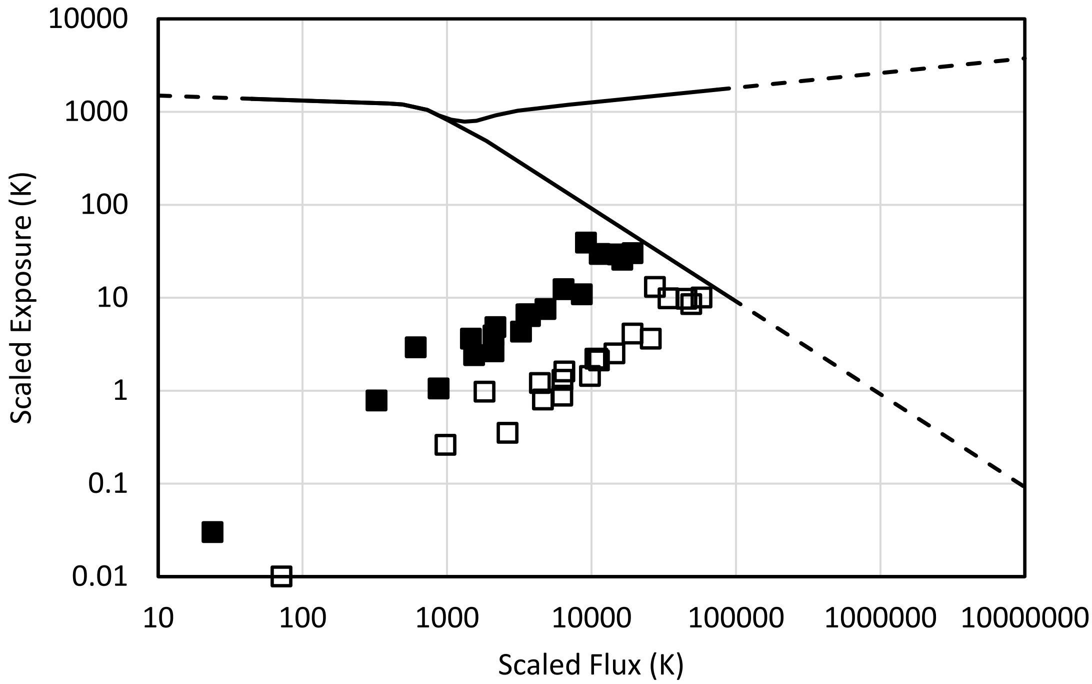


Figure B-15
OECD tests (1 cm diameter cables plotted as solid symbols and 3 cm plotted as hollow symbols)

From testing observations and when plotting the scaled values on the Martin plot, the OECD tests do not suggest any cases where a sustained, growing fire in cable trays outside of the enclosure resulted solely from the HEAF.

B.2.4.3.3 JNRA Tests

The JNRA tests [9-10] are not true prototypical tests. While the tests used prototypical equipment, a portion of each test item's sheet metal enclosure was replaced with expanded metal mesh. This was done to study basic arc electrical properties and thermal effects (e.g., using infrared cameras to study the arc position). The solid enclosure panels replaced with mesh panels significantly impact the thermal environment of the event, and the measured exposures cannot be considered as prototypical exposures. However, since TP cable coupons were present at or near locations where exposure was measured, the exposures can be used to assess sustained ignition. No JNRA test had sustained ignition of cables outside the enclosure. The maximum exposure measured outside of the enclosure during the JNRA tests was under 6 MJ/m^2.

Figure B-16 shows the Martin plot for the JNRA tests. The plot uses the values calculated in Table B-10 based on the fluence and duration from the summary data presented in Section B.2.4. The equations presented in Section B.2.4.2, and the following values are used:

- Conductivity of 0.0002 kW/(m·K)
- Specific heat of 1.5 kg/(kg·K)
- Density of 2,210 kg/m^3

- Q” is the maximum exposure [MJ/m^2] from Section B.2.2.4 for each test
- t is the duration (s) from Section B.2.2.4 for each test
- Scaled flux and fluence calculated for cables 1 cm and 3 cm in diameter

Table B-10
JNRA test data scaled for external flux and exposure

Q" (MJ/m^2)	t (s)	Scaled Flux 1 cm Cable (K)	Scaled Exposure 1 cm Cable (K)	Scaled Flux 3 cm Cable (K)	Scaled Exposure 3 cm Cable (K)
0.2	0.2	34091	4.5	102273	1.5
5.5	3.1	88710	165.9	266129	55.3
2.6	2.8	46429	78.4	139286	26.1
1.7	3.5	24496	51.3	73487	17.1
2.6	4.1	32020	78.4	96059	26.1
0.2	0.8	13060	6.3	39179	2.1

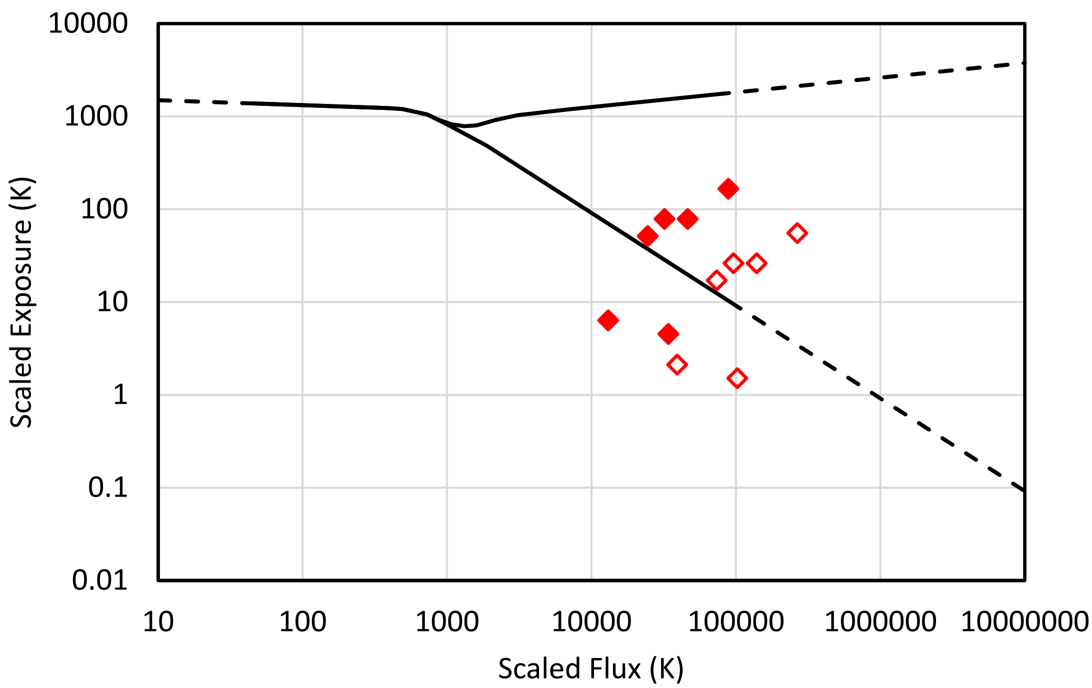


Figure B-16
JNRA tests (1 cm diameter cables plotted as solid symbols and 3 cm plotted as hollow symbols)

From testing observations and when plotting the scaled values on the Martin plot, the JNRA tests do not suggest any cases where a sustained, growing fire in cable trays outside of the enclosure resulted solely from the HEAF.

B.2.4.3.4 2018 Medium Voltage Switchgear Tests

The MV switchgear tests [4] consisted of four tests with each test having five racks of instrumentation and cable coupons (TP). In each of the four tests, Rack 2, 0.9 m from the rear face of the enclosure, and Rack 3, 1.8 m from the rear face of the enclosure, were exposed to the jet that formed when the enclosure was breached by the arc. Videos of each test were taken using a variety of cameras and viewpoints. In all tests, aerosols and the jet quickly obscured Racks 2 and 3, lasting for a few seconds after the end of the arc. Figure B-17 through Figure B-20 are all taken from test video within a few seconds of the end of the arc.

Figure B-17 shows the view from GoPro camera 1 once obscuration has cleared in Test 2-19, nominal test of 25 kA for 2 s. One glowing spot is seen on Rack 3 at 1.8 m. This spot does not appear to flicker, indicating it is likely a hot piece of debris like that seen glowing on the floor.

Figure B-17
Post-test image for Test 2-19

Figure B-18 shows the post-test conditions for Test 2-21, nominal test of 25 kA for 4 s. The left image is GoPro camera 1, and the right image is from a high-definition video camera. The GoPro shows post-test flaming in locations where there is fiber insulation. The insulation materials are manufactured with a process that involves an organic binder. In typical ordinary fire applications of these insulation materials, this binder slowly off-gases as the insulation heats up. The high exposures during the HEAF appear to have resulted in a large enough rate of off-gassing from the fiber insulation for there to be a sustained flame immediately post HEAF. This fire does not appear to involve the cable coupons.

Figure B-18
Post-test image for Test 2-21

Figure B-19 shows the post-test conditions for Test 2-22, nominal test of 32 kA for 2 s. The left image is from GoPro camera 1, and the right image is from the interior full camera viewpoint. Both images show flaming combustion after the HEAF. As with Test 2-21, the locations with flame correspond to locations with insulation materials.

Figure B-19
Post-test image for Test 2-22

Figure B-20 shows the post-test conditions for Test 2-24, nominal test of 32 kA for 4 s. The left is GoPro camera 2 and the right is from a high-definition video camera. The GoPro image shows a number of glowing objects that appear to just be glowing red insulation. The insulation is low density and low conductivity and can heat to glowing temperatures much more easily than the other materials. The image on the right primarily shows glowing materials as well. There are faint signs of flickering in the glowing region, which could be localized flaming; however, the intensity is low and not indicative of something that will sustain itself over time.


Figure B-20
Post-test image for Test 2-24

A review of the video footage for the MV switchgear tests does not indicate sustained flaming combustion of the cable coupons. This includes the up to approximately 14 MJ/m^2 seen by Rack 2 in Test 2-24.

Figure B-21 shows the Martin plot for the MV switchgear tests. The plot uses the values calculated in Table B-11, based on the fluence and duration from the summary data presented in Section B.2.2. The equations presented in Section B.2.4.2, and the following values are used:

- Conductivity of 0.0002 kW/(m·K)
- Specific heat of 1.5 kg/(kg·K)
- Density of 2,210 kg/m^3
- Q" is the exposure from Section B.2.2.5
- q" is the flux from Section B.2.2.5
- Scaled flux and fluence calculated cables 1 cm and 3 cm in diameter

Table B-11
MV switchgear test data scaled for external flux and exposure

Q" (MJ/m^2)	q" (MW/m^2)	Scaled Flux 1 cm Cable (K)	Scaled Exposure 1 cm Cable (K)	Scaled Flux 3 cm Cable (K)	Scaled Exposure 3 cm Cable (K)
0.7	0.2	9650	20.5	28950	6.8
6.6	2.9	145000	199.1	435000	66.4
2.1	1.9	95000	63.3	285000	21.1
14.0	4.8	240625	422.3	721875	140.8
0.2	0.2	8000	5.9	24000	2.0
2.9	1.2	60000	87.5	180000	29.2
0.7	1.0	50000	19.6	150000	6.5
6.4	2.2	110000	193.1	330000	64.4

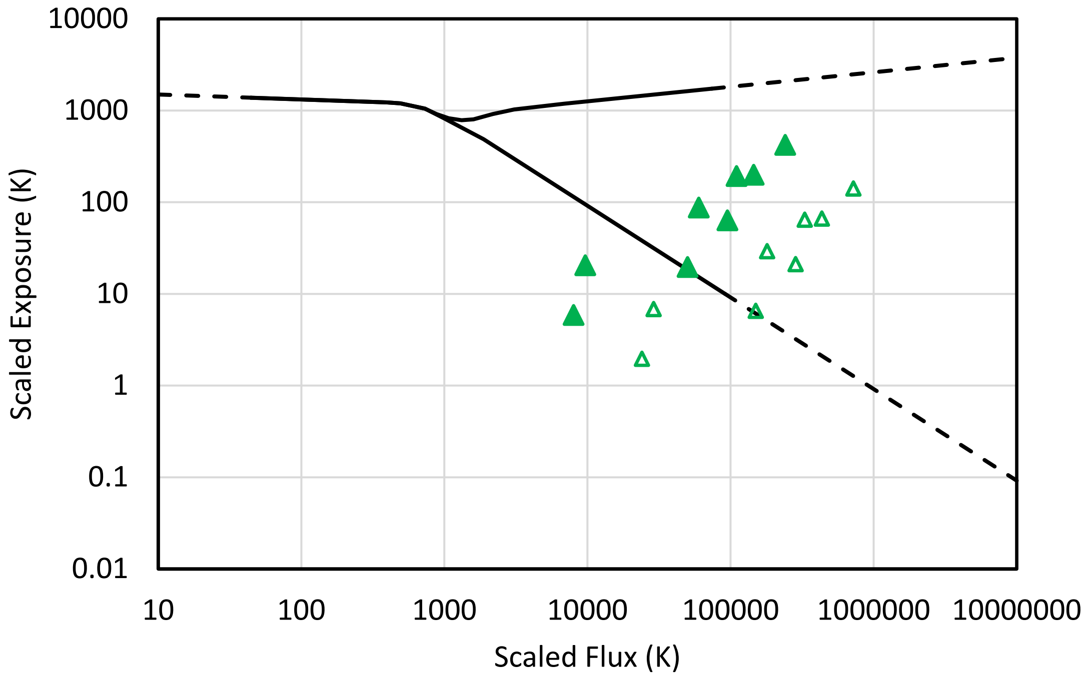


Figure B-21
MV switchgear tests (1 cm diameter cables plotted as solid symbols and 3 cm plotted as hollow symbols)

From testing observations and when plotting the scaled values on the Martin plot, the MV switchgear tests do not suggest any cases in which a sustained, growing fire in cable trays outside the enclosure resulted solely from the HEAF.

B.2.4.3.5 SNL Fragility Tests

SNL performed a series of tests using its solar furnace test facility to evaluate the fragility of electrical cables [8]. Figure B-18 provides an overview of the SNL cable fragility test approach. Exposure consisted of one, two, or three parts with the three-part exposure shown in Figure B-22. All tests began with a constant flux exposure labeled as Q0 in Figure B-22. Some initial tests went from Q0 to zero flux as quickly as the solar furnace can change the flux. Some tests went from Q0 to zero flux over a longer duration (P1). P1 was selected to emulate the decay rate seen in the 2018 MV switchgear tests. This profile is referred to as the "simple" profile. Some tests went from Q0 to an intermediate Q1 value to constant Q2 value of 50 kW/m^2. The value of Q1 and the times for P1 and P2 were selected to approximate the decay seen in the 2018 MV switchgear tests. The 50 kW/m^2 flux represents the combination of some heating from the still hot enclosure plus heat feedback from a postulated sustained flame on a cable tray. This profile is called the "dynamic" profile. During these tests, where video was available, the time when the flame that appeared during Q0 extinguished was recorded. This time of extinguishment can be used to assess whether a sustainable flame was present.

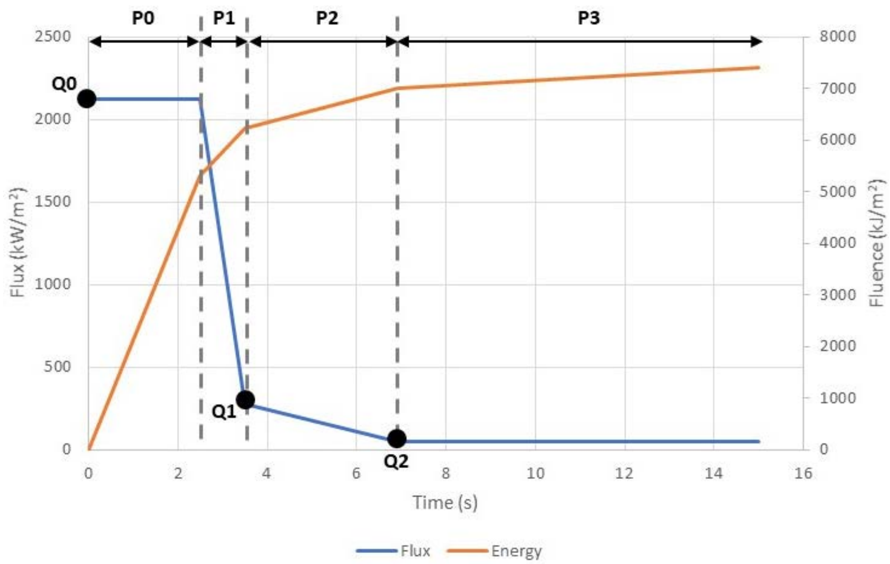


Figure B-22
Simulated HEAF primary and feedback flux profile

Based on the conditions necessary to cause cable damage and the post-HEAF fire behavior seen in OE and testing, we know that severe conditions (e.g., tens of MW/m^2), are needed to cause the bulk ignition of cables. Based on testing, those exposures are only seen if a target is extremely close to the arc (e.g., in the enclosure), or if the target is in a jet from an enclosure breach with a sufficiently long duration arc at high current. Testing shows that the breach is on the order of the enclosure width, which for typical enclosure dimensions, means a 0.6- to 0.9-m wide jet. If a cable tray that is 0.6 m wide is immersed in a 0.6- to 0.9-m wide jet, then the potential initial area of ignition would be on the order of 0.5 m^2. This is a 100 kW fire given typical cable burning rates [34]. A fire of that size that has just been established on a cable tray likely has heat fluxes to the fuel surface of 35 to 50 kW/m^2. If the cable tray is going to maintain sustained ignition post-HEAF, those heat fluxes must be capable of sustaining the flame. If a cable tray post-HEAF cannot sustain combustion given typical flame heat feedbacks, that fire will self-extinguish and not result in a growing, spreading fire.

The SNL tests did not include a cable tray exposed over a prototypical exposure area. They included three cables with a 5-cm diameter exposure area. The flame that results during the HEAF will not provide the same amount of heat feedback as a fully ignited cable tray. However, the solar furnace does provide a surrogate heat feedback in the form of the ramping down of the flux. As the flux ramps down, the cable will try to reach some equilibrium among the heat flux to the cable surface, the heat conduction from the surface into the cable, the energy needed to pyrolyze the cable material, and heat losses from reradiation from the cable surface to the ambient environment of the solar furnace test facility. If the cables self-extinguish before to a flux of 50 kW/m^2, this is indicative of a fire that would not be sustained. If the flame is extinguished at fluxes higher than expected heat feedback from a fire, then that flame was not capable of being a sustained, growing fire. For a fire to have the potential to be a growing, sustained fire, it would need to last some period of time into the 50 kW/m^2 plateau. Since the external flux is being ramped down, the mass of cable means there is some time constant that governs the cable's response to a change in heat flux. At the instant the solar furnace ramp reaches 50 kW/m^2, that time constant means the cable will still be trying to reach its equilibrium from the previously higher flux. This means that extinction at the start of the 50 kW/m^2 plateau represents a non-sustainable fire.

Tests with extinction results from the SNL testing are summarized in Table B-12 for TP cables and Table B-13 for TS cables.

Table B-12
Thermoplastic cable flame extinction data from SNL Solar Furnace Testing

Test	Q0 (MW/m^2)	P0 (s)	Profile	Exposure at Extinction (MJ/m^2)	Notes
1-22	3.0	2.0	Simple	7	Extinction at 870 kW/m^2
1-24	4.6	2.0	Simple	15	Extinction at 390 kW/m^2
1-26	6.0	4.0	Simple	36	Extinction at 30 kW/m^2
1-32	3.0	6.0	Dynamic	24	Extinction at 49 kW/m^2, 1 s into plateau
1-33	3.0	4.0	Dynamic	17	Extinction at 110 kW/m^2
1-34	4.5	2.5	Dynamic	25	Extinction at 450 kW/m^2
1-35	2.0	7.0	Dynamic	21	Extinction at 170 kW/m^2
1-36	3.0	4.0	Dynamic	21	Extinction at 330 kW/m^2

Table B-13
Thermoset cable flame extinction data from SNL Solar Furnace Testing

Test	Q0 (MW/m^2)	P0 (s)	Profile	Exposure at Extinction (MJ/m^2)	Notes
1-23	3.0	2.0	Simple	7	Extinction at 375 kW/m^2
1-25	4.6	2.0	Simple	15	Extinction at 59 kW/m^2
1-27	6.0	4.0	Simple	38	Extinction at 12 kW/m^2
1-28	6.0	8.0	Simple	63	Extinction at 14 kW/m^2
1-29	3.0	8.0	Dynamic	32	Extinction at 49 kW/m^2, 1 s into Q2 plateau
1-30	3.0	10	Dynamic	35	Extinction at 51 kW/m^2 at start of Q2 plateau
1-36	2.0	15.5	Dynamic	36	Extinction at 120 kW/m^2
1-37	3.0	10.0	Dynamic	39	Extinction at 160 kW/m^2

The test results lead to the following observations:

- In all cases for the dynamic profile, extinction occurred before the plateau or at the start of the plateau. As discussed above, these results indicate conditions where a sustained, growing fire would not be expected.
- In four of the seven simple profile tests, extinction occurred before the heat flux reached 50 kW/m^2. As discussed above, these results indicate conditions under which a sustained, growing fire would not be expected.
- In three of the seven simple profile tests, extinction happened below 50 kW/m^2. Even though extinction happened below 50 kW/m^2, these tests are not a reliable indicator of a sustainable flame. The heat flux profile was continuously decreasing, and, as discussed above, the cable conditions will lag the heat flux. That is, it takes some time for the cable to respond to a change in the externally applied heat flux. In the simple test, P1 ramp times from Q0 to no solar flux ranged from approximately 1 to 3 s. This means the last 100 kW/m^2 of ramp for the flux occurred over a period of time that was no more than 0.1 s (100 kW/m^2 × 3 s/3 MW/m^2) for all the simple profile tests. With that rapid of a flux decrease, it cannot be determined whether the extinction below 50 kW/m^2 means that sustained combustion would have occurred had a dynamic profile been used.
- The maximum exposure for a dynamic test with TP cable, Test 1-34, was 25 MJ/m^2 and the value for TS cable, Test 1-37, was 39 MJ/m^2.
- It is noted that there is one simple test, Test 1-28, with an exposure of 63 MJ/m^2. While this is a higher value than the 39 MW/m^2 in Test 1-37, one cannot conclude anything about how that value relates to the threshold for sustained ignition, since there was no pause at 50 kW/m^2.

The extinction results from the SNL test show that cables saw extinction at external fluxes ranging from 50 to 450 kW/m^2. At 50 kW/m^2, extinction occurred at the start of the Q2 plateau. These results indicate that the cables were not at a condition where a sustained, growing fire would be expected. The SNL tests indicate that the threshold for sustain ignition lies above 39 MJ/m^2.

Figure B-23 shows the Martin plot for the SNL tests. The plot uses the values calculated in Table B-14, based on the fluence and duration from the summary data plotted in Figure B-23. The equations presented in Section B.2.4.2, and the following values are used:

- Conductivity of 0.0002 kW/(m·K)
- Specific heat of 1.5 kg/(kg·K)
- Density of 2,210 kg/m^3
- Q" is the exposure (MJ/m^2) from Section B.2.2.2 for each test
- q" is the flux (MW/m^2) from Section B.2.2.2 for each test
- Scaled flux and fluence calculated cables 1 cm and 3 cm in diameter

Table B-14
SNL test data scaled for external flux and exposure

Q" (MJ/m^2)	q" (MW/m^2)	Scaled Flux 1 cm Cable (K)	Scaled Exposure 1 cm Cable (K)	Scaled Flux 3 cm Cable (K)	Scaled Exposure 3 cm Cable (K)
82.0	3.0	150000	2473.6	450000	824.5
7.0	3.0	150000	211.2	450000	70.4
15.0	4.6	230000	452.5	690000	150.8
38.0	6.0	300000	1146.3	900000	382.1
63.0	6.0	300000	1900.5	900000	633.5
32.0	3.0	150000	965.3	450000	321.8
35.0	3.0	150000	1055.8	450000	351.9
37.0	4.5	225000	1116.1	675000	372.0
36.0	2.0	100000	1086.0	300000	362.0
39.0	3.0	150000	1176.5	450000	392.2
7.0	3.0	150000	211.2	450000	70.4
15.0	3.0	150000	452.5	450000	150.8
36.0	3.0	150000	1086.0	450000	362.0
24.0	3.0	150000	724.0	450000	241.3
17.0	3.0	150000	512.8	450000	170.9
25.0	3.0	150000	754.1	450000	251.4
21.0	3.0	150000	633.5	450000	211.2
21.0	3.0	150000	633.5	450000	211.2
3.0	3.0	150000	90.5	450000	30.2
4.6	3.0	150000	138.8	450000	46.3
6.0	3.0	150000	181.0	450000	60.3
3.0	3.0	150000	90.5	450000	30.2
3.0	3.0	150000	90.5	450000	30.2
4.5	3.0	150000	135.7	450000	45.2
2.0	3.0	150000	60.3	450000	20.1
3.0	3.0	150000	90.5	450000	30.2

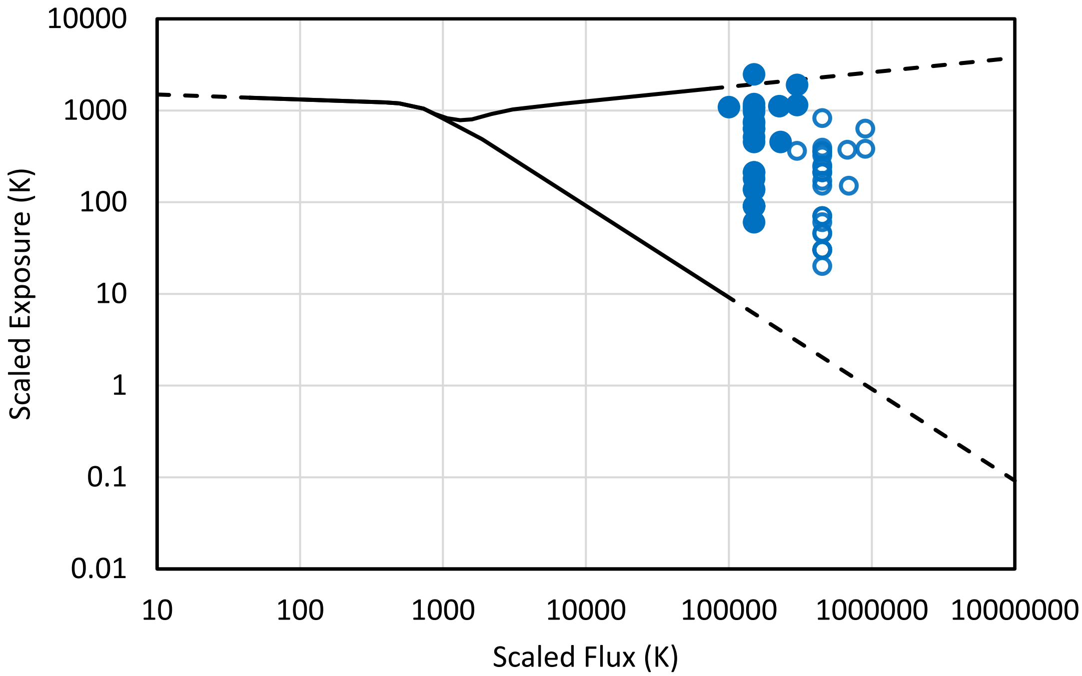


Figure B-23
SNL tests (1 cm diameter cables plotted as solid symbols and 3 cm plotted as hollow symbols)

From testing observations and when plotting the scaled values on the Martin plot, the SNL tests do not suggest any cases in which a sustained, growing fire in cable trays outside the enclosure resulted solely from the HEAF, except for one point. This point is the SNL flux and exposure plotted assuming a cable diameter of 1 cm. The actual cable diameter in the test was larger than 1 cm, which would move the point down into the transient ignition range.

B.2.4.4 Determining Cable Fragility During a HEAF Event

To summarize, the plots presented in Section B.2.4.3 were combined and plotted in Figure B-24. In this plot, the specific heat and conductivity values discussed in the Section B.2.4.2 were used to scale the test data. A density of 2,210 kg/m^3 was used which represents the average density over all the cables tested in NUREG/CR-6931 [12] and NUREG/CR-7010 [3431]. The scaling parameters for Martin's model are dependent on the characteristic thickness of the materials. This dependence is represented in Figure B-24 by plotting two cable diameters: a 1 cm (solid symbols) and 3 cm diameter cable (hollow symbols). These diameters bound the range of cable types used in the NRC testing reflected in NUREG/CR-6931 [12] and NUREG/CR-7010 [34] and will reflect the burning behavior one would expect to see in a United States nuclear power plant for each of the specific test exposures and fluxes. The solid black curves in Figure B-24 are from Figure B-13. The dashed lines extrapolate Martin's data to cover the range of scaled flux and scaled exposure encompassed by the test data.

Also incorporated into the plot are gray points labeled as fragility. The gray fragility points are the 15 and 30 MJ/m^2 exposures (from Section 4) needed to cause cable damage for a range of arc times from 1 to 10 s, as shown in Table B-15.

Table B-15
Fragility exposure scaled for external flux and exposure

Q" (MJ/m²)	q" (MW/m²)	T (s)	Scaled Flux 1 cm Cable (K)	Scaled Exposure 1 cm cable (K)	Scaled Flux 3 cm Cable (K)	Scaled Exposure 3 cm Cable (K)
15.0	15.0	1.0	750000	452.5	2250000	150.8
15.0	7.5	2.0	375000	452.5	1125000	150.8
15.0	3.8	4.0	187500	452.5	562500	150.8
15.0	1.9	8.0	93750	452.5	281250	150.8
15.0	1.5	10.0	75000	452.5	225000	150.8
30.0	30.0	1.0	1500000	905.0	4500000	301.7
30.0	15.0	2.0	750000	905.0	2250000	301.7
30.0	7.5	4.0	375000	905.0	1125000	301.7
30.0	3.8	8.0	187500	905.0	562500	301.7
30.0	3.0	10.0	150000	905.0	450000	301.7

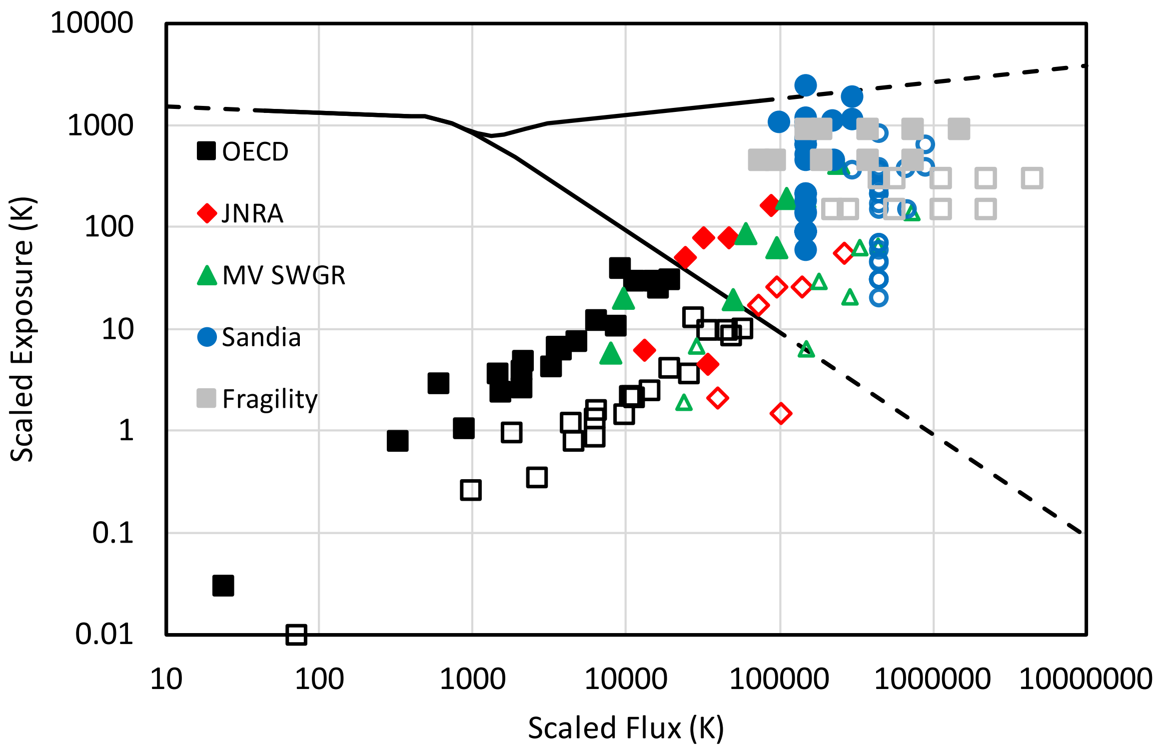


Figure B-24
Test data plotted using Martin's blackened cellulose curve

Plotting the test data on Figure B-24 does match the behavior seen in testing. For all test data the measured exposure during testing was used to scale the y-axis locations of the plotted data:

- For the OECD data, the exposure was reported. The x-axis locations of the test data were plotted by computing the flux as the exposure divided by the arc time. The OECD test data shown are the maximum exposures measured at a cable tray above and just to the side of the enclosure. These trays did not see sustained ignition during testing, which matches the data location in Figure B-24, where the tests all lie in the no-ignition area. Trays over the cabinet, only saw significant damage when there was a large ensuing fire; however, the exposure directly over the cabinet was not measured.
- The JNRA test data shown are the maximum exposures seen in each test. The x-axis locations of the test data were plotted by computing the flux as the exposure divided by the arc time. Some test points are in the no-ignition region, and some test points are in the transient ignition region. This is consistent with test results, which did not show any sustained cable ignition.
- The MV switchgear test data shown are the maximum exposures for Rack 2 (0.9 m) and Rack 3 (1.8 m) for each test. The x-axis locations of the test data were plotted using the average flux measured during the arc duration. The Rack 2 point for Test 2-24 is the estimated value from Ref. 8. Some test points are in the no-ignition region, and some test points are in the transient ignition region. As noted in the discussion of the MV switchgear tests in Section B.2.2.5, transient ignition of cable coupons was not ruled out, just sustained ignition.
- The SNL tests lie in the transient ignition range. The x-axis locations of the test data were plotted using Q0. This matches test observations where transient ignition was seen during testing. Note one solid point in the plot is above the line for sustained ignition. This point is the SNL flux and exposure plotted assuming a cable diameter of 1 cm. The actual cable diameter in the test was larger than 1 cm, which would move the point down into the transient ignition range.
- The fragility points are the 15 MJ/m^2 and 30 MJ/m^2 criteria for the presumed electrical failure of cables. The x-axis locations are plotted using the exposure divided by arc durations of 1, 2, 4, 8, and 10 s. For each set of symbols (solid or hollow), the upper row is 30 MJ/m^2 and the lower row is 15 MW/m^2. The current cable damage fragility criteria all lie within the transient ignition range.

The solid and dashed lines are Martin's curves for blackened cellulose. As discussed above, the behavior of cables during testing coincides with the Figure B-24 location of the tests within Martin's no-ignition and transient ignition regions. This suggests that the blackened cellulose curves on Figure B-24 are a reasonable surrogate for the cables. Additionally, it should be noted that the conductors in the electrical cables serve as a means of transferring heat out of the exposed region during a HEAF. In the longer duration HEAFs needed to achieve very high exposures, heat losses through the conductors effectively increase the mass of cable being exposed. On Martin's plot this would be shown by moving points downward on the plot, suggesting there may be some conservatism in the current plotting of the data. Therefore, it is proposed that the sustained ignition criteria for cable lies on the line dividing transient ignition from sustained ignition for longer duration arcs and is higher than seen from HEAFs during the arcing jet outside the enclosure.

B.2.4.5 Conclusions and Recommendations for Cable Fragility During a HEAF Event

Data from OE and testing are summarized as follows:

- OE does not suggest any cases in which a sustained, growing fire in a cable tray outside of the enclosure resulted solely from the HEAF.
- The OECD tests do not suggest any cases in which a sustained, growing fire in cable trays outside of the enclosure resulted solely from the HEAF.
- The JNRA tests do not suggest any cases in which a sustained, growing fire in a cable tray would have occurred solely from the HEAF.
- The MV switchgear tests do not suggest any cases in which a sustained, growing fire in a cable tray would have occurred solely from the HEAF.
- The SNL test results do not suggest any cases in which a sustained, growing fire in a cable tray would have occurred solely due to a HEAF. The test results also do not suggest that conditions were very close to achieving sustained ignition. The highest exposure during a dynamic ramp test was 39 MJ/m^2.

The Martin plot shown in Figure B-24 demonstrates that the threshold separating the transient ignition and sustained ignition for cables was not met during testing, and a review of OE has not identified any sustained ignition of cables beyond those seen during the enclosure fire. Therefore, it is recommended that sustained ignition is not postulated outside of the enclosure during the arcing jet phase of the HEAF; sustained ignition can only occur within the enclosure and is capable of growing into a sustained electrical enclosure fire.

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