NUREG-2262 EPRI 3002025942

High Energy Arcing Fault Frequency and Consequence Modeling

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D.C. 20555-0001

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High Energy Arcing Fault Frequency and Consequence Modeling

Final Report
April 2023

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D.C. 20555-0001

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ABSTRACT

High energy arcing faults (HEAFs) are one type of hazard modeled in fire probabilistic risk assessments. NUREG/CR-6850 and NUREG/CR-6850, Supplement 1, provide the basic methods to analyze the risk associated with HEAFs in power distribution equipment (switchgear and load centers) and bus ducts (including iso-phase bus ducts), respectively. Since the publication of these two reports, the state of knowledge of HEAF phenomena has advanced significantly. A thorough understanding of the nuclear power plant electrical distribution system and its performance during faulted conditions has been achieved, along with a review and categorization of industry events. Additionally, experimentation (including full-scale testing on HEAF-susceptible equipment, small-scale testing, and simulation) has increased the understanding of parameters that affect the dimensions of the zone of influence (ZOI).

This report combines previous HEAF-related research and provides methods and data to more realistically calculate plant risk due to HEAFs. Ignition frequency and non-suppression estimates are updated with the most recently available industry operating experience. Most importantly, the ZOI selection is greatly expanded. Previously, there was one ZOI for switchgear and load centers, one ZOI for bus ducts, and one ZOI for iso-phase bus ducts. The computational fluid dynamics software Fire Dynamics Simulator (FDS) has been benchmarked against full-scale tests and is used to predict the thermal exposure of targets in the vicinity of a HEAF. FDS simulations are performed for three classes of equipment: load centers, switchgear, and non-segregated bus ducts. The simulations varied parameters such as arc power, arc duration, arc location, electrode composition, and type of equipment. The working group reviewed and grouped the ZOI results from the simulation effort to determine consensus ZOIs for the three equipment classes, with varying levels of detail commensurate with potential risk significance.

A key parameter of the ZOI is the time overcurrent (51) relay setting, or fault clearing time, of the auxiliary power transformer. The faster the fault clearing time, the smaller the energy release. The speed of this protection determines whether the updated medium-voltage switchgear ZOIs are smaller or larger than the ZOI in NUREG/CR-6850. For non-segregated bus ducts, the ZOIs are also dependent on the enclosure material of the bus duct (either aluminum or steel). In general, the ZOIs for non-segregated bus ducts are larger, except for fault clearing times of 2 s or less on the station auxiliary transformer (feed from off-site). The load center supply breaker ZOIs are smaller than the ZOI recommended in NUREG/CR-6850.

Keywords
Arcing fault
Fire events
Fire ignition frequency (FIF)
Fire probabilistic risk assessment (Fire PRA)
High energy arcing fault (HEAF)

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EXECUTIVE SUMMARY

Product Title: High Energy Arcing Fault Frequency and Consequence Modeling

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PRIMARY AUDIENCE: Fire protection engineers, electrical engineers, and probabilistic risk assessment (PRA) engineers developing or reviewing fire risk assessments related to high energy arcing faults (HEAFs). The technical content of this report is based on a basic understanding of nuclear power plant electrical distribution systems and electrical protection features.

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

Given the increased state of knowledge on the HEAF phenomena from both an operating experience and hazard characterization, how should HEAFs be modeled in fire PRAs?

RESEARCH OVERVIEW

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research and the Electric Power Research Institute (EPRI) HEAF working group has been tasked with improving the methodology for analyzing the HEAF hazard at nuclear power plants. Previous technical reports addressed damage and ignition thresholds (fragility) and hazard modeling. RIL 2022-01 documents cable target fragility thresholds. The hazard modeling was conducted using Fire Dynamics Simulator (FDS). FDS simulations of HEAFs are performed for three classes of equipment: load centers, medium voltage switchgear, and non-segregated bus ducts. For each class of equipment, parameters such as arc power, arc duration, arc location, and electrode composition are varied.

In parallel, the working group developed the framework for analyzing HEAFs in fire PRA. The working group developed a generic HEAF fault zone map, which serves as the technical basis for the HEAF durations and energies considered in the FDS simulations. The fault progression trees were discussed at several working group meetings. An expert panel was convened to determine split fractions for medium-voltage switchgear; portions of this exercise are extended to modeling non-segregated bus ducts that have similar fault characteristics and electrical protection.

The HEAF end states in the fault progression trees form the basis for the zone of influence (ZOI) definition and discussion. Where more than one fault type is likely, an event tree and split fractions are provided. As the results of the FDS simulations were completed, the working group met to review and consolidate the results into consensus ZOIs and finalize the fire PRA guidance for each HEAF-related ignition source.

KEY FINDINGS

- The nuclear power plant electrical distribution system (EDS) is divided into different fault zones. Each fault zone contains a portion of the EDS with similar equipment and fault characteristics. The fault zones are summarized in Table 3-1 and shown in Figure ES-1. Auxiliary power transformer and bus protection are described in detail in Section 3 and form the basis for the durations used in the HEAF ZOI simulations.

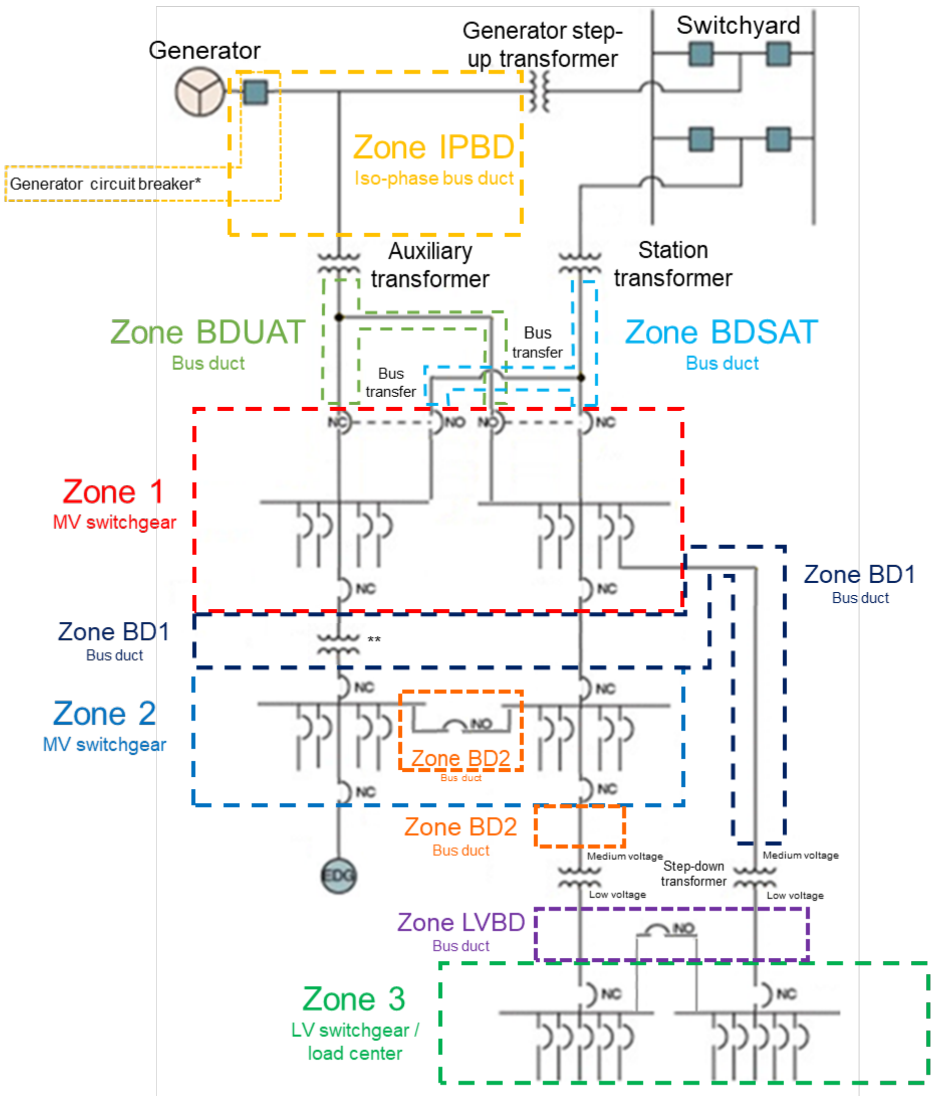

Figure ES-1
HEAF zones for a simplified NPP electrical distribution system

- Section 5.2 provides the ignition source counting guidance for HEAFs in fire PRA:
  - Bin 16.a (load centers): Count the supply breakers (do not count by vertical section).
  - Bin 16.b (medium voltage switchgear): Count the entire switchgear bank (do not count by vertical section). Section 5.2.2.3 introduces a switchgear weighting factor that distributes the generic Bin 16.b frequency based on operating experience.
  - Bin 16.1-1 and Bin 16.1-2 (non-segregated bus ducts): The same counting recommendations as NUREG/CR-6850, Supplement 1 apply for known transition points (Section 5.2.3.1) and unknown transition points (Section 5.2.3.2). For known

transition points, the analyst is cautioned that HEAFs can occur at outdoor environmental access locations (such as ventilation openings, mechanical hatches, or external wall penetrations). These environmental access locations should be considered in the fire PRA target selection/scenario process.
  - Bin 16.2 (iso-phase bus ducts): Generally, count one iso-phase bus per unit (an iso-phase bus includes all three phases).

- Section 5.3 calculates updated ignition frequencies for the HEAF-related bins through 2021 (Table 5-8).

- Section 5.3.1 defines a generator circuit breaker (GCB), the equipment that can be protected by a GCB, and a modifier that can be used in scenarios where the GCB can interrupt a fault.

- Section 5.4 provides an updated HEAF manual non-suppression rate.

- Section 6 provides general guidance on the energetic portion of the HEAF ZOI, how to determine fault clearing times (FCTs), and characteristics of the post-HEAF ensuing fire (for switchgear and load centers).

- Section 7 provides the energetic ZOIs for load centers.

  - Eight ZOIs dependent on the location of the load center supply breaker (end or interior location, and upper or lower elevation) and fragility threshold (either 15 MJ/m^2 or 30 MJ/m^2). See Table 7-1 for a full listing of the ZOI dimensions.
  - These energetic ZOIs are smaller than the ZOIs in NUREG/CR-6850 (e.g., the NUREG/CR-6850 ZOI bounds the new ZOIs).
    - Regardless of the configuration, there is no front or back ZOI for load centers (a post-HEAF ensuing fire is still postulated).
    - An interior supply breaker on the lower half of the load center does not have an external ZOI associated with the energetic phase (a post-HEAF ensuing fire is still postulated).

- Section 8 provides the energetic ZOIs for medium voltage switchgear.
  - Table 8-2 provides the screening ZOIs.
  - Zone 1 (medium-voltage switchgear fed directly from the auxiliary power transformers) configuration specific ZOIs are provided in Table 8-3 (15 MJ/m^2) and Table 8-4 (30 MJ/m^2).
  - Zone 2 (medium voltage switchgear fed by an intermediary switchgear) configuration specific ZOIs are provided in Table 8-5 (15 MJ/m^2) and Table 8-6 (30 MJ/m^2).
  - The ZOI dimensions are sensitive to the backup time overcurrent relay (51) setting of the transformer (commonly referred to as FCT). Faster FCTs are less likely to exceed the ZOI in NUREG/CR-6850.
    - For the 15 MJ/m^2 fragility (thermoplastic targets, aluminum-enclosed bus ducts, etc.) fault points outside the transformer zone of differential protection (Zone 1 main bus bar and loads and Zone 2) are subject to larger ZOIs for

        - unit auxiliary transformers (UAT) FCTs greater than 0.50 s and station auxiliary transformer (SAT) FCTs greater than 4 s.
        - For the 30 MJ/m^2 fragility (thermoset jacketed cables, steel enclosed bus ducts, etc.) fault points outside the transformer zone of differential protection (Zone 1 main bus bar and loads and Zone 2) are subject to larger ZOIs for UAT FCTs greater than 3 s.

- Section 9 provides the energetic ZOIs for iso-phase bus ducts (IPBD) and non-segregated bus ducts (NSBD).
    - Section 9.2.1 provides the ZOI guidance for the IPBD (carried over from NUREG/CR-6850 Supplement 1).
    - Table 9-2 provides the ZOIs for bus ducts.
        - The enclosure material (either aluminum or steel) has an impact on the ZOI dimensions. The steel enclosure, which takes more energy to breach, has a smaller ZOI than the faster-breaching aluminum enclosure.
        - The NSBD ZOIs are generally larger than those in NUREG/CR-6850 Supplement 1.

WHY THIS MATTERS

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

HOW TO APPLY RESULTS

Section 5 provides the analyst updated HEAF-related ignition source counting guidance, fire ignition frequencies, credit for installed generator circuit breakers, and updated HEAF manual non-suppression rate.

Section 6 provides general guidance on the energetic ZOI, how to determine FCTs, and characteristics of the post-HEAF ensuing fire.

Section 7 provides ZOIs for load centers. Section 8 provides ZOIs for medium-voltage switchgear. Section 9 provides ZOIs for non-segregated bus ducts. Section 10 summarizes the guidance for each type of HEAF-susceptible equipment.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Users of this report may be interested in periodic stakeholder engagement opportunities with EPRI and/or NRC on this topic.

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PROGRAM: Nuclear Power, P41; Risk and Safety Management, P41.07.01

IMPLEMENTATION CATEGORY: Plant Optimization

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The report describes research sponsored jointly by the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) performed under a formal Memorandum of Understanding (MOU).

This publication is a corporate document that should be cited in the literature in the following manner:

High Energy Arcing Fault Frequency and Consequence Modeling. EPRI, Palo Alto, CA, and the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Washington, D.C.: 2023. 3002025942 / NUREG-2262.

ACKNOWLEDGMENTS

The authors would like to thank Joe Krvavac of Sargent & Lundy for providing valuable technical input. In particular, the IEEE article *Through-fault capability requirements for unit auxiliary transformers* provided basis for benchmarking and modeling the generator energy decay exponential curve.

EPRI would also like to thank Nenad Uzelac from CIGRE for assisting the authors in obtaining valuable data and insights regarding generator circuit breaker performance and reliability as collected and developed by CIGRE.

Internal and external stakeholders provided comments and suggestions on the draft report when it was published in the Federal Register (87 FR 45806) on July 29, 2022. The authors would like to acknowledge Victoria K. Anderson of the Nuclear Energy Institute, members of the joint NRC/EPRI HEAF working group and the NRC Office of Nuclear Reactor Regulation HEAF LIC-504 team, including the two reference plants (ADAMS ML22201A000) for their feedback and input on the draft report. A record of the draft report, Federal Register notice, and the comments received can be found in ADAMS under accession number ML22353A074.

ABBREVIATIONS

AC	alternating current
ACB	air-cooled circuit breaker
ADAMS	Agencywide Documents Access and Management System
ANSI	American National Standards Institute
ASC	available short circuit
AT	auxiliary transformer
BD	bus duct
BDSAT	bus duct between SAT and Zone 1
BDUAT	bus duct between UAT and Zone 1
BOP	balance of plant
CCF	common cause failure
CFD	computational fluid dynamics
CIGRE	Conseil International des Grands Réseaux Electriques, or International Council on Large Electric Systems
CPT	control power transformer
CT	current transformer
DC	direct current
EDG	emergency diesel generator
EDS	electrical distribution system
EPRI	Electric Power Research Institute
ERFBS	electric raceway fire barrier system
ESF	engineered safety features
ESST	emergency station service transformer
FAQ	frequently asked question
FCT	fault clearing time
FDS	Fire Dynamics Simulator
FEDB	EPRI's fire events database

GCB	generator circuit breaker
GE	General Electric
GF	generator fed
GSU	generator step-up transformer
HEAF	high energy arcing fault
HRR	heat release rate
ICS	integrated control system
IEEE	Institute of Electrical and Electronics Engineers
INPO	Institute of Nuclear Power Operations
IOC	instantaneous overcurrent
IPBD	iso-phase bus duct
IRIS	INPO's Industry Reporting and Information System
kA	kilo-ampere
kW	kilowatts
kVA	kilo-volt-ampere
LC	load center
LV	low voltage
LVPCB	low voltage power circuit breakers
LVBD	LV bus duct
MCC	motor control center
MCCB	molded case circuit breaker
MOU	Memorandum of Understanding
MOV	motor-operated valve
MPT	main power transformer
MV	medium voltage
NEA	Nuclear Energy Agency
NEMA	National Electrical Manufacturers Association
NIST	National Institute of Standards and Technology
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
NSBD	non-segregated bus duct
NSP	non-suppression probability

OECD	Organisation for Economic and Cooperative Development
OPEX	operating experience
PCCBB	primary cable compartment bus bar
PDS	protective device/scheme
PRA	probabilistic risk assessment
RAT	reserve auxiliary transformer
RES	Office of Nuclear Regulatory Research
RMS	Root Mean Square
S/NRA/R	Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority
SAT	station auxiliary transformer (commonly referred to for any off-site power transformer)
SBL	supply breaker limited
SCR	silicon-controlled rectifier
SI	International System of Units
SIS	synthetic insulated switchboard
SNL	Sandia National Laboratories
SOE	sequence of events
SONGS	San Onofre Nuclear Generating Station
SPR	sudden pressure relay
SST	station service transformer
ST	station transformer
SUT	start-up transformer
SWGR	switchgear
SWYD	switchyard
TCC	time-current-characteristic
TOC	time overcurrent
TOL	thermal overload
TP	thermoplastic
TS	thermoset
UAT	unit auxiliary transformer
V	volts

VAC	volts in AC
VDC	voltage in DC
WG	Working Group
WGM	Working Group Member
XFMR	transformer
ZOI	zone of influence

1 INTRODUCTION

Fire probabilistic risk assessments (PRAs) model fire hazards that can occur in commercial nuclear power plants (NPPs). High energy arcing faults (HEAFs) are a unique hazard for bus ducts, switchgear, and load centers that are characterized by a substantial energetic arc followed by an ensuing fire. The arc releases energy in the form of heat, vaporized material, and mechanical force. This arc results in a fire that can damage cables and components. At the time EPRI 1011989/NUREG/CR-6850 [1] was published, the phenomenon was known, but the state of knowledge was low for HEAFs in switchgear and load centers. The zone of influence (ZOI), which is the distance in which a HEAF can cause damage or failure of a target, was developed primarily from a single catastrophic event involving a medium-voltage switchgear. NUREG/CR-6850 did not provide a treatment for bus-duct HEAFs, although they were later addressed in FAQ 07-0035, published in NUREG/CR-6850, Supplement 1 [2]. Recent industry operating experience (OPEX), such as the Onagawa event following the Tohoku earthquake, has led to testing by multiple stakeholders investigating the HEAF phenomena.

Although HEAFs are not the most frequently occurring fire events in NPPs, they have the potential to cause extensive damage to adjacent equipment and cables from the electrical explosion or the post-HEAF ensuing fire.

This report provides a methodology for modeling the hazards resulting from HEAFs with a focus on expected durations and likelihood given various electrical distribution system (EDS) alignments. This report also provides updated fire ignition frequencies, split fractions, and non-suppression probabilities for use in fire PRA.

1.1 Brief History of HEAF Research

HEAF events have occurred in both the United States and internationally and have been of interest in fire PRA development since the early 2000s. Significant events include the 2001 event at San Onofre Nuclear Generating Station (SONGS) and the 2011 event at Onagawa. Researchers used the SONGS event as the primary input to develop the ZOI for switchgear and load centers in NUREG/CR-6850, Appendix M. The HEAF event at Onagawa led to full-scale experimental efforts to learn more about the physical phenomena and potential range of collateral damage [3].

At SONGS 3 on February 3, 2001, a bus supply circuit breaker suffered a fault shortly after closing, and a fire started within the breaker cubicle of a medium-voltage switchgear. The fault persisted as the generator coasted down, lasting an additional 4–15 s, even though the differential protection of the unit auxiliary transformer (UAT) quickly detected it. The fire consumed much of the breaker’s nonmetallic parts and caused substantial melting of current carrying components. Five vertical cabinet sections were damaged and required repair or replacement. The damage also included electrical equipment and cables that were burned directly or damaged by the fire [4]. The damage from this event was used primarily to develop the ZOI in the NUREG/CR-6850, Appendix M HEAF model.

Following the 2011 Tohoku earthquake, an arcing fault occurred in the No. 7 and No. 8 sections of the nonemergency 6.9-kV switchgear at the Onagawa nuclear power plant. The arcing fault led to a fire in all ten vertical sections of the switchgear [5]. Control cables for nonemergency equipment directly above the cabinet were affected by the fire. No emergency components and cables in the room were affected [5].

Following the Onagawa HEAF event, the Secretariat of Nuclear Regulation Authority (S/NRA/R) of Japan's Regulatory Standard and Research Department performed a series of experiments. The Office of Nuclear Regulatory Research (RES) from the U.S. Nuclear Regulatory Commission (NRC) was invited to observe and support the testing that occurred between 2013 and 2015. NUREG/IA-0470 documents the results of these tests [3]. One observation from this test series was a greater-than-expected thermal energy release, which is hypothesized to result from oxidation of aluminum bus bars instead of copper bus bars.

From 2014 to 2016, the U.S. NRC-RES, in collaboration with the Nuclear Energy Agency (NEA), the National Institute of Standards and Technology (NIST), and additional groups though the Organisation for Economic Co-operation and Development (OECD), performed 26 full-scale HEAF experiments. One aspect of this test series was to confirm the ZOI in Appendix M of NUREG/CR-6850. The results of this test series are summarized in NRC Information Notice 2017-04 [6] and in NEA/CSNI/R(2017)7 [7]. Although the experiments primarily tested equipment containing copper bus bars, some results from experiments on aluminum bus bars resulted in greater releases of energy than those involving copper. Additionally, these experiments suggested that aluminum byproducts of a HEAF event—primarily aluminum oxide—could be expelled over far greater distances than the ZOI prescribed in NUREG/CR-6850. Given the apparent significance of these observations, a possible generic issue concerning the vulnerability of current-carrying aluminum components subject to HEAFs was initiated in May 2016 [8].

In 2017, U.S. NRC-RES proposed a second phase of testing to supplement the experiments performed between 2014 and 2016 [9]. These tests would focus on three key areas: arc initiation/location, arc current/voltage, and arc duration. In addition to these parameters, directly comparing aluminum versus copper equipment (primarily bus bars) was a key objective of the follow-on testing. Additional testing on load centers was performed in 2019 [10]. For the 480V test, arcs could not be sustained within the main bus bar compartment section. Several attempts performed at 600V also failed. Only one specific and controlled location within the load center main bus bar compartment could sustain an erratic arc at 600V. A combination of free volume, lack of barriers, and magnetic forces propelling the arc to the ends of the bus bars was the primary cause of arc self-extinguishment. This was evidenced by the significant arc erosion observed at the ends of the bus bars, which was not at the location where the shorting wire was placed. One other test successfully demonstrated that an arc could sustain inside the circuit breaker cubicle, a confined space separate from the main bus compartment and representative of the only two load center HEAF OPEX events.

Concurrently, the Electric Power Research Institute (EPRI) performed detailed reviews of the HEAF operating experience, categorized and ranked the electrical distribution system designs vulnerable to generator-fed faults and susceptibility of safety-related buses, and discussed maintenance and testing practices that may reduce the likelihood of a HEAF event. These reviews are documented in three white papers [11,12,13].

Due to the simplicity of the HEAF model in NUREG/CR-6850, target fragilities were not necessary. In 2020, the NRC and Sandia National Laboratories (SNL) conducted fragility testing to investigate the physics and failure modes of cables exposed to a HEAF. These tests subjected thermoset and thermoplastic jacketed cables to high-heat-flux short-duration exposures. RIL 2021-09 documents the results of the testing [14]. A follow-on effort between EPRI and the NRC analyzed the available data and proposed fragility criteria. RIL 2022-01/EPRI 3002023400 documents this effort [15].

In parallel, modeling options for the effects of HEAFs on surrounding equipment were pursued. Several options were evaluated, including directly using the recorded test and operational data, empirical equations, or more detailed computational fluid dynamics/multi-physics models. NIST's Fire Dynamics Simulator (FDS) was ultimately chosen as the modeling tool. Development of FDS to model HEAFs began in 2019 as a proof of concept. Benchmarking against previous testing began in 2020. Validation and the final HEAF runs were performed in 2021 to support the in-person working group meeting. RIL 2022-09/EPRI 3002025123 documents the methodology, validation, and results [16].

The NRC exited the generic issue process in August 2021. The closure memo identified that additional long-term research was necessary to determine the issues' risk significance [17]. In October 2021, the NRC entered regulatory process LIC-504 [18]. Phase 1 of LIC-504 reaffirmed that no immediate safety issue exists. Phase 2 included two reference plants applying the draft methodology. The NRC's LIC-504 quantitative risk assessment from the two references plants and team recommendations are documented in [19]. This report incorporates insights from the in-person walkdowns and PRA analysis.

1.2 Approach

This report documents a methodology and data to model HEAFs in fire PRA. This report combines the conclusions from previous efforts, including categorization and analysis of NPP electrical design elements, HEAF operating experience, small- and full-scale testing, fragility thresholds, and ZOI determination.

The HEAF working group was initially formed in 2018 to support technical input into the NRC's full-scale testing program. Over time, the discussions and meetings shifted from experimentation into efforts supporting the fire PRA development needs. The working group is composed of technical experts in electrical engineering (including NPP electrical design and protection schemes), fire PRA/fire modeling, operating experience, and experimentation. The working group was tasked to review the NPP electrical design elements, available test data, and the FDS HEAF simulation results to update the methods to more realistically estimate HEAF risk at NPPs.

The working group includes members from both the regulator (members from the NRC/national laboratories) and the nuclear power industry (members from EPRI/nuclear power industry). The working group members are as follows:

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The working group developed and iterated on the technical basis for the fault durations and the initial PRA events trees from 2019 to 2020. Once relative consensus was achieved, the major focus shifted to defining fragility criteria and selecting a modeling tool to predict ZOIs. In November 2021, the working group met to review the output from the FDS simulations and to gain consensus on the ZOIs. This report incorporates the conclusions on fragility and ZOI and provides guidance to the PRA analyst on how to model HEAFs in fire PRA.

1.3 Purpose

This report’s purpose is to provide a methodology for modeling HEAFs in fire PRA. This methodology captures the different types of NPP electrical distribution and protection systems, fault locations, and fault durations that may impact the location, frequency, and consequences of a HEAF.

The methodology described in this report provides the following:

- A generic NPP EDS fault-zone map.
- The technical basis for expected fault durations given a fault in a particular zone.
- New ignition-source counting guidance for Bin 16.a (load centers) and Bin 16.b (medium voltage switchgear).
- Updated HEAF ignition frequencies using operating experience data through 2021.
- Updated HEAF manual non-suppression rate using operating experience data through 2021.

- ZOIs for load centers, MV switchgear, and non-segregated bus ducts (ZOI for the iso-phase bus duct remains unchanged from NUREG/CR-6850 Supplement 1). The equipment specific ZOIs account for the enclosure material (for bus ducts only), fault duration, and fault location.
    - Load centers: Eight energetic ZOIs based on bus supply circuit breaker location (end or interior), elevation (lower or upper), and fragility threshold (15 MJ/m^2 or 30 MJ/m^2).
    - MV switchgear: Screening ZOIs and configuration-/design-specific ZOIs are provided. Screening ZOIs should be applied around the entire switchgear bank. When more detail is necessary, configuration-specific ZOIs with split fractions are provided separately for Zone 1 and Zone 2 switchgear. These configuration-specific ZOIs consider power source, fault clearing time (FCT), fault location, and fragility threshold.
    - NSBD: Forty-four energetic ZOIs are provided that consider the power source, FCT, enclosure material, and fragility threshold.
- The characteristics of the post-HEAF thermal fire for switchgear and load centers and the waterfall for NSBDs.

1.4 Outline of Report

This report is organized as follows:

- Section 2 summarizes terms essential to understanding the HEAF model.
- Section 3 provides a detailed review of common plant EDS fault zones. This section also provides the technical basis for the PRA method application with descriptions of the expected arcing fault durations associated with different EDS protection schemes.
- Section 4 reviews and categorizes the United States NPP HEAF operating experience. This section also describes how the EDS functioned during each HEAF event.
- Section 5 documents the data updates to the HEAF ignition frequency bins and the HEAF manual non-suppression rate.
- Section 6 documents the HEAF fragility considerations, summarizes the arc energies, how to determine transformer FCT, and how to model the post-HEAF ensuing fire for switchgear and load centers.
- Section 7 documents the energetic HEAF ZOI for load centers (also referred to as low-voltage switchgear).
- Section 8 documents the energetic HEAF ZOI for medium-voltage switchgear. Screening ZOIs and refinements, such as configuration-specific ZOIs and their corresponding split fractions, are detailed here.
- Section 9 documents the energetic bus duct HEAF ZOI.
- Section 10 summarizes the updated HEAF methodology documented in the preceding sections.

- Section 11 documents the references.
- Appendix A summarizes the United States HEAF events.
- Appendix B provides the basis for the continued disposition of HEAFs in motor control centers.
- Appendix C summarizes the expert panel on HEAF split fractions.
- Appendix D provides the linkage between the FDS ZOI report [16] and the energetic ZOIs used in Sections 7 through 9.
- Appendix E provides the energetic ZOI tables in International System (SI) units.
- Appendix F provides an assessment of target fragility for equipment types not considered in the HEAF target fragility report [15].
- Appendix G provides examples of how to apply the methodology.

2
TERMINOLOGY

Similar to circuit analysis, the detailed treatment of HEAF scenarios relies upon an understanding of electrical engineering concepts, including NPP EDS design and protective features. A list of the common terms essential to understanding the methodology is as follows:

- Arc fault: A non-zero impedance electrical fault requiring an arc with sufficient plasma to initiate and sustain a fault.
- Arc flash: The rapid release of energy (light and heat) due to an arcing fault between a phase conductor and another phase conductor, a neutral conductor, or a ground [20]. This type of fault is often the result of a brief contact by energized conductors with an initial short circuit of relatively low impedance. The impedance increases as the arc is produced and the surrounding air becomes the conductor. For example, if the electrical protective device that serves an individual load (e.g., motor) operates as designed, the fault will typically be limited to a number of cycles rather than a time interval.
  - For the purpose of classifying fire events, damage is contained within the confines of the component of origin. From post-observation of arc flashes, only minor damage and minimal bus bar degradation occur. There is **not** an ensuing fire.
- Arc blast: An arcing fault may burn away the source of the electrical short during the initial flash. If the fault is not interrupted, it may be sustained long enough to create highly conductive plasma from the vaporized source material [20]. This plasma can sustain the arcing fault, allowing greater lengths of copper or aluminum bus bar or wiring materials to vaporize. This results in an explosive volumetric increase of the heated air-plasma mixture around the arc fault path. A conservative estimate for the volume increase resulting from an arcing fault is 40,000 to 1 [20]. This expansion may produce gas pressures that can damage the initiating and immediately adjacent equipment (e.g., adjacent vertical sections in a switchgear lineup), see Appendix E of RIL 2022-09/EPRI 3002025123 [16] for a detailed review of pressure wave effects. Experiencing the pressure effects associated with an arc blast is possible even if electrical protective systems work as designed.
  - For the purpose of classifying events, the damage zone may include the confines of the component of origin, including damage through pressure-rise effects but does **not** result in an ensuing fire.
- Bank: A grouping of adjoining switchgear vertical sections or load centers (see Figure 5-3). A bank includes both the incoming supply (or supplies) and load cubicles.
- Breaker-failure protection – switchyard (per IEEE C37.95-2002 [21]): A breaker-failure protection or stuck-breaker protection scheme is designed to operate if a breaker in the switchyard fails to trip or clear a fault. A typical breaker-failure relaying scheme is initiated by an auxiliary relay associated with each transformer, bus, transmission line, or other schemes that trip the breaker. The breaker-failure initiated relay starts a timer relay (e.g., 62—time-delay stopping or opening relay). A second input is from an instantaneous overcurrent (IOC) fault-detector (50FD, 50BF) relay or a circuit breaker 52a auxiliary contact. The time-delay relay is set to allow time for the breaker to trip correctly (typically three to five cycles) and for

the overcurrent fault detector to reset, plus a margin. If the overcurrent fault-detector relay is still picked up or the 52a contact is still closed when the timer times out, a lockout relay is tripped. The lockout relay in turn trips all breakers adjacent to the failed breaker. Figure 2-1 shows this process. The figure on the left shows the set of switchyard breakers nearest to the fault trip. If one of those breakers were stuck (failed to trip open), then the breaker-failure scheme will trip all of the surrounding breakers, as seen on the right.

Typical time for the breaker-failure scheme to operate is 8 to 12 cycles, to allow the typical three- to five- cycle switchyard breakers the first opportunity to clear the fault.

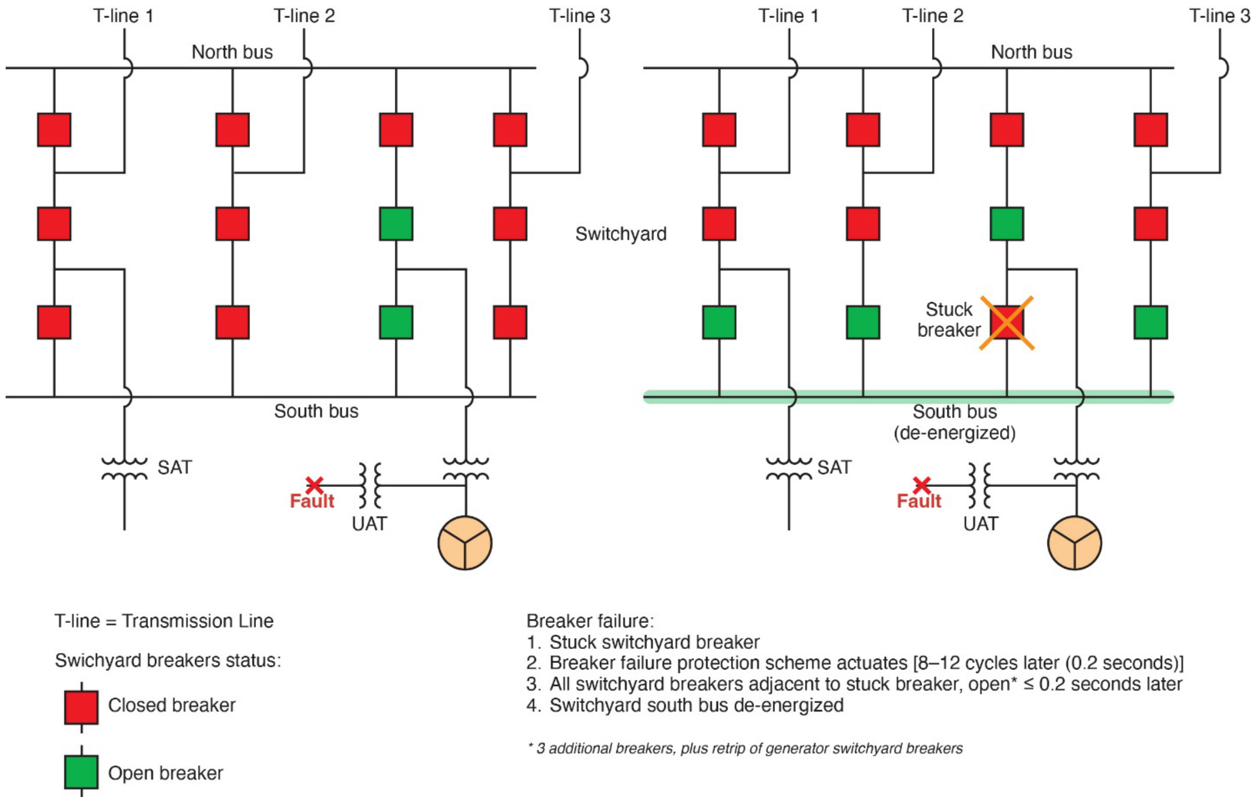


Figure 2-1
Switchyard breaker-failure scheme

- <u>Breaker-failure protection – medium-voltage switchgear</u>: A few NPPs may also have their first downstream (Zone 1) medium-voltage switchgear equipped with breaker-failure protection. This medium voltage protection is distinctly separate from bus differential (87) protection; however, they may complement each other if they both exist. The principle of operation is that if the Zone 1 bus supply circuit breaker fails to open (e.g., to clear a fault on the main bus), the scheme supervisory relay will initiate an auxiliary power transformer lockout (86) and trip the switchyard circuit breakers (SAT) or generator protection/switchyard circuit breakers (UAT) after a short time delay (approximately ≤ 0.2 seconds (≤12 cycles)). This is the basis for the minimum FCT in the Zone 1 MV switchgear with “stuck” bus supply circuit breaker.

An example of such a scheme Is where the bus supply circuit breaker has a primary time overcurrent relay (51) and a backup overcurrent-fault detector relay (50-FD) combined with a timing relay (62). The function of the 50-FD relay is to monitor and allow the primary overcurrent relay to actuate first and open the bus supply circuit breaker. If the bus supply circuit breaker fails to open, the 50-FD relay will not reset and after the timer times out, the protection scheme will initiate an auxiliary power transformer lockout (86). Since circuit breaker interrupting time is typically 3 – 8 cycles, the 62 timer is typically set approximately at 8 to 12 cycles (≤ 0.2 seconds).

- Bus differential (87) protection: Some nuclear power plant medium-voltage switchgear may also be equipped with medium-voltage bus differential (87) protection. The principle of operation is that for any internal switchgear bus fault, the bus differential protection (87) relay will instantaneously send a trip signal to all switchgear bus supply and individual load circuit breakers to isolate the switchgear bus fault from all sources of energy. Should the bus differential scheme fail to operate (e.g., stuck bus supply circuit breaker), the next level upstream (backup) protection must be relied upon to clear the fault.
- Bus-tie: An alternate source of power from another switchgear instead of a transformer. The bus-tie usually consists of one circuit breaker housed in one of the switchgear units. Protection is similar to a bus supply circuit breaker in that it has no instantaneous tripping element to remain coordinated with the bus loads it serves.
- Bus transfer: A manual or automatic power-switching scheme that transfers the MV switchgear supply from one auxiliary power source to another. MV switchgear commonly has at least two bus supply circuit breakers. For switchgear designed with a bus-transfer scheme, the two sources may be the generator-fed UAT and an off-site-powered station auxiliary transformer (SAT). A common bus transfer scheme is the simultaneous fast "dead" bus transfer, where the bus transfer signals are sent to simultaneously: (1) trip open the supply breaker, and (2) close the alternate supply breaker. Because the time to trip a breaker is faster than closing a breaker, a narrow deadband (typically two to three cycles) occurs where there is no power supply to the switchgear. Because motors do not appreciably slow down during the first few cycles, this small deadband is considered acceptable to maintain synchronism of the bus with the alternate supply. Modern systems additionally use high-speed sync-check relays or another form of a supervised bus-transfer scheme. Also, if the failure originated with the switchgear (bus lockout), the bus-lockout signal will prevent the alternate supply breaker from closing in on the faulted bus, resulting in a deenergized bus.
- Class 1E: The U.S. nuclear industry uses this term to specify safety-related equipment according to IEEE Standard 308 [22]. The safety classification of the electric equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal are otherwise essential in preventing significant release of radioactive material to the environment [23].
- Differential protection (ANSI/IEEE Device 87): High-speed electrical protection considered as zone protection because a fault anywhere in the zone of protection (between at least two sets of current transformers [CT]) is cleared instantaneously (within cycles). Differential protection compares currents (and direction of flow) at all terminals of the protected equipment. When current flow becomes unbalanced (e.g., in phase-to-phase or phase-to-ground faults), the differential relays are arranged to cause both the primary and the secondary circuit-switching devices to trip and lock out through a lockout relay (IEEE Device 86). Typical equipment protected by differential protection covered in this report include the following:

  - Transformer primary and secondary (tertiary) switchgear supply breakers.
  - Generator output leads and neutral.
  - Plant or unit differential (unit-connected zone). Zones include the following:
    - Main generator
    - Generator step-up (main power) transformer(s)
    - Generator switchyard breakers
    - Primary side of the unit auxiliary transformer(s)

- Electrical distribution system (EDS): Overall auxiliary power system that includes both safety systems and non-safety systems necessary to support NPP operation.
- Energetic phase: The initial period of a HEAF associated with rapid energy release.
- Ensuing fire: The thermal fire that follows the energetic phase of an arcing fault event.
- Engineered safety features (ESF) transformer: A medium-voltage step down transformer between Zone 1 and Zone 2 medium voltage switchgear (see Figure 3-1). The common voltage transformation is 13.8kV to 4.16kV, although other voltage transformations exist. Transformer designated “ESF” (or similar) are typically dedicated to the safety-related Class 1E buses, but similar (less common) transformations exist for balance of plant (BOP) Zone 1/Zone 2 arrangements (e.g., BOP transformer).
- Generator circuit breaker (GCB): A circuit breaker that is specifically designed and installed between the main generator and transformer (generator step-up and UATs). Connection points are at the 17kV to 25kV iso-phase connections. Under certain fault conditions, the GCB separates the generator from the unit-connected design, which prevents a coasting-down generator from feeding a fault. IEEE Standard C37.013 is the reference standard for GCBs [24].
- Generator-fed fault: The decaying fault energy that the main generator delivers after it has tripped (exciter breaker open). Termination occurs when the generator voltage collapses and the fault extinguishes (approximately 4-15 s based on operating experience and literature).
- Generator step-up transformer (GSU): A transformer specifically used to step up the voltage from a generator (17kV to 25kV) to match the switchyard voltage. The GSU is part of the utility interconnection and is used to export electricity from the generator to the transmission system. The GSU may also be referred to as the main power transformer (MPT).
- HEAF fault zone: HEAF fault zones are defined within the NPP EDS. These fault zones are grouped to identify portions of the EDS with similar ZOI impacts (see Figure 3-1). Because HEAF fault zones are based on location within the EDS and the faulted component, in some cases the HEAF fault zones differ from standard electrical distribution zones of protection.
- High energy arcing fault (HEAF): A fault that results in the rapid release of electrical energy in the form of heat, vaporized metal, and mechanical force. Switchgears, load centers, and bus bars/ducts (440V and above) are subject to this failure mode. Faults of this type are commonly referred to as high energy, energetic, or explosive electrical equipment faults or fires. A HEAF includes the rapid release of energy, over pressurization, and ignition of

localized targets and equipment. HEAFs indicate circuit-protection failure or nonoptimal design resulting in extended-duration arcing fault events.

  - For the purpose of classification, this is an event that damages and breaches the component of origin. The HEAF is accompanied by an ensuing fire for switchgear and load centers.
  - An ensuing fire is not necessary for a bus duct HEAF; however, hot slag from the explosion in a bus duct may cause a fire below (e.g., secondary ignition).

- Instantaneous overcurrent (IOC) relay (ANSI/IEEE Device 50): This relay is common to switchgear discrete-load and cable protection. It is designed for rapid isolation of high energy short-circuit type faults. The IOC relay has no intentional time delay (≤ 0.5 cycles), and the fault isolation time is based primarily on the speed of the circuit breaker (typically three to five cycles).
- Iso-phase bus duct (IPBD): A bus duct where the bus bars for each phase are separately enclosed in their own protective housing. The use of iso-phase bus is generally limited to the bus work connecting the main generator to the main transformer. A HEAF in the IPBD is classified as Bin 16.2.
- Load center: A designation commonly used to describe low-voltage (≤ 1000 VAC) switchgear. A HEAF in a load center is classified as Bin 16.a.
- Load center supply circuit breaker: Low-voltage circuit breakers that supply power from the load center transformer to the low-voltage switchgear (i.e., 480Vac or 600Vac).
- Load circuit breaker: A medium or low-voltage circuit breaker that serves a load such as a: motor load, motor control center (MCC), step-down transformer, another switchgear, or bus-tie.
- Lockout relay (ANSI/IEEE Device 86): A lockout relay is a protection device that can accept multiple inputs and transmit trip signals to one or more circuit breakers to isolate and maintain faulted equipment in a deenergized condition. A lockout relay may be used to deenergize one piece of equipment (e.g., a transformer) or a power lineup in a protected zone (e.g., a generator, transformers, and circuit breakers). An operator must manually reset a lockout relay after the fault has been isolated.
- Low voltage: Voltage ranges from 0-1000 VAC [25].
- Main bus bar: In a switchgear/load center, the current-carrying conductors that connect the high side of the load circuit breakers to the low side of the incoming bus supply circuit breaker(s). When a switchgear supply breaker is closed, it energizes the main bus bars. All load circuit breakers receive their power from the main bus bars.
- Medium-voltage (MV): Voltage ranges from over 1000 VAC to 35,000 VAC [25].
- Non-segregated bus duct (NSBD): A three-phase electrical bus in which all phase bus bars are in one common metal enclosure with no barriers between phases. An NSBD is modular, and when used in an EDS, it may consist of many segmented runs, including extensions and transitions (e.g., tees, vertical to horizontal, 90° turns). Straight horizontal sections approaching 8 ft (2.4 m) and transition points are typically bolted. Note: Not all transitions are bolted; some may have bends or are welded. A HEAF in this bus work is classified as either Bin 16.1-1 or Bin 16.1-2, depending on the location within the EDS.

- Non-segmented bus: A continuous bus (typically enclosed like an NSBD) where the run is sufficiently short that no multiple bus sections have to be connected and bolted. Non-segmented bus is typically short runs of bus (typically ≤8 ft [2.5 m]) between switchgear, from transformer to switchgear, and so on where the only bolted connections are the origination and termination ends of the non-segmented bus (e.g., from a transformer to the switchgear). Typically, non-segmented buses in NPPs are of the non-segregated design, but not all NSBDs are non-segmented: NSBD refers to the type of distribution bus construction, while non-segmented bus refers to HEAF PRA terminology (such as counting transition points for frequency apportionment). Because of these distinctions, the terms non-segregated bus and non-segmented bus are not necessarily interchangeable.
- Power circuit breaker: A circuit breaker is a mechanical device that automatically interrupts the electrical circuit from either an overload condition or a short circuit (fault). The automatic operation of power circuit breakers relies on relays with current sensors and trip logic to operate the circuit breaker trip coil. The speed of circuit breaker interruption is commensurate with protecting the electrical rating of the load, cable, circuit breaker, and switchgear. After a fault is cleared, the circuit breaker can be closed to repower the circuit.
- Station auxiliary transformer (SAT): Also referred to as a station transformer (ST), station service transformer (SST), startup transformer (SUT), or reserve auxiliary transformer (RAT). This transformer steps down switchyard off-site power to the voltage levels used by the plant's EDS. It may feed an intermediate MV ring bus with an additional transformer. The SAT is not permanently part of the unit-connected design but is typically part of the bus transfer scheme associated with the UAT. The SAT might be a two-winding or three-winding transformer (with secondary and tertiary windings). Some NPPs permanently power Class 1E buses from a pair of SATs with no connection to the unit UATs.
- Switchgear: MV (> 1000 VAC) switching equipment. A HEAF in switchgear is classified as Bin 16.b.
- Switchgear bus primary cable compartment bus bar (PCCBB) or riser bar: Switchgear manufacturers frequently use these terms to refer to the switchgear bus work that connects either the circuit breaker to the load (motor or transformer) or the supply (UAT or SAT) to the circuit breaker. Generally, they are contained in the rear compartment of each individual switchgear vertical section.
- Switchyard (SWYD): Utility interconnection for the plant. An outdoor area away from the generating station that contains the high-voltage circuit breakers, transformers, circuit switchers, disconnects, and bus work as well as a dedicated control house with metering, control, and protective relaying.
- Switchyard breaker: High-voltage circuit breaker located in the switchyard. These circuit breakers perform the following:
    - Connect incoming utility transmission lines
    - Connect the main generator to the utility transmission lines
    - Serve as auxiliary transformers for powering the plant EDS for startup and off-site power purposes
- Synchronizing check relay (ANSI/IEEE Device 25): Also referred to as sync check relay. This relay allows closure of the alternate power supply circuit breaker as long as the residual bus voltage and frequency are within 1.33 V/Hz of parallel power supplies, per ANSI

C50.41-2000 [26]. If voltage and/or frequency are greater than 1.33 V/Hz, the sync check relay will block the close signal to the circuit breaker. This is to limit the possibility of damaging the motor or the driven equipment.

- Target fragility: The condition when targets external to the HEAF are damaged.
- Time overcurrent (TOC) relay (ANSI/IEEE Device 51): This relay is widely used for auxiliary power system equipment protection from overloads, high-impedance faults, and backup protection for a selectively coordinated EDS. The TOC relay uses an inverse time-delay element: the higher the current, the faster the relay trips the circuit breaker(s) to isolate the fault. It is used for discrete loads and switchgear supply breakers. When used for transformers, it may be applied as a TOC relay in the wye ground circuit as a 51N or 51G.
- Transformer (XFMR): A passive electrical device used to step down voltage in an EDS with fewer power and voltage requirements (e.g., load centers, small motors). Note: A transformer can be used to step up voltage (such as at a generator) to connect with the high-voltage switchyard.
- Unit-connected design: Refers to the operational configuration of the: (1) main generator, (2) GSU transformer, (3) generator output switchyard breakers, (4) UAT, and (5) associated buses and connections. In the unit-connected design, there is no generator circuit breaker and thus no backup circuit breaker(s) to isolate a generator-fed fault if the UAT secondary side breaker fails to open or is slow to open for a fault between the generator and GSU transformer or anywhere in the UAT to the first-out secondary or tertiary switchgear bus supply circuit breakers. The associated bus and connections include the following:
    - An iso-phase bus that connects the main generator to the low side of the GSU transformer and high side of the UAT.
    - A non-segregated bus that typically connects the UAT low-voltage windings to the first-out switchgear bus supply circuit breakers.
    - Higher-voltage connections between the high side of the GSU transformer to the generator output switchyard breakers.
- Unit auxiliary transformer (UAT): This transformer may also be referred to as the auxiliary transformer (AT). The transformer steps down voltage from the main generator to the plant auxiliary power EDS during power operation. Unless a generator circuit breaker is installed, the UAT is typically deenergized during shutdown (but may be used in maintenance backfeed operation in limited cases). A unit might employ one, two, or three UATs per main generator. Not all NPPs have an UAT. The UAT is part of the unit-connected design, with the primary side integrated with the iso-phase bus duct system. The UAT can be a two-winding or three-winding transformer (with secondary and tertiary windings). Some NPPs power Class 1E buses from the UAT during power operation.
- Zone of influence (ZOI): The space surrounding an ignition source where intervening combustibles and targets may be adversely affected by a fire or explosion (e.g., HEAF). For HEAFs, the ZOI has two components: an initial energetic phase followed by a post-HEAF ensuing fire for switchgear and load centers. Refer to Section 6 for a more detailed description of the energetic and ensuing fire ZOIs.

3
FAULT ZONES AND DURATIONS

This section discusses the concept of fault zones, transformer electrical protection, and the technical basis for the fault durations of switchgear, load centers, and bus ducts.

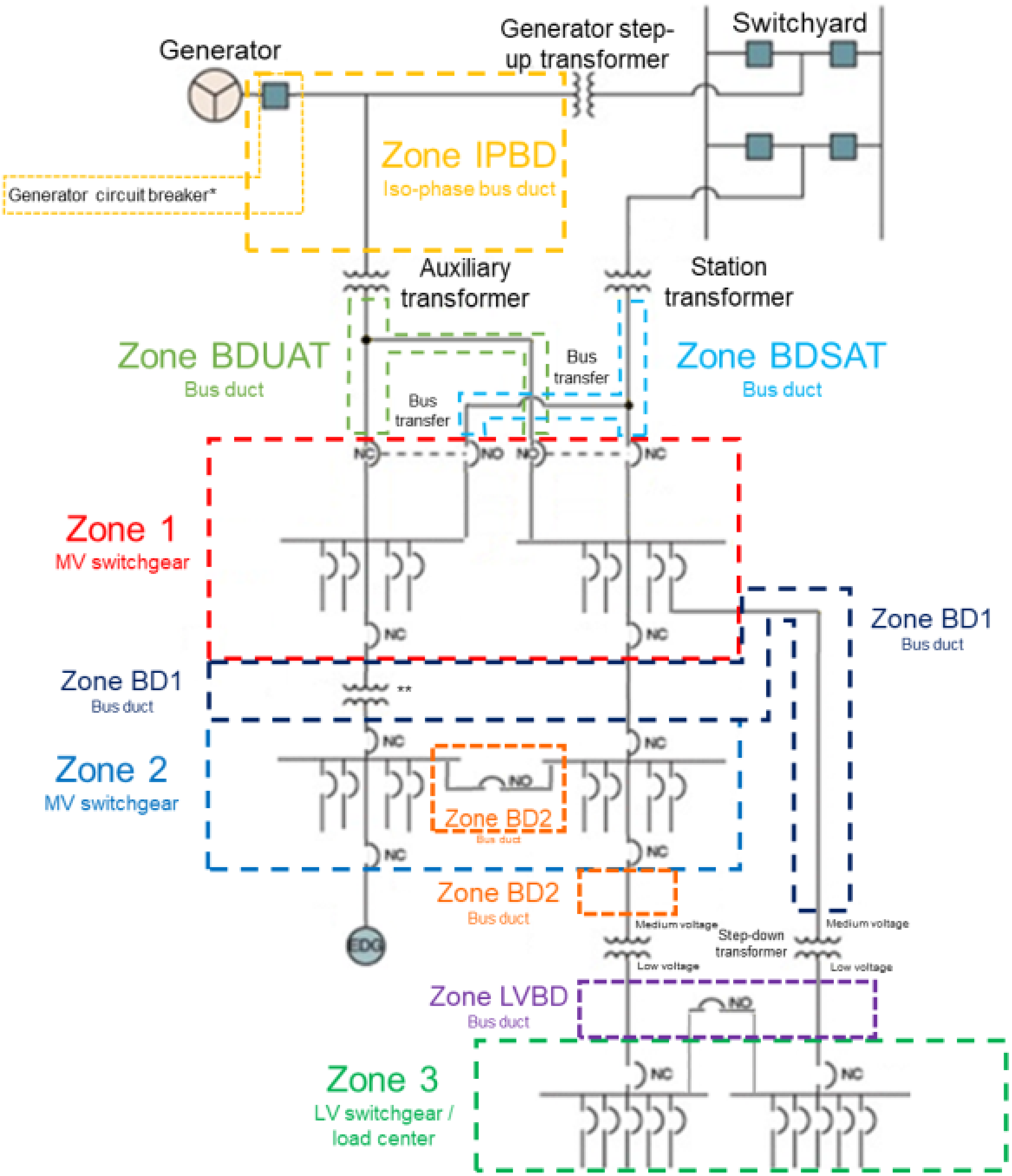
3.1 HEAF Zones

Fault zones are developed for parts of the EDS with similar potential fault durations. Figure 3-1 shows fault zones for a simplified arrangement of nuclear power plant EDS, which expands on the concepts presented in EPRI 3002015992 [12].

Starting in Section 3.3, each fault zone is reviewed in detail to determine the range of potential fault durations. These durations are determined based on the common protection elements available in each zone and how they operate. Fault progression trees summarize the potential fault durations for equipment located within that zone. For completeness, the generic fault progression trees depict the range of end states and include fault durations that lead to both HEAF and non-HEAF outcomes. Because the fire ignition frequency only considers events classified as HEAFs, the non-HEAF end states are not considered in the hazard modeling/ZOI development documented in Sections 7 through 9.

Table 3-1
HEAF zones

HEAF zone	Portion of the EDS	Ignition source bin	Equipment
IPBD	Iso-phase bus duct	16.2	Iso-phase bus duct connecting the station generator to the UAT and GSU transformer.
BDUAT	Bus duct between UAT and Zone 1	16.1-1	NSBD that connects the UAT secondary (tertiary) windings to the first downstream switchgear.
BDSAT	Bus duct between SAT and Zone 1	16.1-1	NSBD that connects the SAT secondary (tertiary) windings to the first downstream switchgear. BDSAT may also be used to represent any off-site power circuit that supports power production from dedicated-system service transformers not shown in the simplified NPP EDS in Figure 3-1. An example is a dedicated off-site power for cooling tower operation.
1	MV switchgear	16.b	First switchgear downstream of the UAT or SAT. This may also be referred to as an “intermediate bus” if it feeds another downstream MV bus.
2	MV switchgear	16.b	Second switchgear bus downstream of the UAT or SAT (via an intermediate bus).
3	Load center	16.a	Load centers or LV switchgear (480 to 1000 VAC).
BD1	MV bus duct between Zone 1 and Zone 2 and Zone 1 and Zone 3	16.1-2	Region of the MV NSBD between the first MV switchgear and either of the following: • The high side of the second MV switchgear bus supply breaker (bus duct from Zone 1 to Zone 2) • The high side of the load center transformer (bus duct from Zone 1 to Zone 3)
BD2	MV bus duct between Zone 2 and Zone 3 and Zone 2 to Zone 2	16.1-2	Region of the MV NSBD between the second MV switchgear and either of the following: • The high side of the load center transformer • Another Zone 2 switchgear (bus-tie)
LVBD	LV bus duct between Zone 1 or Zone 2 to Zone 3, or Zone 3 to Zone 3	16.1-2	Region of the LV NSBD between the Zone 1 step-down transformer and the load center (Zone 1 or Zone 2 to Zone 3) or between load centers (Zone 3 to Zone 3).



*Generator circuit breaker defined in Section 2 and discussed in Section 5.3.1
** ESF stepdown transformer may exist between Zone 1 and Zone 2 switchgear

Figure 3-1
HEAF zones for a simplified NPP EDS

3.2 Transformer Electrical Protection

Transformer electrical protection has a direct bearing on the outcome of energy released during a fault for downstream switchgear and the NSBDs. This is due to the FCT setting of the fault-sensing relay and the circuit breaker opening time. For this methodology, two types of transformer protection schemes are considered. The first is termed “primary protection” (instantaneous), and the second is termed “backup” (time-delayed).

Primary protection uses a protection scheme termed “differential” and is annotated by the relay 87 symbol on electrical drawings. Although primary protection is instantaneous, it has a clearly demarcated boundary of protection called a “zone,” shown as the red-shaded portion of Figure 3-2. A primary protection scheme detects an internal transformer or first-out (Zone 1) switchgear bus supply circuit breaker fault by detecting unbalanced current flow (a fault). It accomplishes this task by monitoring all three phases of the primary, secondary, and tertiary (if applicable) currents. Any imbalance in these currents is considered an internal fault within the protection zone, and all associated circuit breakers are tripped, locking out the transformer and isolating the fault. The circuit breakers tripped are typically the switchyard and the first-out (Zone 1) switchgear bus supply circuit breakers. With proper breaker operation, faults within this differential protection zone are detected and isolated sufficiently fast enough to prevent escalation to HEAF-type consequences. Only faults located within the differential zone of protection can be immediately isolated. Faults outside the differential protection zone are not immediately detectable and require a backup (or secondary) overcurrent protection scheme to detect and isolate the fault. When a fault occurs outside the differential zone, or for faults detected by differential but with a stuck switchgear bus supply circuit breaker, backup protection is relied on to clear the fault.

Backup (secondary) protection typically refers to the transformer primary side TOC relay, annotated by the relay symbol 51 on electrical drawings[1]. This relay works on the principle of limiting through-fault current to prevent transformer damage, as opposed to instantaneously interrupting a fault (e.g., IEEE Std C57.109 [27]). This protection scheme can detect faults outside the differential zone of protection. However, it is intentionally time-delayed, allowing the lower-level protection relays the opportunity to clear the fault first (selective coordination). Instead of detecting unbalanced currents, the 51 relay setting is a combination of current magnitude and duration. The general principle is that the higher the fault current, the faster the relay operates to open the circuit breaker, isolating the fault current. It should be noted that this is not a linear relationship and that inverse TOC relays are used with various characteristics. As a result, the FCT becomes an important parameter in the total energy release and ultimately the ZOI definition.

Transformer backup protection is required when a Zone 1 switchgear bus supply circuit breaker fails to clear a downstream fault (referred to as a “stuck” breaker). Because the fault is outside the transformer differential zone of protection, the fault can only be cleared by the transformer backup protection. Due to the industry variability in FCTs, the transformer protection TOC clearing times are a differentiating factor in the size of the energetic HEAF ZOI. For guidance on how to determine transformer backup protection clearing times, see Section 6.4.

[1] Although the transformer primary-side TOC (51) relay is most commonly used, some stations may have alternate backup protection. Examples include 51G (ground overcurrent), 51N (neutral overcurrent), and 59G (ground overcurrent), all of which provide time-delayed protection for sustained phase-to-ground (neutral) transformer faults.

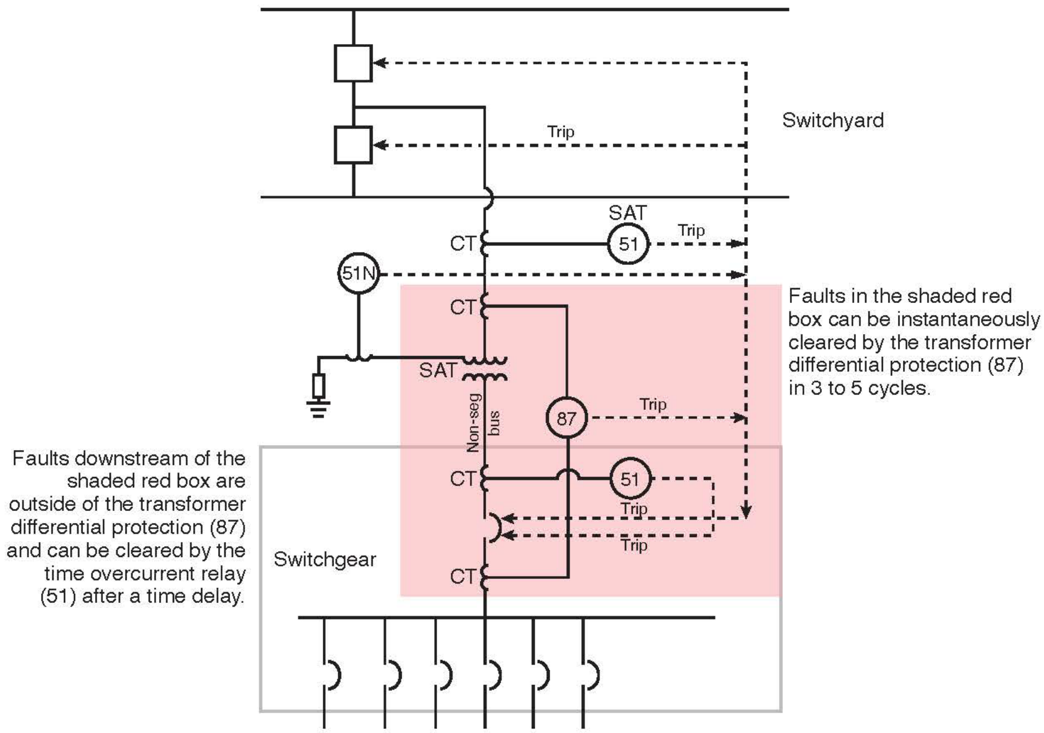


Figure 3-2
Example of SAT instantaneous protection zone (shaded in red)

3.2.1 Unit Auxiliary Transformer

For UAT protection, both differential and TOC relays perform the same function when the trip setpoint is reached. In both cases, a trip signal is typically sent to a lockout 86 relay, which in turn performs the following:

- Trips the main generator
- Opens the exciter field circuit breaker
- Opens the switchyard circuit breakers
- Opens the UAT secondary and tertiary (if applicable) circuit breakers
- Opens the generator circuit breaker (if used)

If the fault is anywhere between the switchgear bus supply circuit breaker differential (87) current transformer (CT) and the load side of the bus supply circuit breaker connection stabs, it is within the transformer differential protection zone (87) and will immediately trip the Zone 1 bus supply circuit breaker, immediately clearing the fault (a HEAF does not occur). If the Zone 1 switchgear bus supply circuit breaker fails to open and clear the downstream fault (or is the cause of the fault), the main generator cannot be isolated and will continue to feed the fault until the generator field voltage collapses and the arc is extinguished, resulting in a HEAF that can last up to 15 s. Similarly, for faults originating on NSBD between the UAT and the Zone 1 switchgear (where there is no circuit breaker that can isolate the NSBD from the main generator), a fault will persist as it is fed by the coast-down energy of the main generator until the field voltage collapses. These last two scenarios are termed “generator-fed faults.” Generator-fed faults can be prevented and immediately isolated if a generator circuit breaker (GCB) exists between the main generator and the primary side of the UAT and as long as the fault is within the differential zone of protection.

For a fault outside the differential zone of protection, there is a specified time delay until the TOC (51) relay setpoint is reached before tripping the main generator and switchyard circuit breakers via the 86 lockout. This time period is referred to as "stiff" because there is no appreciable decay component to the fault and the duration generally falls within the range of 0.2-5 s (see Figure 3-3 for the UAT FCTs for U.S. NPPs). For EDS switchgear alignments fed by the generator and with a stuck Zone 1 switchgear bus supply circuit breaker, the generator will continue to feed the fault until the generator field collapses, resulting in a two-stage fault (i.e., stiff followed by a decaying generator-fed fault). These types of faults can last up to 20 s (5 s stiff plus an additional 15 s generator-fed fault).

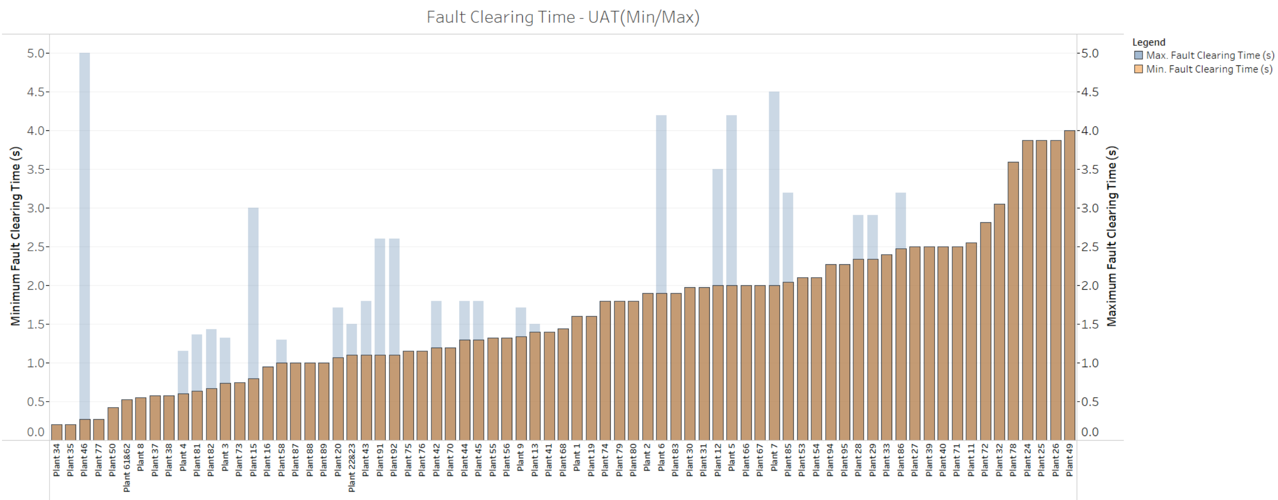


Figure 3-3
UAT TOC FCTs

Faults on switchgear or NSBD fed directly from the UAT can have several outcomes, depending on fault location (within the differential protection zone or reliant on backup TOC protection) and breaker operation. The following summarizes the most common outcomes:

- A fault detected within the differential protection zone (87) in the NSBD between the UAT and Zone 1 MV switchgear results in a generator-fed fault because there is no circuit breaker to isolate the generator from the faulted NSBD. This fault duration can be up to 15 s per operating experience.
    - In the operating experience, an event occurred where an NSBD phase-to-phase fault was immediately detected by differential protection (87), locking out the main generator, but still resulted in a 15 s generator-fed HEAF.
- A fault detected between the switchgear bus supply circuit breaker differential (87) CT and the load side of the bus supply circuit breaker connection stabs is within the transformer differential protection zone (87), and the differential protection will immediately trip the Zone 1 bus supply circuit breaker, immediately clearing the fault and preventing a HEAF.
    - Example: A fault is located on the Zone 1 bus supply circuit breaker load side connection stabs. The fault is detected by the differential protection (87) relay, which

immediately trips the Zone 1 bus supply circuit breaker, isolating the load side primary disconnect fault from the UAT.

- A fault is detected within the differential protection zone (87) with stuck or failed Zone 1 bus supply circuit breaker (the fault occurs at the circuit breaker or upstream of the supply breaker). In this case, the stuck or failed Zone 1 bus supply circuit breaker is not able to clear the fault. The UAT protection (87 differential and 86 lockout) is relied on to trip the main generator. The residual energy from the generator continues to feed the fault until the voltage decays (generator-fed fault). This fault duration can be up to 15 s.
  - Example: FEDB 112 is one similar case where the fault originated within the 87 differential protection zone with a stuck Zone 1 switchgear bus supply circuit breaker. The UAT and main generator differential protection system immediately actuated and the 86 lockout tripped the switchyard circuit breakers. The 86 lockout also sent a trip signal to the switchgear bus supply circuit breaker; however, because the circuit breaker had already failed (stuck closed) because of high resistance of the line-side circuit breaker connection stabs, the circuit breaker failed to open and the main generator continued to feed the fault until the field voltage collapsed.
- For a fault detected outside the zone of differential protection (87), with a stuck or failed Zone 1 bus supply circuit breaker, the UAT TOC protection (51) is relied upon to clear the fault. A time delay occurs before the TOC setpoint is reached. From a survey of U.S. NPPs, this range is between 0.2 and 5 s (see Figure 3-3). Once this setpoint is reached, the UAT protection (86 lockout) is relied upon to trip the main generator and associated circuit breakers. The residual energy from the generator continues to feed the fault until the voltage decays (generator-fed fault). This fault duration has two components: the TOC delay and the 15 s generator-fed fault.
  - Example: No identical events occurred in the operating experience. However, in FEDB 51291, the total fault duration consisted of a stiff-fault current followed by a generator-fed fault. The fault originated within the NSBD downstream of the UAT; however, because of the UAT (187 relay) differential trip leads isolated from the trip circuit, upstream (backup) protection was required to clear the fault. The sequence of events (SOE) recorder showed that it took approximately 6 s for the backup (387 relay) unit differential protection to detect the fault before tripping the generator and switchyard breakers. By that time, an excessive UAT through-fault current duration of approximately 6 s resulted in UAT failure (and subsequent fire), and the tripped generator continued to feed the fault at the UAT for an unspecified time until the generator field voltage collapsed.

3.2.2 Station Auxiliary Transformer

For the SAT protection, both differential (primary) and TOC (backup) relays perform the same function when the trip setpoint is reached. The backup protection is primarily intended to protect the SAT from excessive through-fault current durations and at the same time be selectively coordinated with the downstream Zone 1 MV switchgear.

In both cases, a trip signal is typically sent to a lockout 86 relay, which in turn does the following:

- Opens the switchyard circuit breakers
- Opens SAT secondary and tertiary (if applicable) circuit breakers

Unlike the UAT, there is no post-trip generator-fed fault to contend with. Therefore, with a differential trip, the fault is isolated in cycles (the fault does not persist long enough to reach the severity of a HEAF). If the fault is outside the differential zone of protection and requires clearing by the TOC (51) relay, the fault duration is dictated by the FCT (the time delay associated with the protective relay setpoint). The FCT is an input used to determine the ZOI for SAT-powered switchgear and NSBDs. Figure 3-4 shows the range of SAT backup faults clearing times for U.S. NPPs.

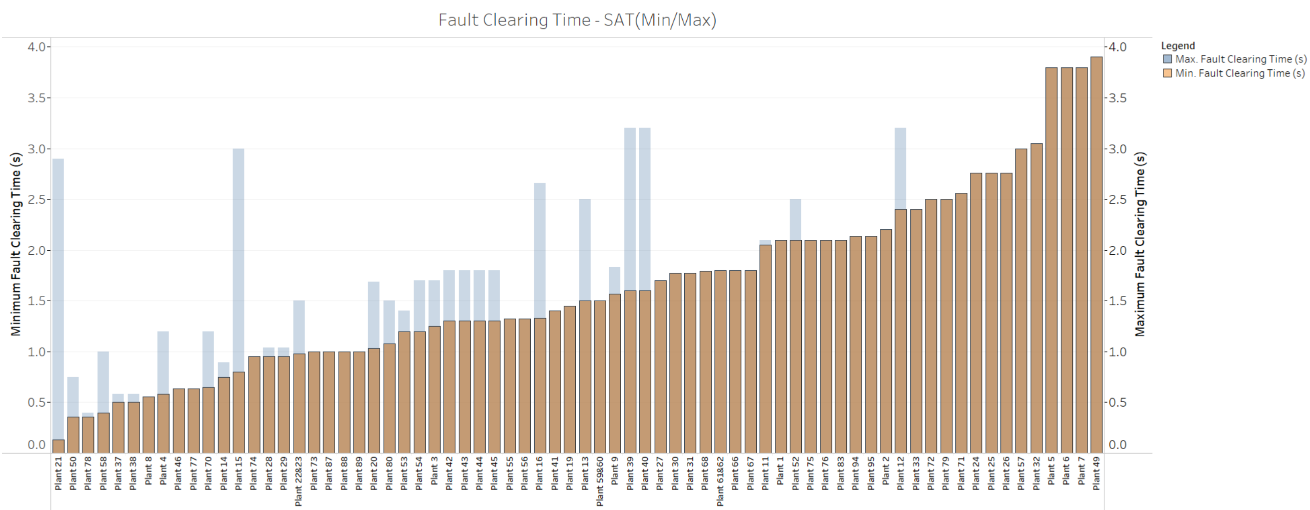


Figure 3-4
SAT TOC FCTs

Faults fed directly from the SAT can have several outcomes, depending on the fault location (within the differential protection zone or reliant on backup TOC protection) and circuit breaker operation. The following summarizes the most common outcomes:

- A fault detected within the differential protection zone (87) in the NSBD between the SAT and Zone 1 MV switchgear is immediately isolated when the SAT primary-side switchgear circuit breakers open.
    - FEDB 10584 was a NSBD fault fed by an off-site power transformer that cleared quickly and had only localized damage.

- A fault detected between the switchgear bus supply circuit breaker differential (87) CT and the load side of the bus supply circuit breaker connection stabs is still within the transformer differential protection zone (87), and the differential protection will immediately trip the Zone 1 bus supply circuit breaker, immediately clearing the fault and preventing a HEAF.
    - Example: A fault is located on the Zone 1 bus supply circuit breaker load-side primary disconnect assembly (connection stab). The fault is detected by the differential protection (87) relay, which immediately trips the Zone 1 bus supply circuit breaker, isolating the load-side primary disconnect fault from the SAT.
- A fault detected within the differential protection zone (87) on the load side of the switchgear supply circuit breaker with proper circuit breaker operation results in immediate fault clearing (no HEAF).
    - Example: A fault occurs at the Zone 1 bus supply circuit breaker load side primary disconnects (or just upstream of the differential CT). This fault is detected by the 87 relay, which trips the Zone 1 bus supply circuit breaker and isolates the fault.
- A fault is detected within the differential protection zone (87) with a stuck or failed Zone 1 bus supply circuit breaker. In this case, the stuck or failed Zone 1 bus supply circuit breaker is not able to clear the fault. The SAT backup protection (51 TOC relay and the 86 lockout) is relied on to trip the switchyard circuit breakers to clear the fault.
    - Example: Fault locations are very specific for this kind of fault. Because the SAT differential protection CTs cover only the Zone 1 MV switchgear bus supply circuit breaker up to the load disconnect stabs, the only credible postulated faults are at the circuit breaker primary disconnect stabs or that the circuit breaker fails to open on demand (i.e., stuck breaker). In these cases, the upstream SAT transformer backup protection (51 TOC relay and 86 lockout) trips the SAT after a predetermined time delay (known as the FCT).
- For a fault detected outside the differential protection zone (87), the SAT backup protection (51 TOC relay and 86 lockout) is relied upon to clear the fault, similar to a stuck Zone 1 MV switchgear bus supply circuit breaker. A preset time delay occurs before the TOC (51) relay setpoint is reached. According to a survey of U.S NPPs, this range is between 0.2 and 5 s. Once this setpoint is reached, the SAT protection (86 lockout) is relied on to open the switchyard circuit breakers to clear the fault.
    - The result is similar to a stuck Zone 1 MV switchgear bus supply circuit breaker because the same SAT TOC (51) relay is relied on to clear the fault.

3.2.3 Minimum and Maximum Fault Clearing Times for Switchgear Bus Supply Circuit Breakers

The MV switchgear bus supply circuit breaker provides a switchable connection between a power source (e.g., auxiliary power transformer) and the switchgear's main bus bars that distribute power to the switchgear loads. In many cases, more than one switchgear bus supply circuit breaker may allow connection to an alternate power source if the preferred power source is unavailable. Switchgear bus supply circuit breakers are also referred to as feeder breakers.

Four nuclear power plant protection and coordination calculations were reviewed to determine the minimum and maximum FCTs for MV switchgear (Zone 1 and Zone 2) bus supply circuit breakers. If a second breaker is located in Zone 1 to interrupt a Zone 2 fault, it is referred to as the "second breaker in two-breaker designs." This Zone 1 second breaker in two-breaker designs primarily benefits the downstream Zone 2 bus (if it has active protection) by providing an additional layer of protection. For Zone 1 faults, this serves as a load branch circuit breaker. If the protection circuitry is disabled (e.g., maintenance switch), it does not have an FCT and is not credited. In several cases, the Zone 2 breaker and Zone 1 second breaker have similar settings.

To determine the FCT ranges, the following steps were performed:

1. Use station one-line diagrams and/or calculation one-lines to determine the time-current-characteristic (TCC) curves for Zone 1, Zone 2, and the Zone 1 second breaker in two-breaker designs (if applicable).
2. Obtain the available short circuit (ASC) current (either from the calculation or derived from the primary transformer impedance). This is the maximum fault current magnitude given a zero-impedance (bolted) fault and is typically dominated by the upstream transformer impedance.
3. Determine the FCT by finding the point where the arcing fault current intersects the 51- relay TOC curve. Record the FCT along with the arcing fault current magnitude and the associated TCC curve.

Table 3-2 summarizes the minimum and maximum FCTs at four NPPs.

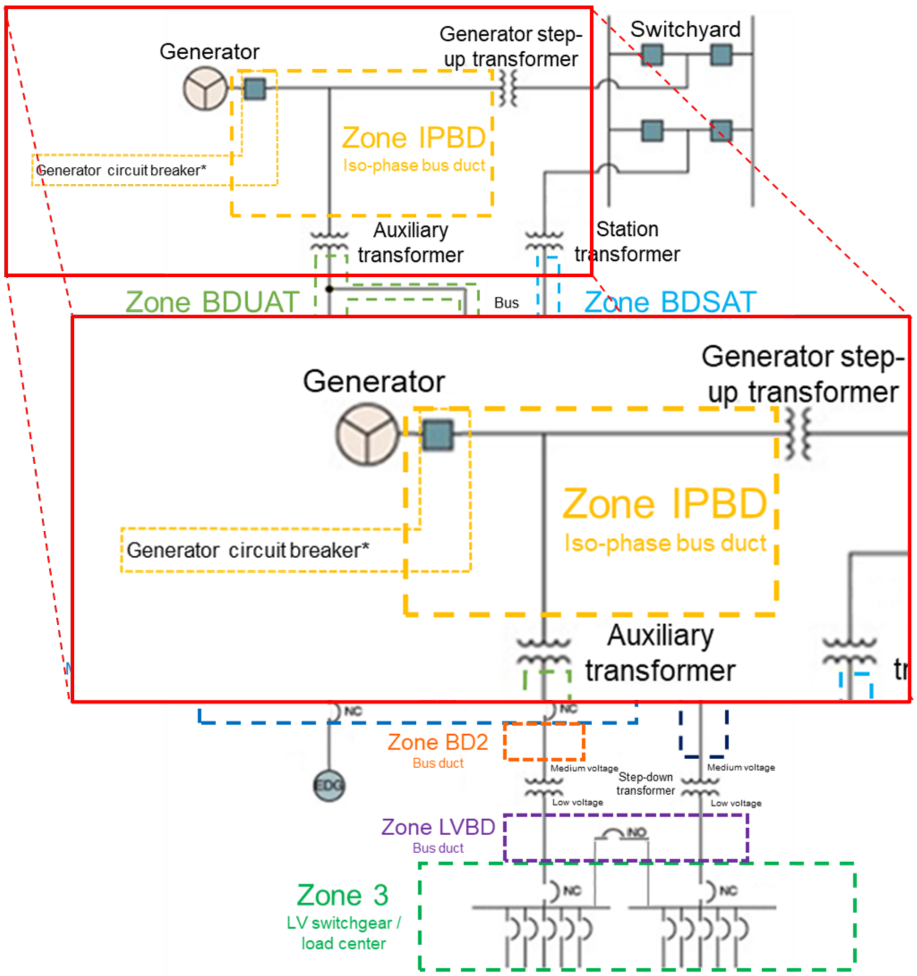
Table 3-2
Minimum and maximum FCTs for MV switchgear

Zone	Minimum FCT (seconds)	Maximum FCT (seconds)
1 (bus supply circuit breaker)	0.8	4.1^
1 (second breaker in two-breaker designs)	0.41	1.8
2 (bus supply circuit breaker)	0.25	2.0^

^The FCTs in Sections 8 and 9 use 4 s (Zone 1) and 2 s (Zone 2), which are the maximum FCTs rounded to the nearest whole number.

3.3 Zone IPBD Faults

Zone IPBD consists of the IPBD that connects the main generator to the low-voltage side of the GSU and the primary side of the UAT.



*Generator circuit breaker is defined in Section 2 and discussed in Section 5.3.1

Figure 3-5
Zone IPBD: Iso-phase bus duct (Bin 16.2)

The unit-connected design has multiple layers of protection, including overlapping differential protection zones (87) that activate the generator protection system (lockout (86), tripping the generator, transformers, and switchyard breakers. The importance of the differential protection system is that it actuates within a few cycles following a fault. The various differential protection schemes include the following[2]:

- Generator differential protection (87G) (see note 1)
- GSU (main) transformer differential protection (87MT)

[2] Legend: G = generator, MT = main transformer, U = unit, GT = generator/transformer, 387 = multiple interlocked differential schemes.

- UAT differential protection (87AT)
- Plant or unit differential protection (87U, 87GT, 387) (see note 1)

The entire IPBD is within and protected by the zone of the plant (or unit) differential protection scheme. The IPBD system includes connections to the main generator, GSU, and UAT (each with their own differential protection zones). Therefore, the plant (or unit) differential can be considered a backup in many cases. However, it is the basis for differential protection during a fault in Zone IPBD.

Note 1: Plant or unit differential protection zone encompasses (i.e., wrap-around):

- Main generator (including neutral)
- GSU (main) transformer
- UAT primary-side iso-phase bus
- Generator switchyard breakers
- Generator circuit breaker (if one exists)

3.3.1 Zone IPBD Protection Overview and Iso-Phase Bus Rating

For a fault in Zone IPBD, the following protection elements are credited to limit the fault duration:

- Plant or unit (overall) differential protection (87—instantaneous): See Section 3.3 and differential protection definition in Section 2.
- Lockout relay (86): See definition in Section 2.
- Breaker-failure protection: See definition in Section 2.
- Iso-phase bus short-time withstand current rating (duration): IEEE Standard C37.23-2003 [28], Section 5.4.3, states that the rated short-time withstand current of all isolated-phase bus is the average root mean square (rms) symmetrical current that it can carry for 1 s.

3.3.2 Zone IPBD Fault Progression

Potential fault scenarios in Zone IPBD (unit-connected design) include the following:

Fault within the unit-connected design (Zone IPBD) is expected to be detected by the plant or unit differential protection (e.g., 87U, 87GT, or 387) and result in a generator protection lockout (86), tripping the main generator, GSU transformer, and switchyard breakers.

- The two generator switchyard breakers are expected to clear in several cycles, preventing the grid from back-feeding the IPBD fault (through the GSU transformer).
    - Note: Even if one of the generator switchyard breakers were to fail stuck, the breaker-failure scheme (50BF, 50FD) would clear the adjacent switchyard breakers, typically within 0.2 s (12 cycles). See Figure 2-1.
- Even though the generator protection lockout (86) will also trip the generator exciter breaker, the generator residual energy will continue to feed the fault until the decaying generator voltage collapses in approximately 4–15 s because of the load imposed by the residual arc energy.

Fault within the unit-connected design (Zone IPBD) with failed differential protection (87) or with the differential protection deactivated (i.e., logic inactive) would result in a delayed clearing and subsequent generator-fed fault. Backup protection is relied on to clear the fault and could be any of the following[3]:

- Generator neutral overvoltage (59N) or generator neutral ground (64G)
- Generator IOC relay (50G)
- Generator distance relay (21)
- Generator negative sequence relay (46)
- Main transformer neutral TOC (51G)
- Main transformer TOC relay (51)

The aggregate of the protection schemes anywhere in Zone IPBD would initiate the generator protection scheme lockout (86), tripping the generator and switchyard breakers typically in under 3 s [21]. However, this would delay the start of the generator-fed fault and the total duration could reach 7-18 s (3 s plus 4-15 s for the generator-fed fault).

Potential fault scenarios in Zone IPBD with GCBs include:

A fault within the IPBD region (Zone IPBD) with a GCB is expected to be detected by the differential protection (87), tripping the GCB, generator, and generator switchyard circuit breakers in several cycles. If the IPBD fault is between the generator and the GCB, the GCB is still expected to open within several cycles; however, the generator will continue to feed that part of the IPBD until the field voltage collapses, extinguishing the fault.

A fault within the IPBD region (Zone IPBD) with a GCB and a stuck switchyard circuit breaker is expected to be detected by the differential protection (87), tripping the GCB, generator, and switchyard generator circuit breakers in several cycles. However, if one of the generator switchyard breakers fails to open (i.e., is stuck) then the breaker-failure scheme (50FD, 50BF) will actuate within 0.2 s (within 12 cycles) and open all adjacent switchyard breakers around the stuck breaker (see the breaker-failure protection definition in Section 2 and Figure 2-1). The total time is 0.2 s.

A fault within the IPBD region (Zone IPBD) with a GCB and failed differential protection. It is assumed that one of the other generator protection scheme elements will detect the fault, such as the negative sequence relay (46) and/or generator backup relay (21). Per IEEE Standard C57.109, this backup relaying is generally less sensitive than differential relaying and has some time delay associated with it. Per IEEE Standard C37.013 [24] and C37.06 [29], the GCB short-time rating is 3 s. The aggregate of the protection schemes in Zone IPBD (including the negative sequence and distance relaying schemes) would initiate the generator protection scheme, tripping the GCB, generator, and switchyard circuit breakers in typically under 3 s.

A fault within the IPBD region (Zone IPBD) with a GCB stuck closed results in a generator-fed fault (the same progression as in a unit-connected design). Although the fault would be detected by the differential protection scheme (87), it is postulated that the GCB could physically fail to open. Therefore, the generator cannot be isolated from the IPBD fault. The generator residual energy will continue to feed the fault until the decaying generator voltage collapses in approximately 4–15 s.

[3] Legend: N = neutral, G = generator.

Note: The two generator switchyard breakers are expected to clear within cycles and prevent the grid from back-feeding the IPBD fault (through the GSU transformer).

3.3.3 Zone IPBD Fault Duration Summary

Table 3-3 summarizes the range of fault durations in Zone IPBD.

Table 3-3
Summary of Zone IPBD fault durations

Zone	Fault Description	Duration
IPBD	IPBD fault interrupted by GCB	cycles
IPBD	IPBD fault interrupted by GCB and stuck switchyard breaker	≤ 0.2 s
IPBD	IPBD fault interrupted by GCB and failed differential protection	≤ 3 s
IPBD	IPBD fault with GCB stuck closed	4–15 s
IPBD	IPBD fault with GCB stuck closed and failed differential protection	7–18 s
IPBD	IPBD fault in unit-connected design	4–15 s
IPBD	IPBD fault in unit-connected design with failed differential protection	7–18 s

Figure 3-6 shows the fault durations for Zone IPBD based on configuration, operation of differential protection, and operation of the generator circuit breaker (if installed). The end states associated with no HEAF consequences are shown in light gray text. For an NPP without a GCB, the consequence is a generator-fed fault (detected through either the differential or backup relaying). For an NPP with a GCB, if the differential protection and GCB operate, a HEAF does not occur. If the GCB fails to open, the consequence is a generator-fed fault.

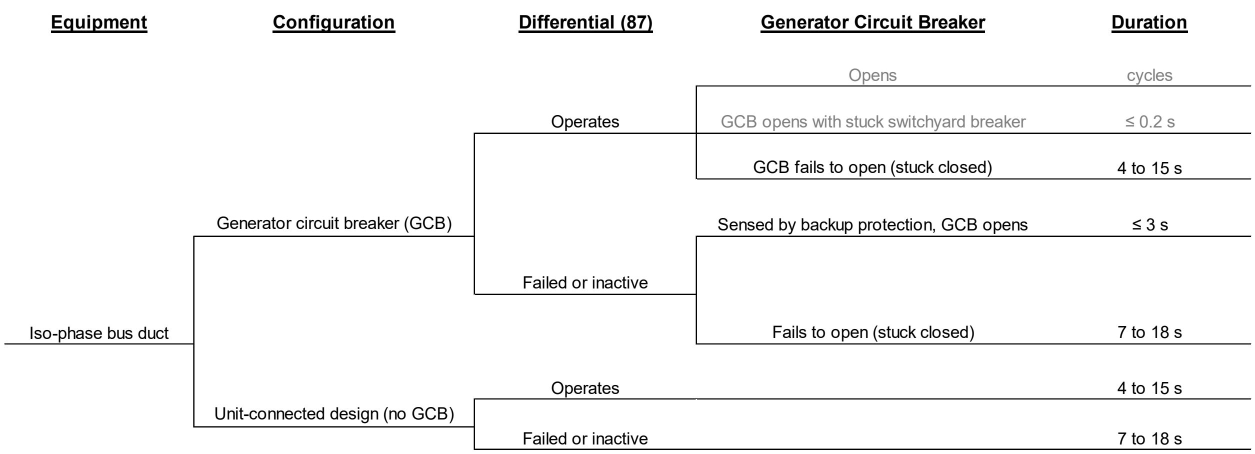


Figure 3-6
Zone IPBD fault durations

3.4 Zone BDUAT Faults

Zone BDUAT consists of the NSBD that runs from the secondary/tertiary windings of the UAT to each first-level MV switchgear (Zone 1).

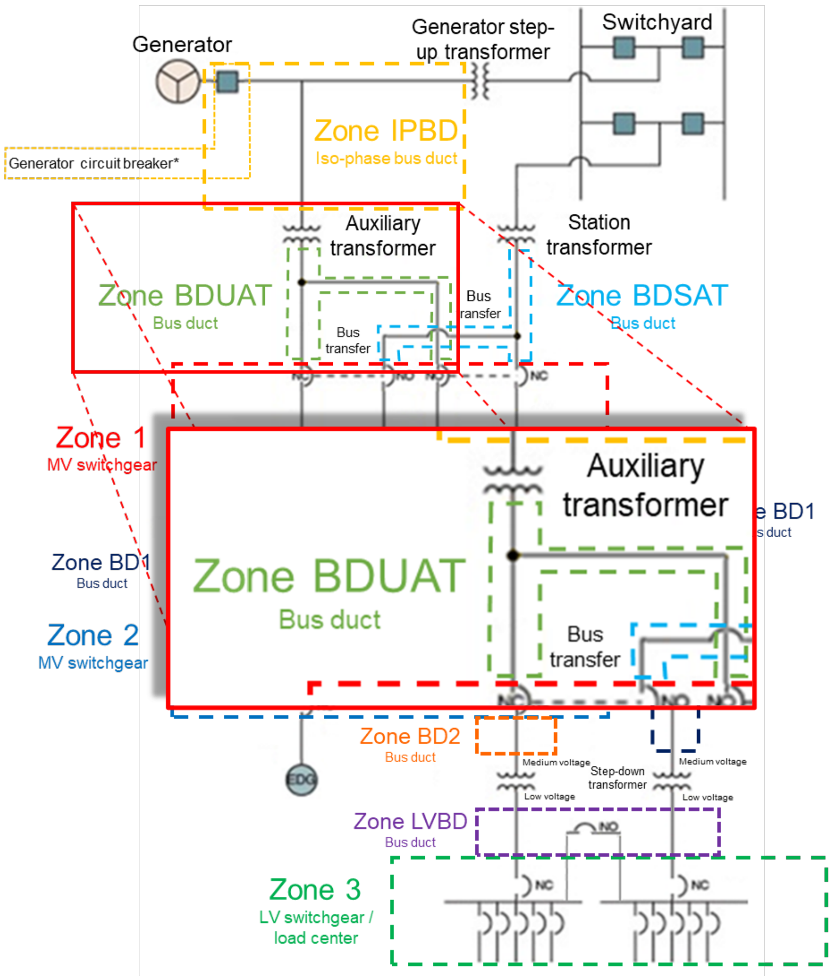


Figure 3-7
Zone BDUAT: MV NSBDs (Bin 16.1-1)

The NSBD is within the UAT differential zone of protection (87AT), which is considered the primary protection. Backup protection varies by transformer type. However, in most cases, this backup protection consists of some form of TOC protection, whether inline or wye winding transformer resistance ground overcurrent (51N, 51G). Other protection may consist of a ground detector relay (59) or neutral ground relay (64).

3.4.1 Zone BDUAT Protection Overview and Non-Segregated Bus Rating

For a fault in Zone BDUAT, the following protection elements are credited to limit the fault duration:

- UAT differential protection (87)—instantaneous: The UAT protection scheme (87AT) CTs are located such that the entire NSBD is within the protection zone. For HEAF analysis purposes, this differential protection is considered the primary protection for the NSBD. A fault within the NSBD is expected to actuate the UAT differential protection scheme and initiate a generator protection lockout (86) in a few cycles, tripping the unit and generator switchyard breakers.

- GCB: The GCB is tripped either from the UAT differential (87) protection scheme or UAT TOC trip, along with generator protection lockout (86), unit trip, and tripping the generator switchyard circuit breakers.
- Lockout relay (86): See definition in Section 2.
- Breaker failure protection: See definition in Section 2.
- Non-segregated bus short time withstand rating (duration): IEEE C37.23-2003 [28], Section 5.4.3, states that the rated short-time withstand current of metal-enclosed bus is the average rms symmetrical current that it can carry for 2 s for non-segregated-phase bus with a rated maximum voltage greater than 0.635 kVAC. However, NSBD design that exceeds this 2 s requirement is possible when specified.

3.4.2 Zone BDUAT Fault Progression

Potential faults in Zone BDUAT for plants with GCBs include:

A fault in Zone BDUAT with a GCB is expected to be detected by the UAT differential protection (87) scheme. The UAT will lockout (86) and initiate a generator protection trip, tripping the unit and generator switchyard circuit breakers. The fault is expected to clear within several cycles of fault detection.

A fault in Zone BDUAT with a GCB and a stuck switchyard breaker is expected to be detected by the UAT differential protection (87) scheme. The UAT will lockout (86) and initiate a generator protection trip (within several cycles). The generator lockout will trip the unit and send trip signals to the two generator switchyard circuit breakers.

However, if one of the generator switchyard breakers fails to open (i.e., is stuck), then the breaker-failure scheme (50FD, 50BF) will actuate within 0.2 s (within 12 cycles) and open all adjacent switchyard circuit breakers around the stuck breaker (see Figure 2-1). Total time is within 0.2 s.

A fault in Zone BDUAT with a GCB and failed UAT differential protection or protection logic inactive is detected by the next level of protection (e.g., the UAT TOC relaying [51, 51N, 51G], ground detector relay [59], or neutral ground [64] relay).

The primary purpose of this second level of transformer protection is to protect the auxiliary transformer from excessive through-fault current durations that could damage the transformer. Per IEEE Standard C57.109 [27], a review of FCTs in Figure 3-3, and a review of an IEEE paper [30], this time delay can range from 0.2-5 s. The UAT's second level of protection is expected to trip via generator lockout (86). Plant-specific timing may differ, and plant protection and coordination calculations should be reviewed for expected UAT tripping times (see Section 6.4).

A fault in Zone BDUAT with a GCB stuck closed results in a generator-fed fault. Although the fault would be detected by UAT differential protection (87AT), which would trip the generator and switchyard circuit breaker, it is possible that the GCB could physically fail to open. Therefore, the generator cannot be isolated from the UAT and the non-segregated bus. Even though the generator protection lockout (86) will also trip the generator exciter breaker, the generator residual energy will continue to feed the fault until the decaying generator voltage collapses in approximately 4–15 s.

Note: The two generator switchyard circuit breakers are also expected to clear in several cycles because of the 86 lockout, preventing the grid from back-feeding the NSBD fault (through the GSU and UAT).

Potential faults in Zone BDUAT for plant designs without GCBs (unit-connected design) include the following:

<u>A fault in Zone BDUAT in a unit-connected design</u>: is expected to be detected by the UAT differential protection (87AT) and result in a generator protection lockout (86), tripping the main generator, GSU transformer, and switchyard circuit breakers.

- The two generator switchyard breakers are expected to clear in cycles, preventing the grid from back-feeding the NSBD HEAF (through the GSU and UAT transformers).
    - Note: Even if one of the generator switchyard circuit breakers were to fail stuck closed, the breaker failure scheme (50BF, 50FD) would typically clear the adjacent switchyard breakers in under 0.2 s.
- Even though the generator protection lockout (86) will also trip the generator exciter circuit breaker, the generator residual energy will continue to feed the fault until the decaying generator voltage collapses in approximately 4–15 s.

<u>A fault in Zone BDUAT in a unit-connected design with failed UAT differential protection (87AT) or protection logic inactive</u> results in a delayed clearing and a generator-fed fault. Backup protection is then relied on to clear the fault and may be any one of the following:

- UAT primary side TOC (51) relay
- UAT neutral overcurrent (51N, 51G) relay
- UAT ground fault detector (59N) relay
- UAT neutral ground (64) relay

The primary purpose of this second level of transformer protection is to protect the auxiliary transformer from excessive through-fault-current durations that could damage the transformer. Per IEEE Standard C57.109 [27], a review of FCTs in Figure 3-3, and a review of an IEEE paper [30], this time delay can range from 0.2 to 5 s. The UAT's second level of protection would be expected to trip via generator lockout (86). However, this delay in generator protection lockout (86) would also delay the start of a potential generator-fed fault. Generator-fed faults have been documented to range from 4–15 s. Therefore, the total event duration (until the fault is extinguished) could range from 4.2–20 s (0.2–5 s for the second level of transformer protection followed by 4-15 s of generator-fed fault).

OPEX note: A HEAF has occurred where the UAT differential (87) protection was inadvertently left disabled. The event duration was close to the range postulated above. A distinguishing difference between the actual event and the idealized accident sequence described above is that the UAT transformer failed, and the failure was picked up by the plant's unit differential (387) protection scheme: the UAT primary CTs were within the zone of the unit differential (387) protection and initiated the generator protection lockout (86) in approximately 6 s. The generator likely fed the UAT fault until the voltage collapsed; however, the duration was not documented.

3.4.3 Zone BDUAT Fault Duration Summary

Table 3-4 summarizes the range of fault durations in Zone BDUAT.

Table 3-4
Summary of Zone BDUAT fault durations

Zone	Fault Description	Duration
BDUAT	NSBD fault with GCB opening	cycles
BDUAT	NSBD fault with GCB and stuck switchyard breaker	≤ 0.2 s
BDUAT	NSBD fault with GCB and failed UAT differential protection	0.2–5 s
BDUAT	NSBD fault with GCB stuck closed	4–15 s
BDUAT	NSBD fault with GCB stuck closed and failed UAT differential protection	4.2–20 s
BDUAT	NSBD fault (unit-connected design)	4–15 s
BDUAT	NSBD fault with failed UAT differential protection (87AT) (unit-connected design)	4.2–20 s

A fault in Zone BDUAT is expected to result in an UAT protective trip (86) lockout and subsequent turbine-generator trip. Similar to Zone IPBD, the main generator has the potential to feed the fault during the generator coast-down. Figure 3-8 shows the fault durations based on configuration, operation of differential protection, and operation of the generator circuit breaker (if installed). End states associated with successful protection and not capable of producing a fault duration sufficient to result in HEAF-type consequences are shown in light gray text. Successful operation of the GCB within the protection zone will not result in HEAF-like consequences. The remaining progressions (with the exception of the backup protection for the GCB operation) result in a generator-fed fault.

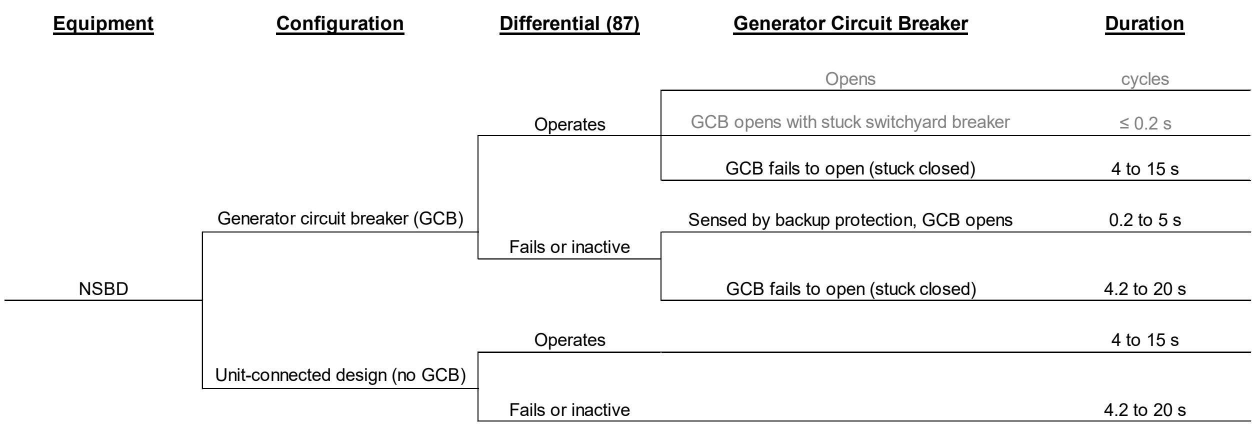


Figure 3-8
Zone BDUAT fault durations

3.5 Zone BDSAT Faults

Zone BDSAT consists of the NSBD that runs from the secondary/tertiary windings of the SAT to each first-level MV switchgear (Zone 1).

Also, as described in Table 3-1, BDSAT may also be used to represent any off-site power circuit that supports power production from dedicated system service transformers not shown in the simplified NPP EDS in Figure 3-1.

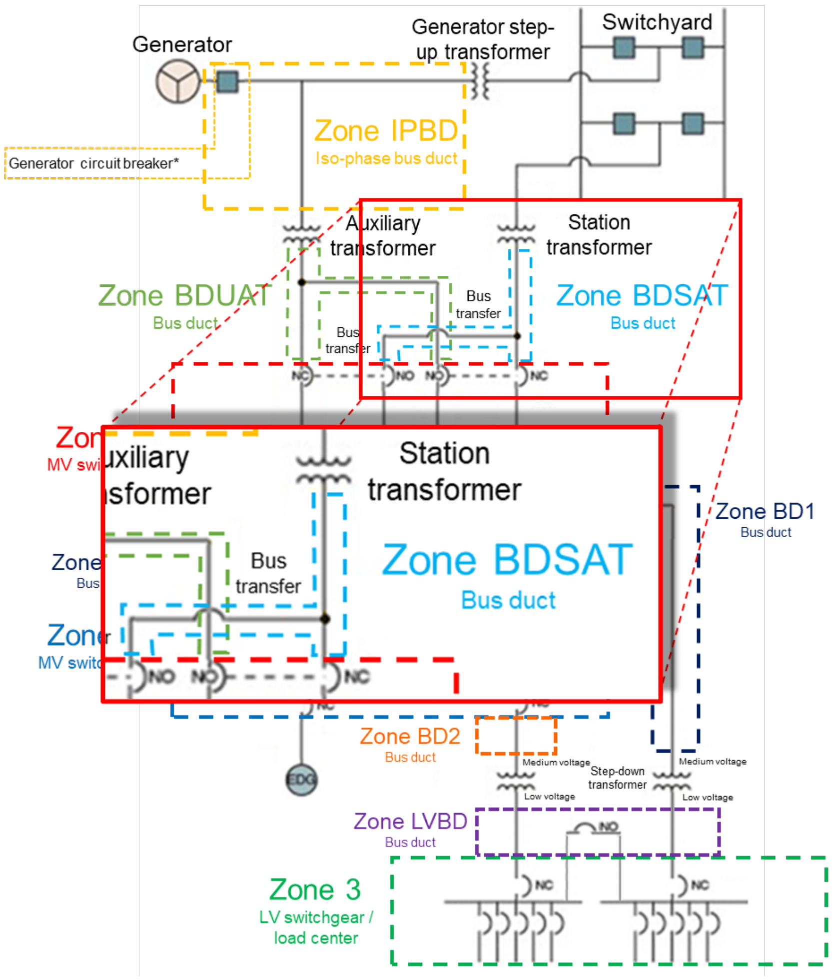


Figure 3-9
Zone BDSAT: MV NSBDs (Bin 16.1-1)

Zone BDSAT is wholly contained within the SAT differential zone of protection (87ST, 87R, and so on), which is considered the primary protection. Backup protection varies by transformer type. However, in most cases this backup protection consists of some form of TOC protection, whether in-line or wye-winding transformer resistance ground overcurrent (e.g., 51N, 51G). Other protection may consist of a ground detector relay (59) or neutral ground relay (64).

3.5.1 Zone BDSAT Protection Overview and Non-Segregated Bus Rating

For a fault in Zone BDSAT, the following protection elements are credited to limit the fault duration:

- SAT differential protection (87) – instantaneous: The SAT protection scheme (87) CTs are located so that the entire NSBD is within the protection zone. For HEAF analysis purposes, this differential protection is considered the primary protection for the NSBD. A fault in the NSBD is expected to actuate the SAT differential protection (87) scheme and initiate a lockout (86), tripping the SAT switchyard breakers (and any dedicated SAT breaker) within a few cycles.
- Lockout relay (86): See definition in Section 2.
- Breaker-failure protection: See definition in Section 2.
- Non-segregated bus short-time withstand rating (duration): IEEE C37.23-2003 [28], Section 5.4.3, states that the rated short-time withstand current of metal-enclosed bus is the average rms symmetrical current that it can carry for a period of 2 s for non-segregated-phase bus with a rated maximum voltage greater than 0.635 kVAC. However, NSBD designs that exceed this requirement are possible when specified.

3.5.2 Zone BDSAT Fault Progression

Potential faults in Zone BDSAT include the following:

A fault in Zone BDSAT with active differential protection and switchyard circuit breakers is expected to be detected by the SAT differential protection (87) scheme. The SAT will lockout (86) and initiate a trip of the SAT switchyard circuit breakers (and any dedicated SAT circuit breaker) within a few cycles.

A fault in Zone BDSAT with active differential protection and a failed SAT switchyard circuit breaker is expected to be detected by the SAT differential protection (87) scheme. The SAT will initiate a lockout (86) trip signal to the SAT switchyard breakers (and any dedicated SAT breaker). In the event one of the switchyard circuit breakers fails to open (i.e., is stuck), the breaker-failure scheme (50FD, 50BF) will activate and clear all adjacent circuit breakers around the stuck breaker within 0.2 s (within 12 cycles). See Figure 2-1.

A fault in Zone BDSAT with failed differential protection or protection logic inactive is expected to be detected by the next level of protection (e.g., the SAT TOC relaying [51, 51N, 51G], ground detector relay [59], or neutral ground [64] relay).

The primary purpose of this next level of transformer protection is to protect the transformer from excessive through-fault-current durations that could damage the transformer. Per IEEE Standard C57.109 [27], a review of FCTs in Figure 3-4, and a review of an IEEE paper [30], this time delay generally ranges from 0.2-5 s. The SAT TOC protection would be expected to trip (via lockout [86]) the SAT switchyard circuit breakers (and any dedicated SAT breaker) within this FCT (typical range of 0.2–5 s). The timing of the backup relaying may differ, and protection and coordination calculations should be reviewed for actual SAT tripping times (see Section 6.4).

3.5.3 Zone BDSAT Fault Duration Summary

Table 3-5 summarizes the range of fault durations in Zone BDSAT.

Table 3-5
Summary of Zone BDSAT fault durations

Zone	Fault Description	Duration
BDSAT	NSBD fault with active differential protection and switchyard breakers	cycles
BDSAT	NSBD fault with active differential protection and failed SAT switchyard breaker	≤ 0.2 s
BDSAT	NSBD fault with failed differential protection	0.2–5 s

Figure 3-10 presents the fault durations in Zone BDSAT considering the performance of differential protection and the first switchyard breaker. The end states that have successful protection and are not capable of resulting in HEAF-level consequences are shown in light gray text.

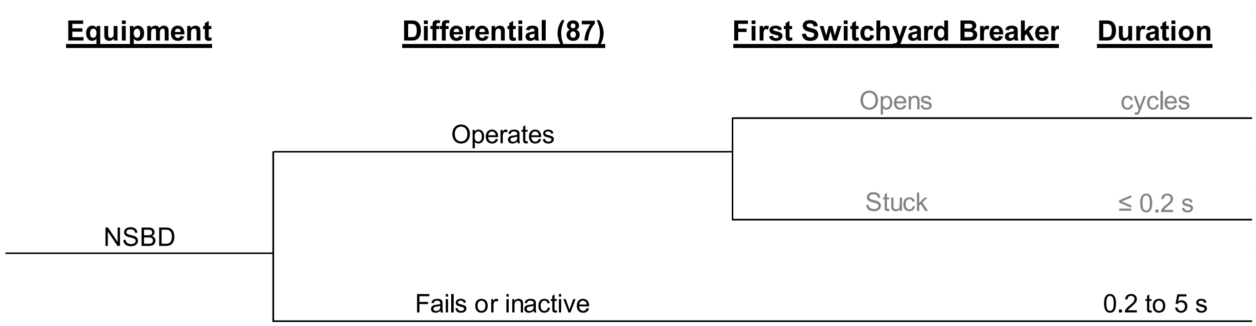


Figure 3-10
Zone BDSAT fault durations

3.6 MV Switchgear Zone 1 Faults

Zone 1 includes the first MV switchgear downstream of either the UAT or SAT. Within the MV switchgear, a fault can develop in the switchgear supply side (including the incoming circuit breaker), the main bus bar, or the load cubicle. The protection elements and durations can differ based on the location within the switchgear.

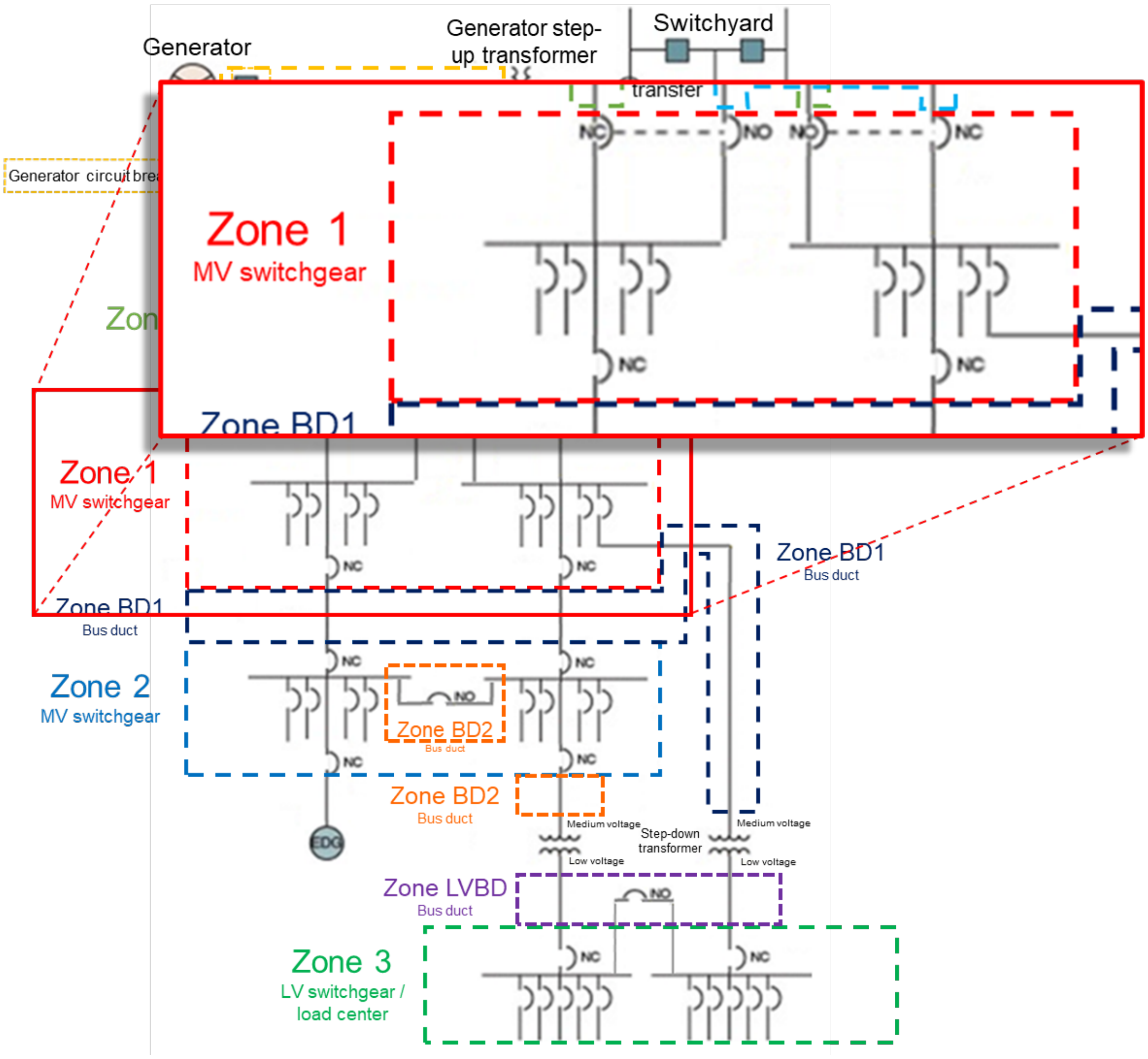


Figure 3-11
Zone 1: MV switchgear (Bin 16.b)

Figure 3-12 shows the three locations, which are summarized as follows:

1. The supply side of the switchgear bus supply circuit breaker, including the circuit breaker connection stabs to the switchgear, differential protection (87) and TOC relay CT, and primary compartment bus work (see the lower half of the red box in Figure 3-12 as an example).
2. The main bus bars, including the bus work connecting the main bus to each switchgear circuit breaker cubicle interface connection, outside the zone of the transformer differential protection (87) CTs (see the green box in Figure 3-12).
3. The load circuit breaker and load-side bus work or load cabling (see the blue box in Figure 3-12).

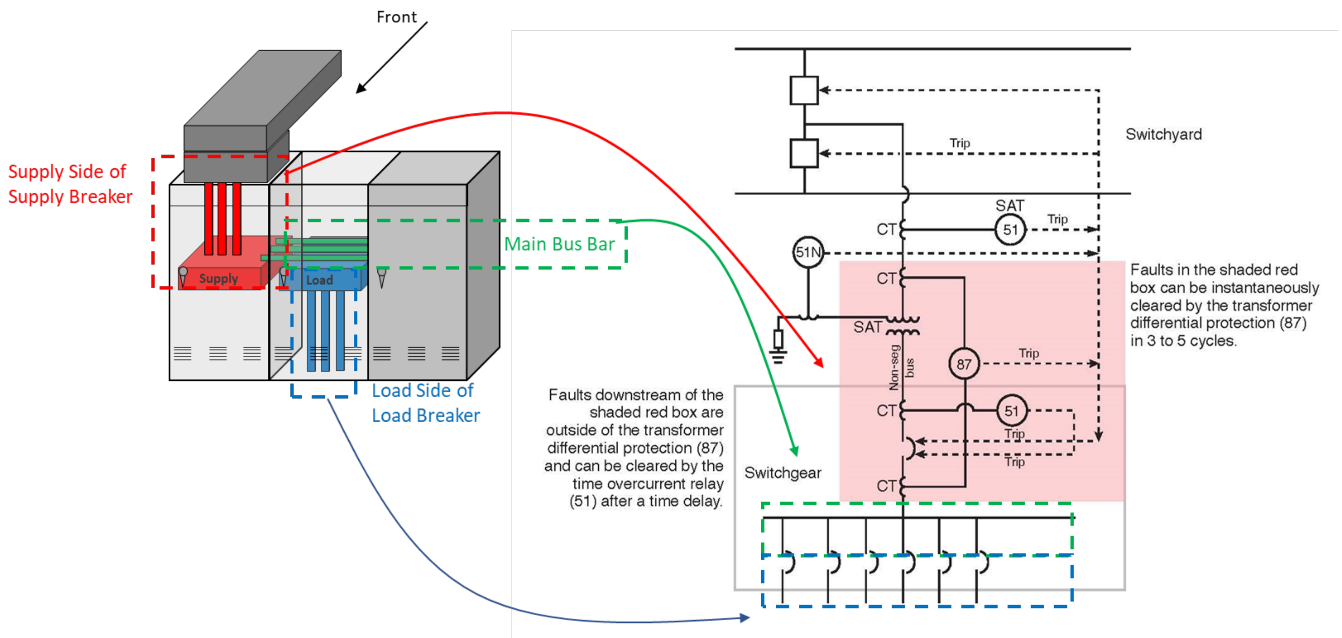


Figure 3-12
MV switchgear fault locations

3.6.1 Zone 1 Protection Overview

For a fault in Zone 1, the following protection elements are credited to limit the fault duration:

- Bus protection TOC (51 – delay): The switchgear TOC (51) protection relay CTs are located within the physical zone where the incoming transformer power supply connects to the switchgear bus supply breaker. The CTs may either be part of the circuit breaker connection stabs (e.g., horizontal draw-out) or on the primary cable compartment bus in the rear of the switchgear (e.g., vertical-lift style—see the CT shown in Figure 3-13).

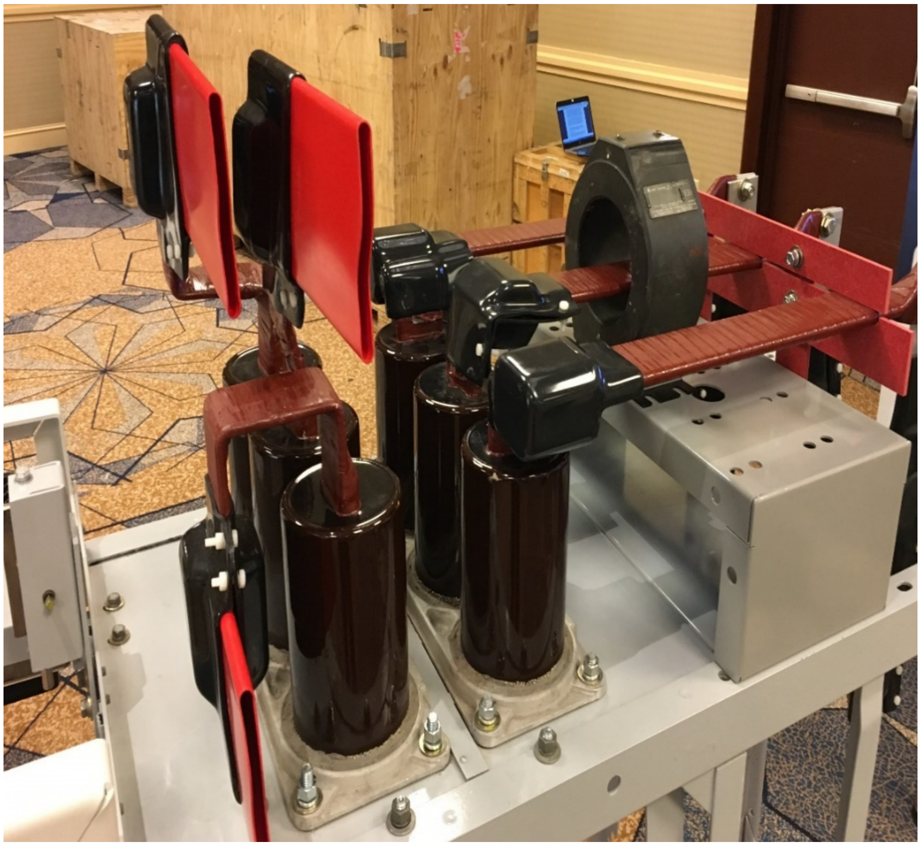


Figure 3-13
Primary cable compartment bus and overcurrent CT (51) for incoming supply (vertical-lift circuit breaker)

- Transformer protection (87 – instantaneous): The UAT and SAT differential protection scheme (87) is considered the primary protection for UAT/SAT faults (including NSBD and switchgear bus supply circuit breakers) and is designed to interrupt any fault in this protection zone within several cycles.

  The UAT CTs used with this protection scheme are located as follows:

  1. The transformer primary (high-voltage side).
  2. Downstream (load side) of the Zone 1 switchgear bus supply breaker(s) at the breaker stabs that connect the breaker to the main bus bars. The bus supply breakers are within the zone of UAT/SAT differential (87) protection (see Figure 3-12).

  Because the Zone 1 switchgear bus supply circuit breakers are part of the active UAT/SAT differential (87) protection scheme, the bus supply circuit breakers will trip for incoming power supply faults inside the switchgear up to all six breaker stabs and also lock out (86) the UAT/SAT. An exception is if the interface connections of the switchgear bus supply breaker and/or switchgear cubicle/breaker stabs failed in a way that that damaged the circuit breaker and cannot open to clear the fault.

- Lockout relay (86): See definition in Section 2.
- Breaker-failure protection: See definition in Section 2.
- Bus differential (87) protection: See definition in Section 2.

3.6.2 Zone 1 Supply Side Fault Progression

Potential faults in Zone 1 (supply side) are discussed below.

The Zone 1 switchgear supply side includes the switchgear bus supply circuit breaker, which includes the circuit breaker connection stabs to the switchgear, the differential protection (87) with the TOC (51) CTs, and the primary compartment bus work (see Figure 3-12).

The Zone 1 supply side's switchgear bus supply circuit breaker is within the zone of transformer differential protection (87) scheme, up to and including the load-side of the bus supply circuit breaker primary disconnect stabs. The primary objective of the transformer differential protection (87) scheme is to immediately de-energize the auxiliary power transformer to prevent it from feeding any fault that originates within this zone (including internal transformer faults). This is done by tripping open all primary (switchyard) and secondary/tertiary transformer circuit breakers for SAT circuits and tripping the generator along with the primary (switchyard) and secondary/tertiary circuit breakers for the UAT circuits. This differential scheme is particularly important when the Zone 1 fault is upstream of the Zone 1 switchgear bus supply circuit breaker (primary cable compartment bus up to and including the circuit breaker primary side disconnects) since opening of the bus supply circuit breaker has no effect in clearing the fault.

For faults on the load side of the switchgear bus supply circuit breaker but upstream of the differential protection (87) CT (i.e., on the load side of the switchgear bus supply circuit breaker connection stabs), the circuit breaker will open in a few cycles to clear the fault as part of the differential protection trip sequence. Even if the Zone 1 switchgear bus supply circuit breaker is collaterally damaged by the fault at the load-side circuit breaker stabs where the differential protection (87) CTs are located, the fault will still be detected by the differential protection (87) scheme, resulting in a trip and lockout of the upstream transformer within a few cycles.

A Zone 1 supply-side fault with a failed, stuck bus switchgear supply breaker can have different outcomes. The outcome depends on which lineup the switchgear is fed from:

- Generator/UAT with a GCB
- Generator/UAT without a GCB
- Off-site/SAT

Zone 1 supply side via generator/UAT with a GCB

A Zone 1 supply-side fault fed from the UAT via a GCB with a stuck switchgear bus supply breaker is within the zone of the UAT differential (87) protection scheme. The fault can be sensed by the switchgear bus supply TOC (51) relay; however, the fault is expected to clear in several cycles because of the speed of the UAT differential protection. The UAT differential protection is expected to initiate the generator protection lockout (86) scheme, tripping the following:

- Generator circuit breaker
- Generator switchyard breakers (to prevent the switchyard from back feeding the fault)
- Reactor and/or turbine

A Zone 1 supply-side fault fed from the UAT with a stuck GCB and stuck switchgear bus supply breaker will progress to a generator-fed fault. This progression has two failures: the switchgear bus supply circuit breaker and the GCB stuck closed (independent failure). The fault is detected by the UAT differential protection (87) scheme which initiates a generator protection lockout (86). The main generator switchyard circuit breakers will open in cycles and isolate the switchyard/grid from feeding the fault. However, because the main generator cannot be isolated from the UAT/switchgear (i.e., the GCB is stuck closed), the energy can flow through the two stuck breakers and feed the fault for an estimated 4-15 s during generator coast-down.

A Zone 1 supply-side fault fed from the UAT via a GCB with failed (or inactive) UAT differential (87) protection is expected to be detected by the next level of protection (e.g., the UAT TOC relaying [51, 51N, 51G], ground fault detector [59], or neutral ground [64] relay) and trip the GCB as part of the UAT and generator protection scheme.

The primary purpose of this second level of transformer protection is to protect the transformer from excessive through-fault-current durations that could damage the transformer. Per IEEE Standard C57.109 [27], a review of FCTs in Figure 3-3, and a review of an IEEE paper [30], this time delay can range from 0.2–5 s. The UAT's second level of protection is expected to trip the generator protection lockout (86), including the GCB. The only benefit gained by the GCB is the reliability added by introducing an additional layer of protection. It does not offer instantaneous clearing; like the differential protection, it must wait for the backup TOC relay to sense the fault and initiate the trip command.

A Zone 1 supply-side fault fed from the UAT with a stuck GCB and failed (or inactive) UAT differential (87) protection will see a delayed clearing time and a generator-fed fault. This progression has two failures, the switchgear bus supply circuit breaker and the GCB stuck closed (independent failure). The second level of transformer protection is relied on to clear the fault and may be any one of the following:

- UAT primary side TOC (51) relay
- UAT neutral overcurrent (51N, 51G) relay
- UAT ground fault detector (59N) relay
- UAT neutral ground (64) relay

The primary purpose of the transformer's secondary protection is to protect the transformer from excessive through-fault-current durations that could damage the transformer. Per IEEE Standard C57.109 [27], a review of FCTs in Figure 3-3, and a review of an IEEE paper [30], this time delay can range from 0.2–5 s. The UAT TOC protection is expected to trip the following (via generator protection [86 lockout]):

- Generator switchyard circuit breakers (to prevent the switchyard from back-feeding the fault)
- Reactor and/or turbine

However, this delay in generator protection lockout (86) also delays the start of the generator-fed fault. Generator-fed faults have been documented to range from 4–15 s. Therefore, the total event duration could range from 4.2–20 s (0.2-5 s for the second level of transformer protection followed by 4–15 s of generator-fed fault).

Zone 1 supply side via generator/UAT without a GCB (unit-connected design)

A Zone 1 supply-side fault fed from a UAT in a unit-connected design with a stuck switchgear bus supply breaker is expected to develop into a generator-fed fault. The fault is detected by the UAT differential protection scheme (87) initiating a generator lockout (86). The main generator switchyard circuit breakers will open in cycles and isolate the switchyard/grid from feeding the fault. However, because the main generator cannot be isolated from the UAT/switchgear, the generator coast-down energy can continue to feed the fault for an estimated 4–15 s.

A Zone 1 supply-side fault fed from a UAT in a unit-connected design with failed (or inactive) UAT differential protection (87AT) results in a delayed clearing followed by a generator-fed fault.

The second level of transformer protection is relied upon to clear the fault and may be any one of the following:

- UAT primary-side TOC (51) relay
- UAT neutral overcurrent (51N, 51G) relay
- UAT ground fault detector (59N) relay
- UAT neutral ground (64) relay

The primary purpose of the transformer's secondary protection is to protect the transformer from possible damage by excessive through-fault-current durations. Per IEEE Standard C57.109 [27], a review of FCTs in Figure 3-3, and a review of an IEEE paper [30], this time delay can range from 0.2–5 s. The UAT TOC protection would be expected to trip the following (via generator protection [86 lockout]):

- Generator switchyard breakers (to prevent the switchyard from back-feeding the fault)
- Reactor and/or turbine

However, this delay in generator protection lockout (86) also delays the start of the generator-fed fault. Generator-fed faults have been documented to range from 4–15 s. Therefore, the total event duration could range from 4.2–20 s (0.2-5 s for the second level of transformer protection followed by 4–15 s of generator-fed fault).

Zone 1 supply side via off-site/SAT

<u>A Zone 1 supply-side fault fed via off-site/SAT</u> is within the zone of the SAT differential (87) protection scheme. The fault would also be sensed by the switchgear bus supply TOC (51) relay; however, because of the speed of the SAT differential protection, the fault is expected to clear in cycles because the SAT differential protection would trip the switchyard primary-side switchyard circuit breakers (including the SAT breaker, if it exists) and deenergize the SAT.

<u>A Zone 1 supply-side fault fed via off-site/SAT with a stuck switchgear bus supply circuit breaker</u> is within the zone of the SAT differential (87) protection scheme. The fault would also be sensed by the switchgear bus supply TOC (51) relay. However, the fault is expected to clear in several cycles because of the speed of the SAT differential protection. The SAT differential protection is expected to initiate the generator protection lockout (86) scheme, which trips the following:

- Generator switchyard breakers (to prevent the switchyard from back-feeding the fault)
- Reactor and/or turbine

<u>A Zone 1 supply-side fault fed via off-site/SAT with a stuck switchyard circuit breaker</u> is within the zone of the SAT differential (87) protection scheme. The fault would be sensed by the switchgear bus supply TOC (51) relay; however, because of the speed of the SAT differential protection scheme (87), an instantaneous trip signal to the transformer primary switchyard circuit breakers (and/or dedicated SAT breaker) would occur first. If one of the transformer switchyard circuit breakers fails to open (i.e., a stuck breaker), then the breaker-failure protection scheme would operate and trip all breakers adjacent to the failed stuck breaker (see Figure 2-1). The time to clear the fault would be within 0.2 s (typical breaker-failure scheme is 8–12 cycles).

<u>A Zone 1 supply-side fault fed via off-site/SAT with failed (or inactive) SAT differential protection (87)</u> would result in a delayed clearing. The second level of transformer protection is relied upon to clear the fault and may be any one of the following:

- SAT primary-side TOC (51) relay
- SAT neutral overcurrent (51N, 51G) relay

- SAT ground fault detector (59N) relay
- SAT neutral ground (64) relay

The primary purpose of this next level of transformer protection is to protect the transformer from excessive through-fault-current durations that could damage the transformer. Per IEEE Standard C57.109 [27], a review of FCTs in Figure 3-4, and a review of an IEEE paper [30], this time delay can range from 0.2–5 s. The SAT TOC protection is expected to trip (via lockout [86]) the SAT switchyard breakers (and any dedicated SAT breaker) within this FCT.

3.6.3 Zone 1 Switchgear Main Bus Bar Fault Progression

Faults within the main bus bars section occur anywhere on the switchgear main bus bars and the bus work connecting the main bus to each switchgear circuit breaker cubicle interface connection. This part of the switchgear is outside the UAT or SAT differential protection zone (87), and auxiliary power transformer differential protection is no longer credited.

Potential faults in Zone 1 main bus bars include the following:

A Zone 1 main bus bar fault with a functional switchgear bus supply breaker. This fault is outside of the zone of transformer differential (87) protection and is sensed by the switchgear bus TOC relay (51) and the upstream transformer overcurrent or neutral TOC relay (51, 51N, 51G), ground fault detector (59), or neutral ground (64) relay. Because it is expected that the switchgear bus TOC relay is faster than the transformer protection, the bus TOC relay is expected to trip the switchgear bus supply circuit breaker first, within 4 s (see Table 3-2).

For plants with medium-voltage switchgear bus differential (87) protection or switchgear level breaker-failure protection, the time to trip is within 0.2 seconds.

A Zone 1 main bus bar fault with failed stuck switchgear bus supply circuit breaker can have different outcomes, depending on which lineup the switchgear is fed from:

- Generator/UAT with a GCB
- Generator/UAT without a GCB
- Off-site/SAT

Zone 1 main bus bar via generator/UAT with a GCB

A Zone 1 main bus bar fault fed via a UAT with a GCB and a stuck switchgear bus supply circuit breaker. This fault is outside the zone of the UAT differential (87) protection scheme, and the CT associated with the switchgear bus supply circuit breaker TOC (51) is ineffective because it cannot trip a stuck circuit breaker. The next level of backup protection for a switchgear bus with a stuck breaker is the transformer primary TOC (51) relay, neutral/ground TOC relay (51N, 51G), ground fault detector (59), or neutral ground (64) relay.

This outcome is similar to the case of the Zone 1 supply-side fault fed from the UAT via a GCB with failed (or inactive) UAT differential (87) protection and is expected to see a time delay that may range from 0.2–5 s.

A Zone 1 main bus bar fault fed via a UAT with a stuck GCB and stuck switchgear bus supply circuit breaker will progress into a generator-fed fault. This progression has two failures, the switchgear bus supply circuit breaker and the GCB stuck closed (independent failure). Because the fault is outside the UAT zone of differential (87) protection scheme and the switchgear TOC (51) relay cannot trip a stuck switchgear bus supply circuit breaker, the upstream UAT TOC (51, 51N, 51G), ground fault detector (59), or neutral ground (64) relay is expected to detect the fault and isolate the switchyard/grid from feeding the fault.

This outcome is similar to the case of the Zone 1 supply-side fault fed from a UAT with a stuck GCB and failed (or inactive) UAT differential (87) protection, with a total duration from 4.2–20 s (0.2–5 s for the relay trip followed by a generator-fed fault of 4–15 s).

Zone 1 main bus bar via generator/UAT without a GCB

A Zone 1 main bus bar fault fed from a UAT in a unit-connected design with a stuck switchgear bus supply circuit breaker will develop into a generator-fed fault.

This fault is outside the zone of the UAT differential (87) protection scheme, and the CT associated with the switchgear bus supply circuit breaker TOC (51) is ineffective because it cannot trip a stuck circuit breaker. The next level of backup protection for a switchgear bus with a stuck breaker is the transformer primary TOC (51) relay or neutral/ground TOC relay (51N, 51G), ground fault detector (59), or neutral ground (64) relay.[4]

The outcome is similar to the case of the Zone 1 supply-side fault fed from a UAT in a unit-connected design with a stuck switchgear bus supply breaker, with a total duration from 4.2–20 s.

Zone 1 main bus bar via off-site/SAT

A Zone 1 main bus bar fault fed from off-site/SAT with a stuck switchgear bus supply circuit breaker is outside the zone of the SAT differential (87) protection scheme, and the CT associated with the switchgear bus supply circuit breaker TOC (51) is ineffective because it cannot trip a stuck circuit breaker. The next level of backup protection for a switchgear bus with a stuck breaker is the transformer primary TOC (51) relay, neutral/ground TOC relay (51N or 51G), ground fault detector (59), or neutral ground (64) relay.[4]

This outcome is similar to the case of the Zone 1 supply side fault fed via off-site/SAT with failed (or inactive) SAT differential protection (e.g., 87ST) and is expected to range from 0.2 to 5 s.

A Zone 1 main bus bar fault fed from off-site/SAT with a stuck switchgear bus supply circuit breaker and a stuck switchyard circuit breaker is outside the zone of the SAT differential (87) protection scheme, and the CT associated with the switchgear bus supply circuit breaker TOC (51) is ineffective because it cannot trip a stuck circuit breaker. The next level of backup protection for a switchgear bus with a stuck breaker is the transformer primary TOC (51) relay, neutral/ground TOC relay (51N or 51G), ground detector (59), or neutral ground (64) relay.

The SAT TOC protection would send a trip signal to the switchyard primary-side switchyard circuit breakers. If one of the transformer switchyard breakers fails to open (i.e., stuck breaker), then the breaker-failure protection scheme would operate and trip all breakers adjacent to the failed breaker (see Figure 2-1). The time to clear the fault would typically range from 0.4–5.2 s (an expected FCT range of 0.2–5 s plus 0.2 s, which is a typical breaker-failure scheme of 8–12 cycles).

[4] Note: A few NPPs may have MV switchgear that is equipped with bus differential/bus breaker-failure schemes (e.g., 50FD and 62). For switchgear equipped with differential protection/breaker-failure schemes, the switchgear bus supply circuit breaker is supervised. If the circuit breaker remains stuck after a short time delay, the breaker-failure scheme will trip and lock out the upstream transformer approximately 8 to 12 cycles later (within 0.2 s). The FCT is expected to be faster than the MV switchgear 51 TOC relay.

3.6.4 Zone 1 Load-Side Fault Progression

Potential scenarios in Zone 1 (load side of the load breaker) include the following:

A fault on the load side of any one of the switchgear load circuit breakers is expected to be interrupted by that load circuit breaker's IOC (50) relay (within several cycles). For designs with an engineered safety features (ESF) transformer feeding Zone 2, the protective device would be an IOC (50) relay and selectively coordinated with the Zone 1 bus supply circuit breaker IOC (50) relay.

If the load breaker fails stuck closed, the backup protection is the switchgear bus supply breaker's TOC relay (51), as described in the Zone 1 main bus bar fault progression (Section 3.6.3).

3.6.5 Zone 1 Fault Duration Summary

Table 3-6 documents the range of fault durations from Section 3.6.2 (Zone 1 supply side), Section 3.6.3 (Zone 1 main bus bars), and Section 3.6.4 (Zone 1 load side).

Table 3-6
Summary of Zone 1 fault durations

Initiation Location	Fed Via	Fault Description	Duration
Zone 1 supply-side fault	All lineups	Fault between switchgear 87 CT and load side of bus supply circuit breaker (with switchgear bus supply breaker functional)	cycles
	UAT via GCB	Fault on switchgear incoming bus work from UAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck)	cycles
	UAT via GCB	Fault on switchgear incoming bus work from UAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck) with failed UAT differential (87) protection (interrupted by GCB)*	0.2–5 s
	UAT via GCB	Fault on switchgear incoming bus work from UAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck) with stuck GCB*	4–15 s
	UAT via GCB	Fault on switchgear incoming bus work from UAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck) with stuck GCB and failed UAT differential (87) protection**	4.2–20 s
	UAT (unit-connected design)	Fault on switchgear incoming bus work from UAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck)	4–15 s
	UAT (unit-connected design)	Fault on switchgear incoming bus work from UAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck)* with failed UAT differential protection (87AT)	4.2–20 s
	Off-site/SAT	Fault on switchgear incoming bus work from SAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck)	cycles
	Off-site/SAT	Fault on switchgear incoming bus work from SAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck)* with stuck switchyard circuit breaker	≤ 0.2 s
	Off-site/SAT	Fault on switchgear incoming bus work from SAT up to the line side of the bus supply circuit breaker (or bus supply circuit breaker stuck)* with failed SAT differential protection (87)	0.2–5 s

Initiation Location	Fed Via	Fault Description	Duration
Zone 1 main bus bar fault	All lineups	Fault with functional switchgear bus supply breaker	≤ 4 s
	SWGR with bus differential or breaker-failure protection	Fault detected by medium-voltage switchgear bus differential protection or breaker-failure protection	0.2 s
	UAT via GCB	Fault with stuck switchgear bus supply breaker	0.2–5 s
	UAT via GCB	Fault with stuck GCB and stuck switchgear bus supply breaker**	4.2–20 s
	UAT (unit-connected design)	Fault with stuck switchgear bus supply breaker	4.2–20 s
	Off-site/SAT	Fault with stuck switchgear bus supply breaker	0.2–5 s
	Off-site/SAT	Fault with stuck switchgear bus supply breaker and stuck switchyard breaker**	0.4–5.2 s
Zone 1 load-side fault	All lineups	Fault with fully functional switchgear load breaker	cycles
	All lineups	Fault with failed (stuck closed) switchgear load breaker and functional switchgear bus supply breaker	≤ 4 s
	UAT via GCB	Fault with failed stuck load breaker and stuck switchgear bus supply breaker**	0.2–5 s
	UAT via GCB	Fault with failed stuck load breaker, stuck GCB, and stuck switchgear bus supply breaker**	4.2–20 s
	UAT (unit-connected design)	Fault with failed stuck load breaker and stuck switchgear bus supply breaker**	4.2–20 s
	Off-site/SAT	Fault with failed stuck load breaker and stuck switchgear bus supply breaker**	0.2–5 s
	Off-site/SAT	Fault with failed stuck load breaker, stuck switchgear bus supply breaker, and stuck switchyard breaker**	0.4–5.2 s

*Depending on fault location, this may be the result of two independent failures.

**At least two independent failures must occur for this scenario.

Figure 3-14 shows the fault durations for Zone 1 based on fault location within the switchgear, breakers upstream that can clear the fault, power source, generator circuit breaker (if installed), and performance of switchyard breakers. Light gray text indicates the end states associated with successful protection that are not capable of producing fault duration sufficient enough to create a HEAF.

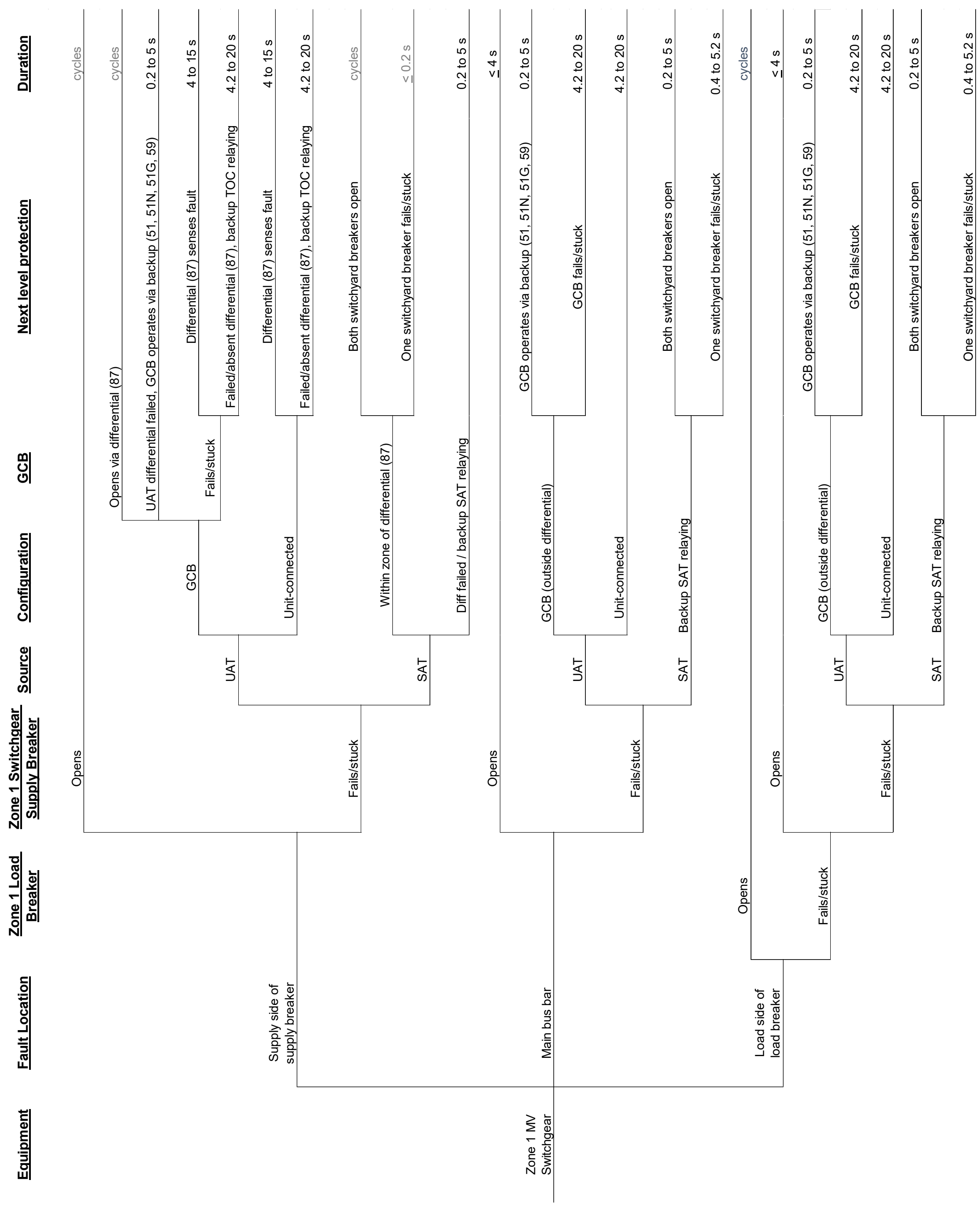


Figure 3-14
Zone 1 fault durations

3.7 Zone BD1 Faults

This section evaluates faults that initiate in MV NSBD between the first switchgear and the high side of the second switchgear bus supply circuit breaker (bus duct from Zone 1 to Zone 2) or the high side of the load center (bus duct from Zone 1 to Zone 3).

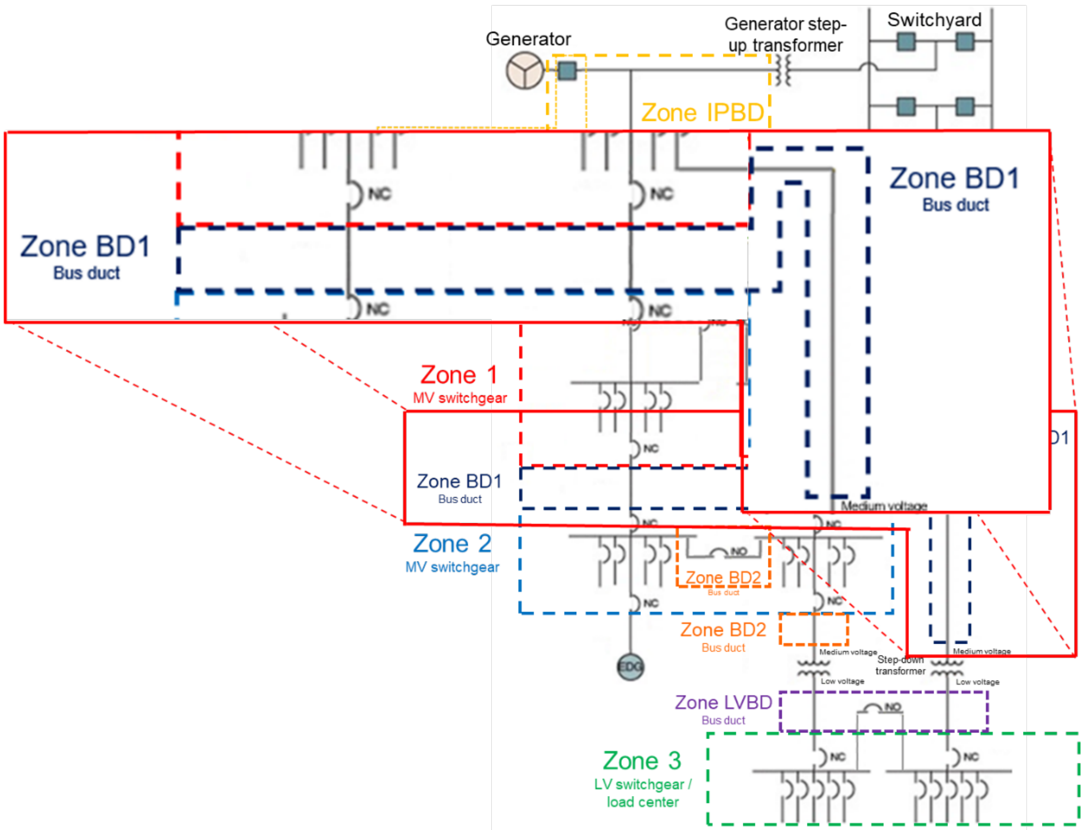


Figure 3-15
Zone BD1: MV NSBD (Bin 16.1-2)

This zone is an extension of the Zone 1 load section of the switchgear. In this case, the load is downstream of the MV switchgear at the same voltage level (that is, no transformer).

For the subsequent fault progression analysis, it is assumed that either no Zone 1 load (branch) circuit breaker exists, or if a circuit breaker exists, it is treated as a maintenance switch. Even if a trip element/relay exists, the protection overlaps with the Zone 2 bus supply breaker (and is not coordinated with the Zone 2 bus supply circuit breaker). However, the trip element/relay would be coordinated with the Zone 1 bus supply breaker. Nonetheless, this protection (if it exists) is not credited in the fault progression.

Because Zone BD1 is an extension of the Zone 1 load section of the switchgear, the fault must be cleared by the Zone 1 switchgear bus supply circuit breaker (≤ 4 s, as determined in Section 3.2.3). If the fault is not cleared, it follows the Zone 1 switchgear main bus bar fault progression (Section 3.6.3).

3.7.1 Zone BD1 Fault Duration Summary

Table 3-7 summarizes the range of durations in Zone BD1.

Table 3-7
Summary of Zone BD1 fault durations

Zone	Fed Via	Fault Description	Duration
BD1	All	Functional Zone 1 switchgear bus supply breaker	≤ 4 s
	UAT via GCB	Fault with “stuck” Zone 1 switchgear bus supply breaker	0.2–5 s
	UAT via GCB	Fault with “stuck” GCB and “stuck” Zone 1 switchgear bus supply breaker *	4.2–20 s
	UAT (unit connected design)	Fault with “stuck” Zone 1 switchgear bus supply breaker	4.2–20 s
	Offsite/SAT	Fault with “stuck” Zone 1 switchgear bus supply breaker	0.2–5 s
	Offsite/SAT	Fault with “stuck” Zone 1 switchgear bus supply breaker and “stuck” switchyard breaker*	0.4–5.2 s

*Two independent failure scenarios.

Figure 3-16 shows the fault durations for Zone BD1 based on the operation of the zone 1 switchgear supply breaker, power source, and generator circuit breaker (if installed).

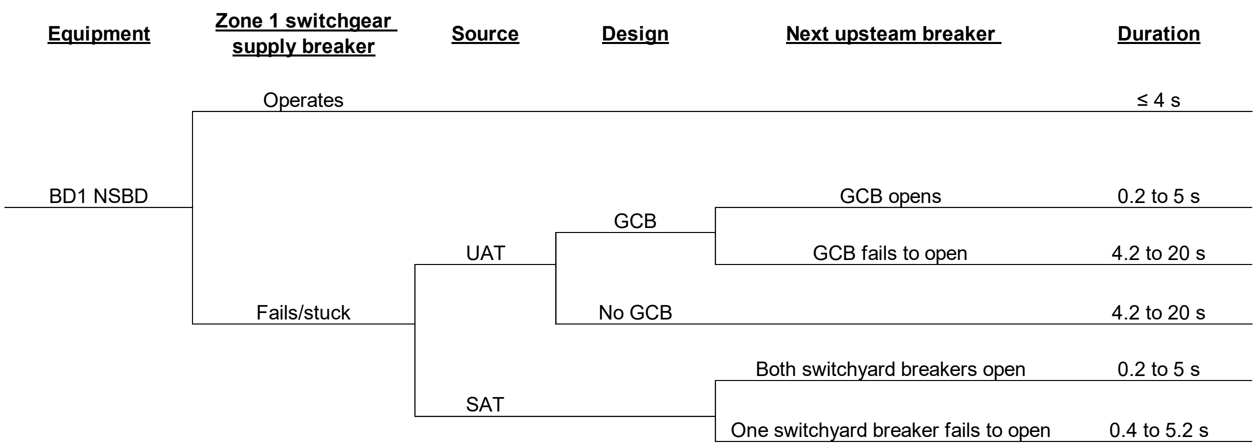


Figure 3-16
Zone BD1 fault durations

3.8 MV Switchgear Zone 2 Faults

Zone 2 is fed from one of the Zone 1 load branch circuit breakers without an IOC (50) relay. The Zone 2 switchgear bus supply circuit breaker is physically part of the Zone 2 switchgear and is selectively coordinated with the upstream Zone 1 switchgear bus supply breaker to clear a Zone 2 fault (that results in a bus lockout) before Zone 1 bus supply protection actuates.

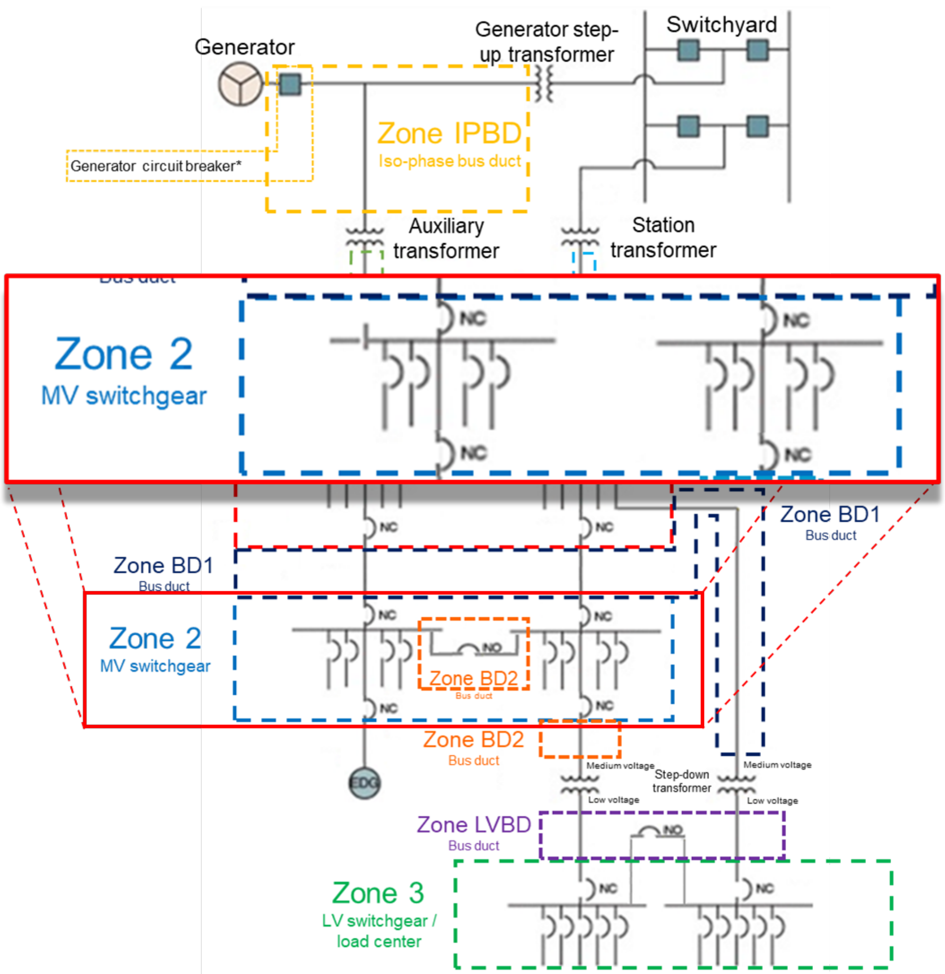


Figure 3-17
Zone 2: MV switchgear (Bin 16.b)

The Zone 1 feed to Zone 2 may be one of the following:

- A straight bus connected directly to an NSBD or cable from the Zone 1 switchgear load cubicle without a circuit breaker.
- A Zone 1 load branch circuit breaker feeding Zone 2:
    - A circuit breaker that does not contain a trip element or overcurrent protection (commonly referred to as a maintenance switch)

  - A circuit breaker with overcurrent protection, selectively coordinated with the Zone 1 switchgear bus supply breaker (but not necessarily coordinated with the Zone 2 bus supply breaker).

- The Zone 1 to Zone 2 path may include a medium voltage ESF step-down transformer (e.g., 13.8 kV to 4.16 kV).

For the subsequent fault progression analysis, it is assumed that either no Zone 1 load branch circuit breaker exists or, if it does, the protection is not credited in Zone 2. The exception to this is when there is a Zone 1 load circuit breaker feeding an ESF transformer between Zone 1 and Zone 2.

Similar to fault scenarios in Zone 1, fault scenarios in Zone 2 are analyzed by compartmentalizing the switchgear into three sections and determining whether the Zone 2 switchgear bus supply circuit breaker has failed stuck closed. The three fault locations include the following:

- Zone 2 supply side of bus supply circuit breaker, including circuit breaker connection stabs to the switchgear, TOC (51) current transformers, and primary compartment bus work (see Figure 3-12).
- Zone 2 main bus bars, including the bus work connecting the switchgear/circuit breaker interface connection:
  - Downstream of the switchgear bus supply circuit breaker TOC relay (51) CTs.
    - Breaker stabs (e.g., horizontal draw-out circuit breaker switchgear).
    - Primary cable compartment bus work (e.g., vertical-lift circuit breaker switchgear). See Figure 3-13.
  - Upstream of the switchgear load circuit breaker.
- Zone 2 load side of the load breaker:
  - Includes switchgear load circuit breaker overcurrent 50/51 relays (and in some cases an instantaneous ground fault relay [50G]).

3.8.1 Zone 2 Protection Overview

For a fault in Zone 2, the following protection elements are credited to limit the fault duration:

- <u>Switchgear bus supply circuit breaker TOC (51) – delay</u>:
  The switchgear bus supply circuit breaker TOC (51) protection relay CTs are located within the physical zone where the incoming Zone 1 power supply connects to the switchgear bus supply circuit breaker. The CTs may either be part of the circuit breaker connection stabs (e.g., horizontal draw-out) or on the primary cable compartment bus in the rear of the switchgear (e.g., vertical-lift style—see Figure 3-13).
- <u>Switchgear bus load circuit breaker overcurrent relays (50/51) and ground fault (50G)</u>:
  The switchgear load sections are typically equipped with both instantaneous (50) and TOC (51) relays. Some plants may also include ground fault protection in the form of a 50G relay.
  - 50 instantaneous relay: This relay operates instantaneously (several cycles) for cable or load faults (e.g., short circuits or large arc faults). The load circuit breaker is

immediately tripped for these faults. Not present on ESF transformer designs, only 51 TOC relays are used.

- 51 TOC relay: This relay operates after a time delay. The primary purpose of the relay is to protect the load (e.g., motor, load-center transformer, and so on) from a sustained overload. Time delay varies with the severity of the overload and is set to be selectively coordinated with the switchgear bus supply circuit breakers. These relays are inverse-TOC type, where the FCT is inversely proportional to the fault current.
- 50G relay: Typically used for delta ungrounded EDS. This scheme consists of one large CT where all three cables pass through one CT (commonly referred to as a "donut" CT). The principle of operation is that a ground fault will create an imbalance between the three phase currents because of some of the current is going to ground. Once the imbalance setpoint is reached, the load circuit breaker is immediately tripped (cycles).

3.8.2 Zone 2 Switchgear Supply Side Fault Progression

The Zone 2 supply side includes the switchgear bus supply circuit breaker, including circuit breaker connection stabs to the switchgear, switchgear bus supply TOC (51) CTs, and primary compartment or riser bus work (see Figure 3-13).

<u>A Zone 2 supply side fault with a functional switchgear bus supply circuit breaker</u>. Faults within the Zone 2 bus supply circuit breaker TOC (51) relay CT zone of protection are expected to clear within 2 s.

<u>A Zone 2 supply side fault with a switchgear bus supply circuit breaker failed stuck or outside of the protection zone</u>. Faults upstream of the Zone 2 bus supply breaker TOC (51) relay CTs are outside the protection zone and must be cleared by the Zone 1 switchgear bus supply circuit breaker (within 4 s).

This duration can also be used when the fault was detectable in the Zone 2 supply side; however, either the breaker failed stuck closed, breaker connection stabs faulted, or the overcurrent (51) protection system failed.

<u>A Zone 2 supply side fault with switchgear bus supply circuit breaker failed stuck or outside of the protection zone and an upstream (Zone 1) switchgear bus supply circuit breaker stuck</u> will progress as Zone 1 stuck bus supply circuit breaker fault (no credit for a Zone 1 load branch circuit breaker, if it exists).

<u>ESF transformer designs.</u> For EDS designs with an ESF transformer between Zone 1 and Zone 2, a fault with a Zone 2 "stuck" breaker is considered to progress the same where the upstream Zone 1 bus supply circuit breaker TOC (51) relay clears the fault. See Section 6.4.3 for further details.

3.8.3 Zone 2 Switchgear Main Bus Bar Fault Progression

The Zone 2 main bus bar includes the main bus bar and the bus work connecting to the switchgear's circuit breaker stab connections.

<u>A Zone 2 main bus bar fault with a functional bus supply circuit breaker</u> is within the protection zone of the Zone 2 supply side TOC (51) protection CTs and will trip the Zone 2 switchgear bus supply circuit breaker within 2 s because the Zone 2 switchgear bus supply circuit breaker must

be selectively coordinated with the Zone 1 bus supply circuit breaker. (See Table 3-2 for further discussion on MV switchgear FCTs).

A Zone 2 main bus bar fault with a Zone 2 switchgear bus supply circuit breaker failed stuck must be cleared by the Zone 1 switchgear bus supply circuit breaker within 4 s.

A Zone 2 main bus bar fault with a Zone 2 switchgear bus supply circuit breaker failed stuck and an upstream (Zone 1) switchgear bus supply circuit breaker stuck will progress the same as a Zone 1 stuck bus supply circuit breaker fault (no credit for a Zone 1 load branch circuit breaker, if it exists).

3.8.4 Zone 2 Switchgear Load-Side Fault Progression

The Zone 2 load circuit breaker and downstream bus work that powers the load (e.g., motor or load center) have the following potential fault progressions:

A Zone 2 load-side fault with a functional load circuit breaker is detected by the IOC (50) protection relay and immediately trips the load circuit breaker in several cycles.

A Zone 2 load-side fault with a failed stuck load circuit breaker is expected to be cleared by the upstream Zone 2 bus supply circuit breaker within 2 s (because the Zone 2 switchgear bus supply circuit breaker must be selectively coordinated with the Zone 1 bus supply circuit breaker).

This duration can also be used if either the load circuit breaker failed stuck closed, the circuit breaker connection stabs faulted, or the IOC (50) protection system failed.

A Zone 2 load-side fault with a Zone 2 switchgear bus supply circuit breaker failed stuck must be cleared by the Zone 1 switchgear bus supply circuit breaker within 4 s.

A Zone 2 load-side fault with failed stuck load breaker, a Zone 2 switchgear bus supply circuit breaker stuck, and an upstream (Zone 1) switchgear bus supply circuit breaker stuck will progress the same as a Zone 1 stuck bus supply circuit breaker fault (no credit for a Zone 1 load branch circuit breaker if it exists).

3.8.5 Zone 2 Switchgear Fault Duration Summary

Table 3-8 summarizes the fault durations from Section 3.8.2 (Zone 2 supply side), Section 3.8.3 (Zone 2 main bus bar), and Section 3.8.4 (Zone 2 load side).

Table 3-8
Summary of Zone 2 fault durations

Initiation Location	Fed Via	Fault Description	Duration
Zone 2 supply side fault	All lineups	Fault (within TOC (51) protection zone) cleared by Zone 2 bus supply circuit breaker	≤ 2 s
	All lineups	Fault with stuck Zone 2 switchgear bus supply breaker with functional Zone 1 switchgear bus supply breaker	≤ 4 s
	UAT via GCB	Fault outside 51 protection zone or stuck Zone 2 switchgear bus supply breaker and stuck Zone 1 switchgear bus supply breaker	0.2–5 s
	UAT via GCB	Fault outside 51 protection zone or stuck GCB, stuck Zone 2 switchgear bus supply breaker, and stuck Zone 1 switchgear bus supply breaker	4.2–20 s

Table 3-8
Summary of Zone 2 fault durations

Initiation Location	Fed Via	Fault Description	Duration
Zone 2 supply side fault	UAT (unit-connected design)	Fault outside 51 protection zone or stuck Zone 2 switchgear bus supply breaker and a stuck Zone 1 switchgear bus supply breaker	4.2–20 s
	Off-site/SAT	Fault outside 51 protection zone or stuck Zone 2 switchgear bus supply breaker and a stuck Zone 1 switchgear bus supply breaker	0.2–5 s
	Off-site/SAT	Fault outside 51 protection zone or stuck Zone 2 switchgear bus supply breaker, a stuck Zone 1 switchgear bus supply breaker, and stuck switchyard breaker	0.4–5.2s
Zone 2 main bus bar fault	All lineups	Fault with functional Zone 2 switchgear bus supply breaker	≤ 2 s
	All lineups	Fault with stuck Zone 2 switchgear bus supply breaker and functional Zone 1 switchgear bus supply breaker	≤ 4 s
	UAT via GCB	Fault with stuck Zone 2 switchgear bus supply breaker and stuck Zone 1 switchgear bus supply breaker*	0.2–5 s
	UAT via GCB	Fault with stuck GCB, stuck Zone 2 switchgear bus supply breaker, and stuck Zone 1 switchgear bus supply breaker**	4.2–20 s
	UAT (unit-connected design)	Fault with a stuck Zone 2 switchgear bus supply breaker and a stuck Zone 1 switchgear bus supply breaker*	4.2–20 s
	Off-site/SAT	Fault with a stuck Zone 2 switchgear bus supply breaker and stuck Zone 1 switchgear bus supply breaker*	0.2–5 s
	Off-site/SAT	Fault with a stuck Zone 2 switchgear bus supply breaker, stuck Zone 1 switchgear bus supply breaker, and stuck switchyard breaker**	0.4–5.2s
Zone 2 load side fault	All lineups	Functional Zone 2 switchgear load breaker	cycles
	All lineups	Fault with stuck switchgear load breaker and functional Zone 2 switchgear bus supply breaker	≤ 2 s
	All lineups	Fault with stuck Zone 2 switchgear load breaker, a stuck Zone 2 bus supply breaker, and a functional Zone 1 switchgear bus supply breaker*	≤ 4 s
	UAT via GCB	Fault with stuck Zone 2 load breaker, stuck Zone 2 switchgear bus supply breaker, and stuck Zone 1 switchgear bus supply breaker**	0.2–5 s
	UAT via GCB	Fault with stuck Zone 2 load breaker, stuck GCB, stuck Zone 2 switchgear bus supply breaker, and stuck Zone 1 switchgear bus supply breaker**	4.2–20 s
	UAT (unit-connected design)	Fault with stuck Zone 2 load breaker, stuck Zone 2 switchgear bus supply breaker, and a stuck Zone 1 switchgear bus supply breaker**	4.2–20 s
	Off-site/SAT	Fault with stuck Zone 2 load breaker, stuck Zone 2 switchgear bus supply breaker, and stuck Zone 1 switchgear bus supply breaker**	0.2–5 s
	Off-site/SAT	Fault with stuck Zone 2 load breaker, stuck Zone 2 switchgear bus supply breaker, stuck Zone 1 switchgear bus supply breaker, and stuck switchyard breaker**	0.4–5.2 s

*If fault is within the Zone 2 bus supply circuit breaker 51 zone of protection, then this scenario requires two independent failures.

**If fault is within the Zone 2 bus supply circuit breaker 51 zone of protection, then this scenario requires at least three independent failures.

Figure 3-18 shows the fault durations for Zone 2 based on fault location within the switchgear, breakers upstream that can clear the fault, power source, generator circuit breaker (if installed), and performance of switchyard breakers. The end states that are associated with successful protection and not capable of producing HEAF-level consequences are shown in light gray text.

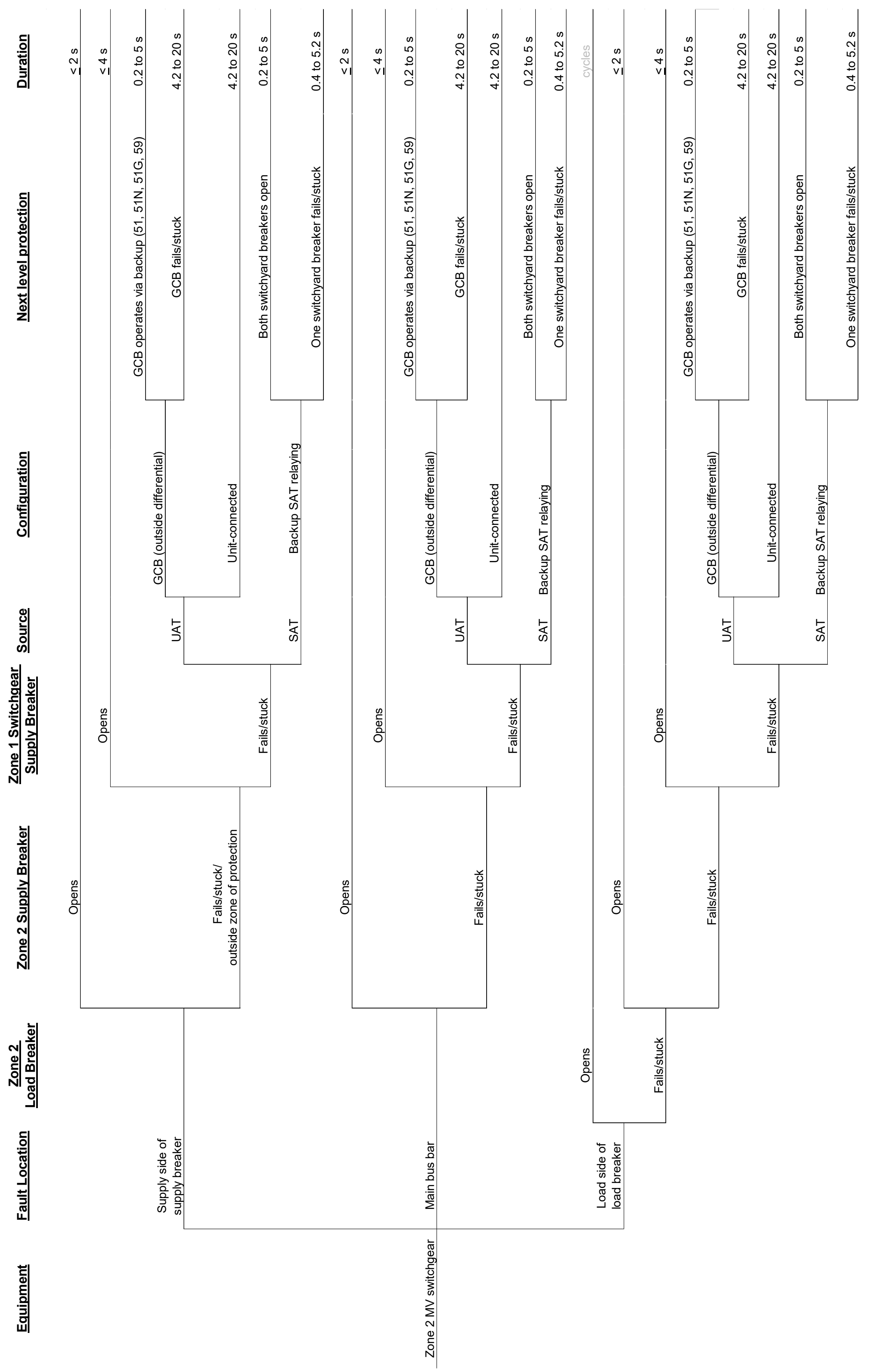


Figure 3-18
Zone 2 fault durations

3.9 Zone BD2 Fault Durations

This section evaluates faults that initiate in the NSBD that feeds Zone 3 (load centers) from Zone 2 (second MV switchgear).

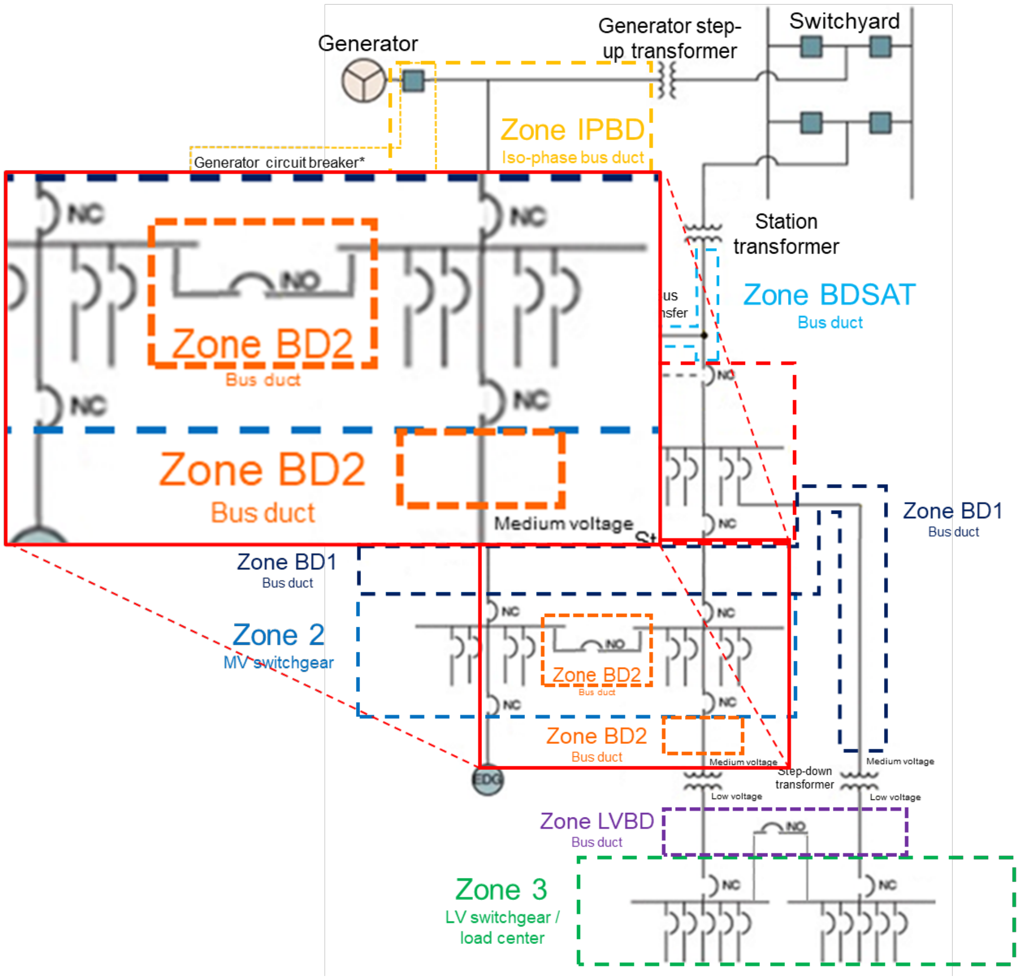


Figure 3-19
Zone BD2: MV NSBD (Bin 16.1-2)

BD2 is an extension of the Zone 2 switchgear load branch portion of the switchgear. In this case, the power flows through a step-down transformer that serves the load centers.

Protection is expected to be a TOC relay (51) that will trip the bus supply circuit breaker to the load center transformer in less than 2 s, because it must be selectively coordinated with and operate before the upstream Zone 2 bus supply circuit breaker. Therefore, a fault in Zone BD2 will have the same fault progression as a fault that occurs in the Zone 2 load breaker, except that the duration is 2 s rather than cycles.

> Note: Zone 2 load breakers serving Zone 3 do not have an instantaneous (50) trip element (or if they do, it is set above the available fault current and is considered nonfunctional). As such, for proper coordination with the Zone 2 bus supply circuit breaker, the Zone 3 bus supply circuit breaker (which is a Zone 2 load branch) TOC (51) relay is set slightly lower than the Zone 2 supply breaker. This is the basis for an arc duration under 2 s rather than under 4 s (as for Zone 1) as described in Section 3.2.3.

3.9.1 Zone BD2 Fault Duration Summary

Table 3-9 documents the range of fault durations in Zone BD2. The duration ranges associated with at least three independent protection system failures are based on operation of the auxiliary power transformer backup TOC (51) protection (i.e., UAT and SAT). Although the arc voltage is expected to remain the same throughout the MV EDS, the fault-current magnitude may be attenuated by circuit impedance, and the time to fault clearing may be a fraction of a second slower. In properly designed medium voltage EDS systems, the fault current is still expected to be in the range of the 51 overcurrent inverse-time characteristic curve, such that the total integrated FCT energy and corresponding ZOI will not appreciably change.

Table 3-9
Summary of Zone BD2 fault durations

Zone	Fed Via	Fault description	Duration
BD2	All	Fault with a functional Zone 2 switchgear load branch breaker	≤ 2 s
	All	Fault with a stuck Zone 2 switchgear load branch breaker and a fully functional Zone 2 switchgear bus supply breaker	≤ 2 s
	All	Fault with a stuck Zone 2 switchgear load branch breaker, a stuck Zone 2 switchgear bus supply breaker, and a functional Zone 1 switchgear bus supply breaker**	≤ 4 s
	UAT via GCB	Fault with a stuck Zone 2 load breaker, a stuck Zone 2 switchgear bus supply breaker, and a stuck Zone 1 switchgear bus supply breaker***	0.2–5 s
	UAT via GCB	Fault with a stuck Zone 2 load breaker, a stuck Zone 2 switchgear bus supply breaker, a stuck Zone 1 switchgear bus supply breaker, and a stuck GCB****	4.2–20 s
	UAT (unit-connected design)	Fault with a stuck Zone 2 load breaker, a stuck Zone 2 switchgear bus supply breaker, and a stuck Zone 1 switchgear bus supply breaker***	4.2–20 s
	Off-site/SAT	Fault with a stuck Zone 2 load breaker, a stuck Zone 2 switchgear bus supply breaker, and a stuck Zone 1 switchgear bus supply breaker***	0.2–5 s
	Off-site/SAT	Fault with a stuck Zone 2 load breaker, a stuck Zone 2 switchgear bus supply breaker, a stuck Zone 1 switchgear bus supply breaker, and a stuck switchyard breaker****	0.4–5.2 s

**Two independent failure scenario.

***Three independent failure scenario.

****Four independent failure scenario.

Figure 3-20 shows the fault durations for Zone BD2 based on the operation of breakers that can clear the fault, power source, generator circuit breaker (if installed), and performance of switchyard breakers.

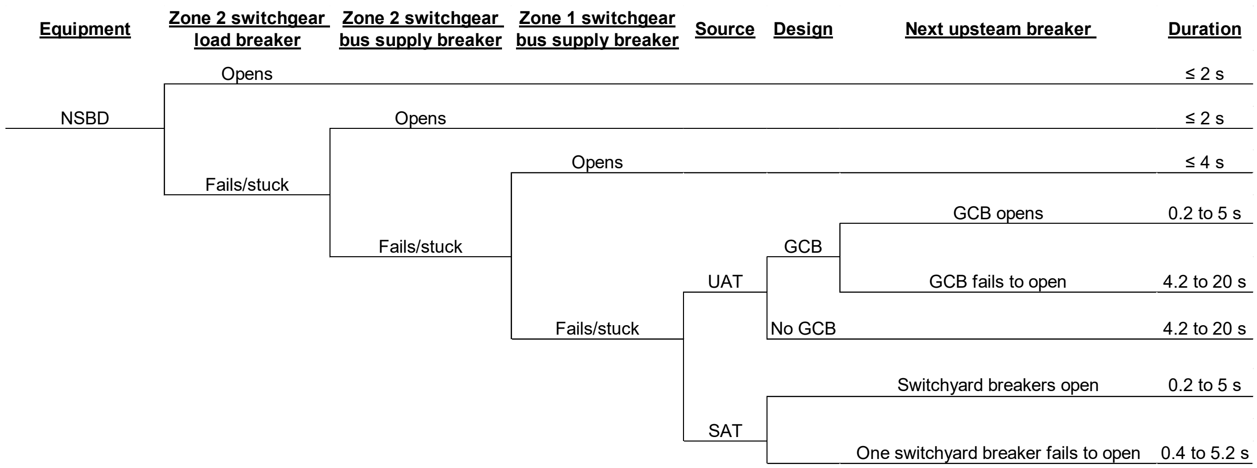


Figure 3-20
Zone BD2 fault durations

3.10 Zone LVBD Faults

This section evaluates faults that initiate in the NSBD that feeds Zone 3 (load centers) from the secondary side of the step-down transformer or between load centers in Zone 3.

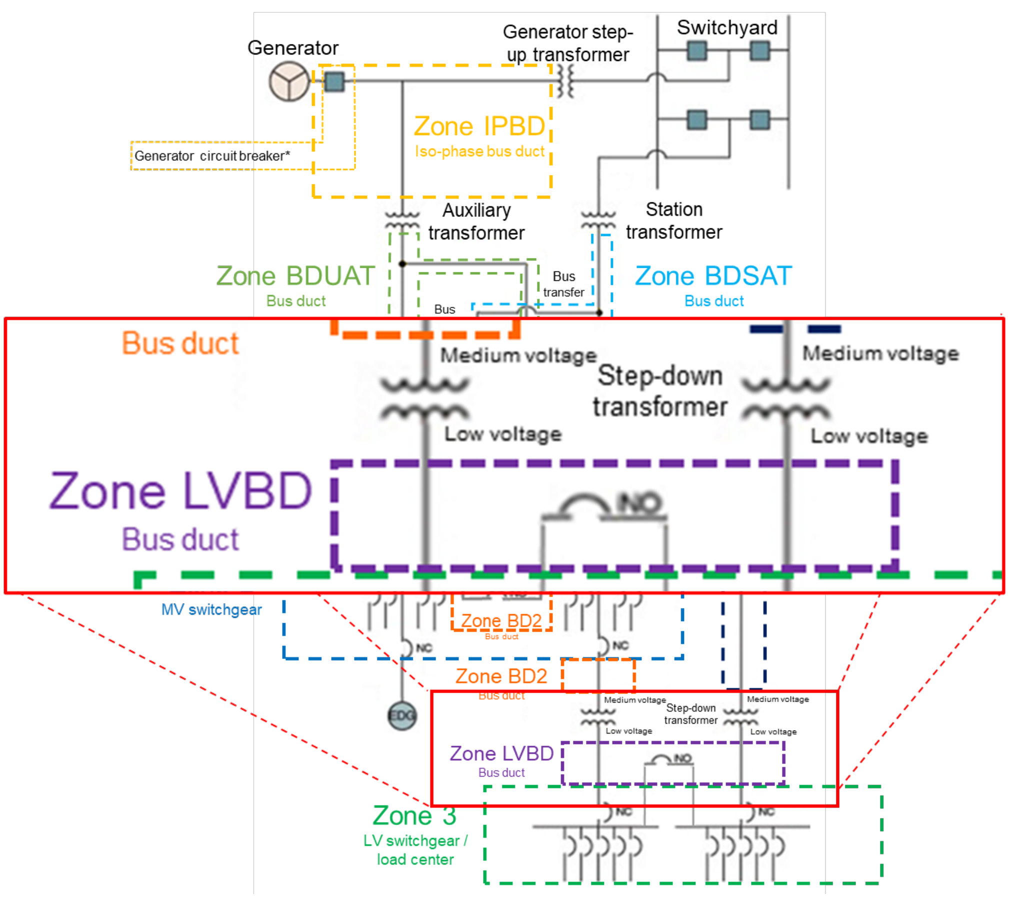


Figure 3-21
Zone LVBD: LV NSBD (Bin 16.1-2)

A LVBD is sometimes used as a connection between the secondary side of a step-down transformer and the load center when the transformer is not an integral section of the load center or connected with cables. In this case, the power flows through a step-down transformer that serves the load centers.

Protection is expected to be a TOC relay (51) that will trip the load branch circuit breaker to the load center transformer (transformer protection) in typically less than 2 s because it must be selectively coordinated with and operate before the upstream bus supply circuit breaker.

A LVBD may also connect load centers and is an extension of a load center load branch to another load center or motor control center (MCC). This may be through a straight connection or a load circuit breaker from the supplying load center.

Protection for these cases is expected to be a TOC relay (51) of the load branch circuit breaker or the supply breaker of the load center feeding the fault and is expected to operate within 2 s (because circuit breakers must be selectively coordinated).

3.10.1 Zone LVBD Fault Duration Summary

Table 3-10 summarizes the fault durations in Zone LVBD.

Table 3-10
Summary of Zone LVBD fault durations

Zone	Fed Via	Fault Description	Duration
LBVD	All	Fault with a functional upstream MV switchgear load breaker	≤ 2 s
	All	Fault with a functional upstream LV supply breaker	≤ 2 s

3.11 Load Center (Zone 3) Faults

Zone 3 involves fault scenarios in load centers.

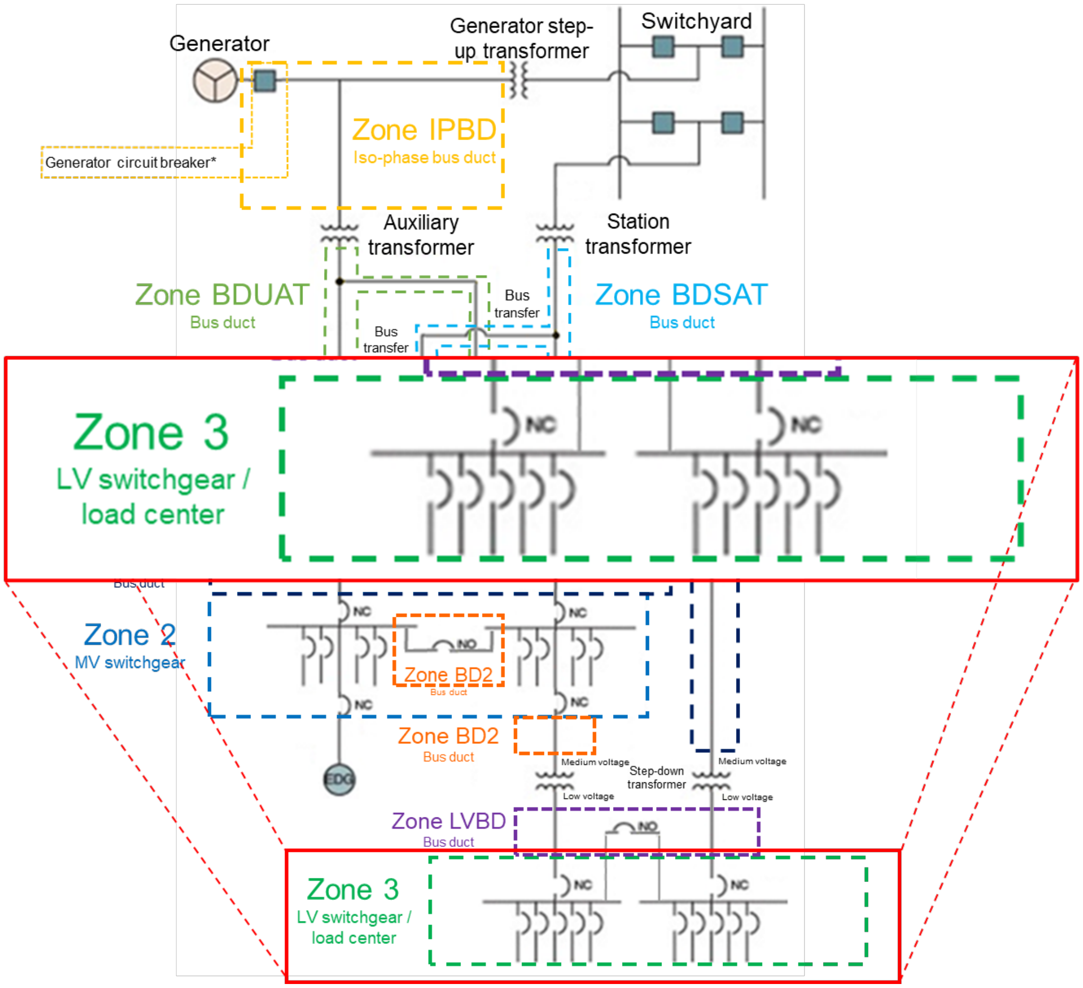


Figure 3-22
Zone 3: Load centers (Bin 16.a)

For a fault in Zone 3, the following protection elements are credited to limit the fault duration:

- Load center transformer protection: For the purposes of the fault progression analysis, the step-down transformer is considered small (under 3000 kVA) and is not protected by a differential protection (87) scheme. It is protected by the upstream MV feeder circuit breaker fed from either Zone 1 or Zone 2 (see Figure 3-1) using standard TOC (51) relays (located in Zone 1 or Zone 2).
    - TOC (51) – delay: This relay operates after a time delay. The relay's primary purpose is to protect the load center transformer from faults and extreme overloads. Time delay varies with the overload severity. It is selected and set to protect the transformer and be selectively coordinated with the respective upstream MV switchgear bus supply circuit breaker. These relays are of the inverse TOC type where the FCT is inversely proportional to the fault current.

- Load center low-voltage power circuit breaker (LVPCB): LVPCBs operate similarly to MV circuit breakers. CTs sense current; however, their trip unit characteristics differ from standard MV overcurrent relays. These trip units may include long-time, short-time, and instantaneous protection TCC zones.
  - The load center bus supply circuit breaker includes the TCC characteristic above, with the exception that it will not have an instantaneous element (or it is set above the available system fault current). The fast trip associated with the supply breakers is the short-time delay trip. It is set to be selectively coordinated with all the load breakers and is typically limited to a 0.5 s or shorter trip delay at the system available fault current.
  - Transformer protection may not always be selectively coordinated with the load center bus supply circuit breaker (in certain areas). When only one load center is supplied by a transformer (the typical case), it does not matter which breaker trips first for a fault in the load center (i.e., the MV load branch circuit breaker or load center bus supply circuit breaker). This overlap is limited and typically occurs in the region between the fault and overload.

3.11.1 Zone 3 Protection Overview

Per historical operating experience, LV HEAFs occur less frequently than MV HEAF events. The only two load center HEAF events originated in the bus supply circuit breaker cubicle at the connection stab finger cluster area (inside the load center breaker compartment), and no HEAF events have been reported in the load center main bus bar compartment. The following two factors are theorized to influence the low frequency of LV HEAFs:

- Available energy
- Compartment geometry, including the free air volume, bus bar design arrangement, and others

Both LV HEAF events involved arcing currents below the TOC (51) setting for rapid isolation (in one case, the arc persisted for 41 s and still had to be manually terminated). The other reported HEAF event similarly stated that that the current was too low to be rapidly isolated by the TOC (51) relay and ultimately self-extinguished (no duration was given). The descriptions of the LV HEAF events indicate that the current part of the energy was relatively low compared to MV HEAF events. However, larger load center transformers (e.g., over 2500 kVA) have the potential to allow larger energy let-through to sustain high-impedance arcing faults if the corresponding TOC (51) relay settings are too high.

Arcing events in LV systems escalate to HEAFs less frequently because they do not have the energy to sustain, and typically remain as arc flash events.

Zone 3 Load Center Geometric Effects on Arc Development

Load center circuit breaker cubicles are tightly confined spaces. The main bus work and runback bus bars are in a relatively much larger common compartment that mostly consists of free air volume.

The two OPEX events were caused by high-resistance circuit breaker connections that originated in the circuit breaker cubicle (a tightly confined air space). It is postulated that over time, the high-resistance breaker connection heated the connections. This further increased the connection resistance until a thermal runaway condition occurred, in which the current increased sufficiently to arc over and ionize the air between breaker connection stabs. (The circuit breaker stabs were located within the breaker cubicle, a tight space with very little free air. The arc was able to ionize the limited air volume to a temperature that could sustain the arc.)

This part of the load center (breaker finger stabs) is composed of copper before transitioning to the main bus bars (regardless of the balance of the load center current-carrying conductor materials such as aluminum or copper. There is no known use of aluminum as a medium in the circuit breaker connection stab finger design.

Compared to the load center main bus bar compartment, this is a much larger compartment of free volume. Even if an arc were to develop between bus bars, the driving arc voltage is too low for a long arc length. In addition, much more air needs to be ionized to achieve the equilibrium necessary to sustain the arc for a long period of time. Furthermore, the arc tends to travel quickly along the main bus bars away from the source until it reaches the ends of the bus bars, where the arc length increases and self-extinguishes.

This rapid, self-extinguishing arcing behavior was observed in several of the 2019 NRC's LV tests [10] on the same test unit with an arc initiation wire placed in multiple locations throughout the load center main bus. Only one test was able to sustain an arc for the intended 8 s, where the voltage and current were increased to a level that would challenge realism when factoring in transformer size and protection settings. For example, based on a review of several protection and coordination calculations, a fault for a 1500 kVA transformer is expected to clear by the upstream MV branch circuit breaker or transformer protection within 3.5 s for a fault magnitude of 20 kA (or more). A test performed at 600 VAC at 19.4 kA, which is 4.4 kA greater than 15 kA, typically cleared in 8 s (or less) for a 1500 kVA transformer. Therefore, a fault is expected to be isolated in significantly less than 8 s for a fault current of 19.4 kA, given transformers smaller than 1500 kVA (based on arc wire location being on the main bus bars downstream of the supply breaker).

However, for cases in which a larger 2500 kVA transformer is used, it may be possible to see fault currents at the 25 kA level for 8 s if the load center supply circuit breaker has failed (stuck). It is expected that at fault currents of this magnitude, the fault would be cleared by the upstream transformer protection (i.e., some overlap in LV bus supply circuit breaker and transformer protection TOC TCC curves).

Therefore, for fault currents that exceed the tripping threshold in the rapid-clearing part of the TOC relay, the backup protection can be considered the dedicated load center transformer protection scheme and the fault terminated within the given long TOC-tripping characteristics of the 51 relay protecting the transformer.

3.11.2 Zone 3 Operating Experience

Both load center HEAF events originated in the load center bus supply circuit breaker. Therefore, the LV bus supply breaker could not be credited to isolate the fault (and was treated as stuck). Because the arc was on the line-supply side of the circuit breaker, upstream protection would be required to clear the fault. Reportedly, the current was too low to trip the remaining upstream active protection (e.g., upstream load center transformer protection circuit breaker); therefore, credited protection is not available at these low currents for these types of faults (originating as high-impedance faults inside the supply circuit breaker cubicle/breaker connection stabs). For fault currents that are less than the tripping threshold in the rapid-clearing part of the TOC relay, the fault must either self-extinguish or be manually interrupted by the operator.

No operating experience has been reported where load center HEAFs originated in the main bus bar or runback bus bar compartments.

3.11.3 Zone 3 Fault Progression

The fault progression for a load center supply circuit breaker is as follows:

- For fault currents that exceed the tripping threshold in the rapid-clearing part of the transformer TOC relay (51), the backup can be considered the dedicated load center transformer protection scheme and the fault can be terminated within 2 s (see discussion of Zone BD2). This is greater than a load center's general design capability to sustain a 0.5 s duration of rated fault current. However, per IEEE [31], faults terminated in less than 2 s are within the low-energy output levels for which NRC LV switchgear tests show that damage at this duration does not represent a HEAF damage state [10].

- For fault currents that are less than tripping threshold in the rapid-clearing part of the transformer protection TOC relay, long-duration faults greater than 2 s are possible (event 50935 lasted up to 41 s at a fault current under the tripping threshold). However, the total integrated arc energy levels are expected to be no greater than 90 MJ under these circumstances (see Section 7.2).

The fault progression for a load center main bus bar fault is as follows:

- Based on operating experience, no self-sustaining LV faults that were observed on the main bus bars resulted in a HEAF. However, if the load center supply circuit breaker failed to trip (stuck closed), it is theoretically possible to produce an arc fault without sufficient resistance to trip in the rapid-clearing part of the transformer TOC (51) relay but that has a sufficiently high current level at a long enough duration to introduce arc damage below the threshold of a HEAF. However, under these circumstances, the total integrated arc energy levels are expected to be 90 MJ or less (see Section 7.2).

- For faults in which the load center supply breaker is stuck but the fault currents <u>exceed</u> the tripping threshold in the rapid-clearing part of the transformer TOC relay, the backup can be considered the dedicated load center transformer protection scheme and the fault terminated within 2 s. This is greater than the general design capability for a load center of 0.5 s per IEEE [31]. However, faults terminated in less than 2 s are within the low-energy-output level for which recent NRC tests of LV switchgear [10] show that damage at this duration does not represent a HEAF.

- For cases in which there is not a stuck closed load center supply circuit breaker, the fault is expected to clear rapidly by the load center supply LVPCB short time delay for low-impedance faults, within 0.5 s [31].

The fault progression for a load center load circuit breaker fault is as follows:

- Based on operating experience, no self-sustaining faults on the load circuit breakers or load-side connections resulted in a HEAF. However, if the load center supply circuit breaker fails to trip (stuck closed) and the fault initiates at the stuck closed load circuit breaker, it is theoretically possible to produce an arc fault that does not have sufficient resistance to trip the rapid-clearing part of the transformer TOC (51) relay but is of sufficiently high current level at a long enough duration to introduce significant arc damage. However, under these circumstances, total integrated arc energy levels are expected to be no greater than 90 MJ (see Section 7.2).

- For faults in which the load center supply circuit breaker and load circuit breaker are stuck closed, but the fault currents exceed the tripping threshold in the rapid-clearing part of the transformer protection TOC relay, the backup can be considered the dedicated load center transformer protection scheme and fault terminated within 2 s. However, faults terminated in less than 2 s are within the low-energy-output level in which recent NRC test results of LV switchgear show that damage at this duration does not represent a HEAF.

- For cases in which at least one of the load center circuit breakers (supply or load) properly trips to isolate the fault, the fault is expected to clear rapidly by the load center supply LVPCB short time delay for low-impedance faults, within 0.5 s [31].

3.11.4 Zone 3 Fault Duration Summary

Table 3-11 summarizes the range of fault durations in Zone 3.

Table 3-11
Summary of Zone 3 fault durations

Initiation Location	Fault Description	Duration
Zone 3 supply side fault	Fault current exceeding the tripping threshold of the transformer TOC relay	≤ 2 s
	Fault current lower than the tripping threshold of the transformer TOC relay	Dependent on fault current (≤ 90 MJ)
Zone 3 main bus bar fault	Functional load center supply bus breaker	0.5 s
	Stuck load center supply bus breaker and a fault current exceeding the tripping threshold of the transformer TOC relay	≤ 2 s
	Stuck load center supply bus breaker and a fault current lower than the tripping threshold of the transformer TOC relay	Dependent on fault current (≤ 90 MJ)
Zone 3 load side fault	Functional load breaker or supply bus breaker	0.5 s
	Stuck supply bus breaker and a fault current exceeding the tripping threshold of the transformer TOC relay	≤ 2 s
	Stuck supply bus breaker and a fault current lower than the tripping threshold of the transformer TOC relay	Dependent on fault current (≤ 90 MJ)

Figure 3-23 shows the fault durations in Zone 3 based on fault location, performance of the load center supply breaker and if the fault current is above or below the relay setting.

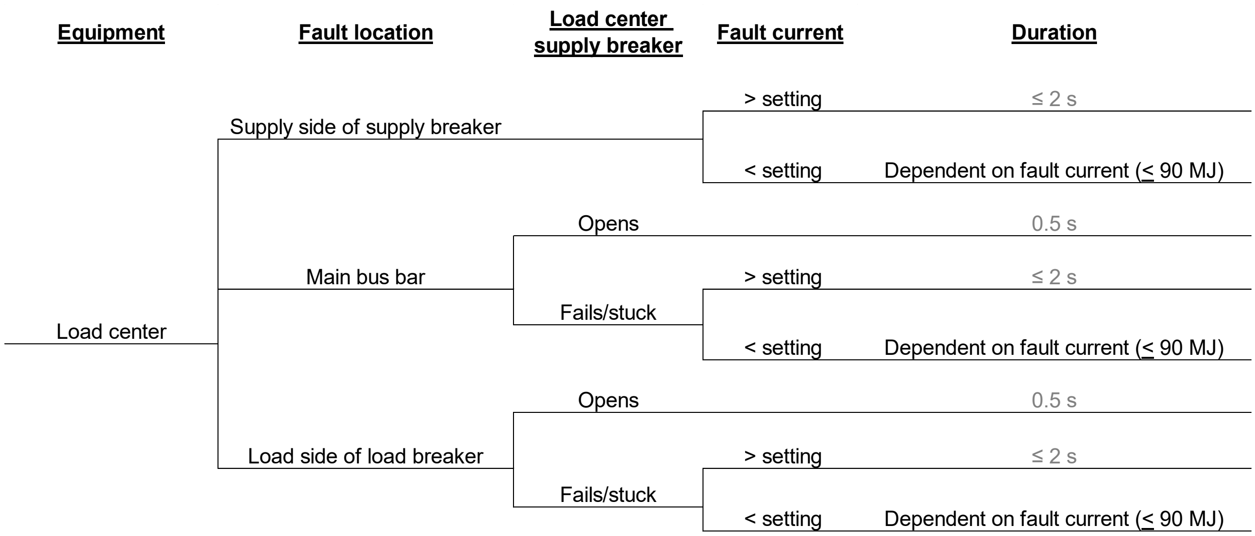


Figure 3-23
Zone 3 fault durations

4
U.S. NUCLEAR POWER PLANT ELECTRICAL DISTRIBUTION SYSTEM HEAF OPERATING EXPERIENCE

This section consolidates pertinent information about HEAF events. The EPRI fire events database (FEDB) documents 23 HEAFs from 1979 to 2021 [32,33]. HEAF events release significantly more energy than arc flash events and may result in extensive equipment damage that can challenge plant operation.

This section provides information about these events for determining HEAF end states and frequencies. This section consists of the following four subsections.

- Section 4.1: HEAF event overview/commonality observations
- Section 4.2: HEAF events where protective devices worked as designed
- Section 4.3: HEAF events with protective device failures
- Section 4.4: HEAF events where currents were too low for isolation by protective devices

Table 4-1 summarizes the HEAF events considered in HEAF frequency calculation. The working group determined that these events meet the threshold for inclusion in the HEAF-related frequency bins. For each event, Table 4-1 contains the FEDB identifier (event ID), the date of the event, the equipment and ignition source bin, and notable event characteristics that are reviewed in the following sections.

Table 4-1
Summary of HEAF events considered

Event ID	Date	Location	HEAF Characteristics
575	3/19/1987	NSBD (Bin 16.1-1)	Generator-fed fault (Table 4-2) Protective device/scheme (PDS) operated correctly (Section 4.2 and Table 4-3)
922	7/10/1987	NSBD (Bin 16.1-1)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
678	3/2/1988	NSBD (Bin 16.1-1)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
100	5/15/2000	NSBD (Bin 16.1)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)

Table 4-1
Summary of HEAF events considered (cont.)

Event ID	Date	Location	HEAF Characteristics
10584	7/27/2008	NSBD (Bin 16.1-1)	PDS operated correctly (Section 4.2 and Table 4-3)
162	8/5/2009	NSBD (Bin 16.1-1)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
50909	3/7/2010	NSBD (Bin 16.1-2)	PDS operated correctly (Section 4.2 and Table 4-3)
50926	2/12/2011	NSBD (Bin 16.1-2)	Protective device failure (Section 4.3 and Table 4-4)
51291	12/9/2013	NSBD (Bin 16.1-1)	Generator-fed fault (Table 4-2) Protective device failure (Section 4.3 and Table 4-4)
51764	1/17/2017	NSBD (Bin 16.1-1)	PDS operated correctly (Section 4.2 and Table 4-3)
51765	12/16/2020	NSBD (Bin 16.1-1)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
929	10/9/1989	IPBD (Bin 16.2)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
127	6/18/2004	IPBD (Bin 16.2)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
51199	7/26/2013	IPBD (Bin 16.2)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
434	8/2/1984	LVSWGR (Bin 16.a)	Current lower than isolation protection device (Section 4.4 and Table 4-5)
50935	6/7/2011	LVSWGR (Bin 16.a)	Current lower than isolation protection device (Section 4.4 and Table 4-5)
732	7/6/1988	MV SWGR (Bin 16.b)	PDS operated correctly (Section 4.2 and Table 4-3)
947	1/3/1989	MV SWGR (Bin 16.b)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)

Table 4-1
Summary of HEAF events considered (Cont.)

Event ID	Date	Location	HEAF Characteristics
74	6/10/1995	MV SWGR (Bin 16.b)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
106	2/3/2001	MV SWGR (Bin 16.b)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
112	8/3/2001	MV SWGR (Bin 16.b)	Generator-fed fault (Table 4-2) PDS operated correctly (Section 4.2 and Table 4-3)
50910 (first event)	3/28/2010	MV SWGR (Bin 16.b)	Protective device failure (Section 4.3 and Table 4-4)
50910 (second event)	3/28/2010	MV SWGR (Bin 16.b)	Protective device failure (Section 4.3 and Table 4-4)

4.1 Overview/Commonality Observations

The majority of HEAFs occurred within the non-Class 1E and power production parts of the EDS:

- Twenty-two of the HEAF events were on non-Class 1E systems.
- One HEAF event was on the LV Class 1E system.

Seven out of nine HEAFs that originated within MV and LV switchgear originated at the switchgear supply breaker. Possible reasons include the following:

- Switchgear protective device settings must be selectively coordinated with all load breakers, including the largest. By default, supply breakers do not contain instantaneous trip elements

  (IEEE/ANSI 50 relay). For example, in terms of the energy delivered (RI^2t), supply circuit breakers allow as much as 40 times more energy to feed a fault than a load breaker does (e.g., 120 cycles [supply] for fault interruptions versus three cycles [load]).

- Switchgear arcing events have occurred with load breakers. However, given the speed of load breaker interruption (e.g., three cycles) due to the IOC relays (IEEE/ANSI 51 relay), these are limited to arc flash events and do not escalate to HEAF events.

Out of 23 events, at least 14 (61%) originated within the unit-connected design as defined in EPRI 3002015992 [12] and resulted in a generator-fed HEAF for an estimated duration range of 4-15 s:

- Three events originated in the iso-phase bus duct (Bin 16.2).

- Seven events originated in bin 16.1, NSBD, downstream of the UAT secondary/tertiary and upstream of the switchgear bus supply circuit breaker.
- Three of these events consisted of switchgear bus supply circuit breaker failures that were involved with an active bus transfer at the time. (These resulted from manual bus transfers from off-site power to the generator-fed UAT during power ascension activities).
- One of these events occurred as part of an automatic bus transfer failure at 100% power due to a grid response.

In these 14 events, a breaker was not available to isolate the generator's coast-down energy from feeding the faults. Table 4-2 lists the generator-fed events, originating equipment, and additional detail for each event.

The other nine HEAF events had variable circumstances as follows:

- Two MV NSBD events were fed from the off-site power (SAT).
- Three were due to failed primary electrical protection as follows:
    - MV switchgear upstream circuit breaker had no DC control/trip power because of a failed fuse (stuck breaker)—two events.
    - LV NSBD failed because of failed protection (mechanical failure of 86 lockout device)
- Two LV events involved the load center main bus supply circuit breaker (one of these events occurred on a Class 1E load center). The HEAF energy was primarily due to the time component (duration) because the fault current was too low for the upstream protection to isolate the fault in a timely manner. The following occurred:
    - The HEAF was manually isolated by opening the upstream transformer circuit breaker by operations after 41 s.
    - The HEAF self-extinguished before the overcurrent (51) relay timed out.
- One primary cable compartment bus bar (PCCBB) HEAF occurred without a circuit breaker. This was a bus-tie and the upstream bus supply circuit breaker operated per design.
- One lower-tier MV NSBD had one circuit breaker downstream of the UAT. The upstream bus supply breaker operated per design.

Table 4-2
Generator-fed HEAF events

Event ID	Date	Equipment	Additional Information
51199	7/26/2013	IPBD	Generator-fed fault for approximately 10 s
929	10/9/1989	IPBD	Fault within the iso-phase bus duct
127	6/18/2004	IPBD	Fault started in the IPBD at the main transformer low voltage bushing box.
51291	12/9/2013	NSBD	Reported duration: 4-5 s until UAT exploded. Note: UAT protection was disabled (87 trip leads lifted), and the fault was detected 6 s later by upstream unit differential protection (387) and initiated generator lockout.
162	8/5/2009	NSBD	Between UAT and switchgear bus supply breaker
100	5/15/2000	NSBD	Between UAT and switchgear bus supply breaker
678	3/2/1988	NSBD	10 ft damage and damage to adjacent cables
922	7/10/1987	NSBD	30 ft damage
575	3/19/1987	NSBD	Damage to both 4 kV and 6.9 kV NSBD
51765	12/16/2021	NSBD	Damage limited to the NSBD
112	8/3/2001	MV SWGR	Bus transfer failure (supply breaker from UAT)
106	2/3/2001	MV SWGR	Catastrophic breaker fault
74	6/10/1995	MV SWGR	Bus transfer failure (supply breaker from UAT)
947	1/3/1989	MV SWGR	Integrated control system (ICS) damage

4.2 HEAF Events Where Protective Devices Worked as Designed

The working group reviewed the HEAF events to document fault location and duration for 17 of the 23 events in which the protection schemes operated as expected.

The HEAF duration is based on the maximum expected speed of the PDS reported in the operating experience (see notes prior to Table 4-3).

The speed of the protective device does not always define the duration of a HEAF event. The most commonly observed scenario is a generator-fed fault. Even though the protection system immediately detects and rapidly initiates a generator protection lockout (tripping switchyard breakers and generator exciter field breaker in cycles), the generator continues to feed the fault through the UAT until the arc voltage collapses and can no longer sustain the fault. Generator-fed faults are given the range of 4-15 s.

However, outside of generator-fed faults and without explicit HEAF duration in the operating experience, the default HEAF duration is considered to be the maximum expected time for the PDS to act.

Table 4-3 is ordered as follows:

- HEAF events that are interrupted by the PDS are presented first, grouped by location within the EDS (HEAF ignition source bins)
- Generator-fed faults are presented at the end of the table, grouped by location within the EDS (HEAF ignition source bins)

A few of the HEAF event descriptions provide the actual PDS operating time. However, many of the events reported the protection scheme that detected the fault and operated (e.g., main generator protection, transformer differential protection/lockout, or bus supply breaker overcurrent). Conservative assumptions about PDS speed assuming proper operation are the following:

- Main generator protection: five to eight cycles (within 0.15 s).
- Differential/lockout protection: five to eight cycles (within 0.15 s).
- Load breaker (e.g., motor): five to eight cycles (within 0.15 s).
- Instantaneous overcurrent (IOC–ANSI 50 device): three to eight cycles (within 0.15 s).
- Timed overcurrent (TOC–ANSI 51 device): variable.[5]
- If overcurrent trip description does not distinguish between TOC and IOC: within 4 s.
- Bus supply breaker is assumed to be selectively coordinated with associated downstream load protective devices for motors and transformers (load centers), which will introduce additional layers of protection than just the final load breaker—the maximum coordinated TOC relay (51) delay for these breakers: within 4 s.
- Other: Some of the event descriptions only provide generic messages such as “protection cleared the fault before major damage” or “fault cleared quickly,” and do not identify the protection scheme that operated or its duration. In these cases, the delay is assumed to be within 2 s.
- Undervoltage relays have been reported to operate because of depressed voltage during the fault. Some are inherently instantaneous, while other stations insert a short time delay to ride through anticipated transients (e.g., line switching or lightning) and may have up to a 0.75 s delay (within 0.75 s).

[5] Assumed within 4 s for a switchgear bus supply circuit breaker downstream of an auxiliary power transformer and 2 s for a switchgear bus supply circuit breaker downstream of an intermediate MV switchgear.

Table 4-3
17 out of 23 events where PDS operated correctly

Event ID	Date	HEAF Location	PDS	PDS Speed	Damage/Notes
51764	1/17/2017	NSBD	TOC	about 1 s	1. HEAF duration = PDS speed 2. Power alignment: off-site power (ESST)
50909	3/7/2010	NSBD	Ground fault and lockout bus overcurrent relays	≤ 2 s	1. HEAF duration = PDS Speed 2. NSBD purpose is bus tie and downstream of intermediate switchgear bus supply circuit breaker fed from UAT 3. Damage was limited to faulted section of bus duct 4. Successful opening of UAT bus supply breaker to bus/NSBD
10584	7/27/2008	NSBD	Relay operation resulted in clearing the 161-kV line (operated per MCR annunciation)	≤ 2 s	1. HEAF duration = PDS Speed 2. Power alignment: off-site power Outdoors: Damage was identified as failed bus work between cooling tower transformer A and the C and D cooling tower switchgear (failed flex link)
732	7/6/1988	SWGR powered by SAT: Bus cross-tie breaker closed in on fault by operations	TOC	about 1.15 s	1. HEAF duration: about 1.15 s 2. Three-phase fault (This event is counted as Bin 16.b HEAF)
51199	7/26/2013	IPBD	Unit differential trip and main generator lockout	0.33 s (20 cycles)	HEAF duration: 4–15 s (generator-fed fault) Fault followed routine monthly IPBD cooling fan swap (dislodged backdraft damper blade)
929	10/09/1989	IPBD	Main generator and transformer differential protection	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault)
127	6/18/2004	IPBD	Main generator protection	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault)
162	8/5/2009	NSBD	Main generator differential lockout	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault)
100	05/15/2000	NSBD	Main generator (differential) protection (immediate trip)	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault)
678	3/2/1988	NSBD	Differential protection immediately cleared fault	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault)

Table 4-3
17 out of 23 events where PDS operated correctly (cont.)

Event ID	Date	HEAF Location	PDS	PDS Speed	Damage/Notes
922	7/10/1987	NSBD	Available documentation does not address protection actuation (assumed differential protection operated similar to event 678)	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault)
575	3/19/1987	NSBD	Differential protection immediately actuated	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault) The destructive nature of the fault hampered investigation; not known in which bus duct (4 kV or 6.9 kV) the initial fault occurred
51765	12/16/2021	NSBD	Differential protection immediately actuated	0.15 s	HEAF duration: 4–15 s (generator-fed fault)
112	8/3/2001	SWGR: bus supply circuit breaker from UAT/MAT (primary stabs)	Generator transformer protection scheme, including bus lockout**	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault) Bus transfer failure
106	2/3/2001	SWGR: bus supply circuit breaker (consequential second fault in RAT breaker cubicle)	UAT differential and overload protection**	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault) Bus transfer failure
74	6/10/1995	SWGR: supply breaker from UAT	Main generator protection scheme	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault) Note: Fast dead bus transfer scheme failure (UAT and SUT) unintentionally paralleled on switchgear bus
947	1/3/1989	SWGR: cause of failure unknown; however, bus transfer was in progress**	UAT (1T) Φ differential alarms, generator lockout and turbine trip**	< 0.15 s	HEAF duration: 4–15 s (generator-fed fault) (ICS cable damage)

**Active manual bus transfer by operations from off-site power to the UAT in support of startup/power ascension at time of HEAF event.

4.3 HEAF Events with Protective Device Failures

Four HEAF events reported failures of the primary protection scheme resulting in extended HEAF durations beyond the equipment rating of the equipment. One resulted in a generator-fed fault with significant damage (UAT catastrophic failure).

Table 4-4
Four out of 23 HEAF events with protective device failures

FEDB ID	Date	Location	HEAF Duration	Protection Failures
51291	12/9/2013	NSBD	6 s (generator was still on-line: both the generator and switchyard were feeding the HEAF through UAT)	1. **Primary:** UAT differential relay (187AT) trip leads were disconnected (nonfunctional). If functional, would have initiated generator lockout in six cycles (0.1 s). 2. **Backup:** Per SOE, the unit differential relay (387) actuated 6 s into the event and successfully initiated the generator lockout; however, by that time the UAT had catastrophically failed. 3. **Generator-fed fault:** Did not commence until after 6 s; however, by that time the decaying generator energy was feeding the UAT fault/fire, not the NSBD.
50926	2/12/2011	NSBD (480 VAC)	12 s	1. **Primary:** Protective relay failed to initiate a trip due to mechanical binding of the 86 lockout relay latch mechanism. 2. Fault cleared itself after 12 s.
50910 (two events)	3/28/2010	1. Cable (switchgear source of power) 2. Switchgear tie breaker	First event: 20 s Second event: 3 min (the fault current was initially too low to trip 52/19 until the arc flash occurred 3 min later)	<u>**First fault:**</u> **Primary:** Loss of dc control power resulted in breaker 52/24 failing to open and clear fault (failed dc control fuse: maintenance oversight). **Secondary:** Protection from upstream breaker 52/20 began timing but did not operate in sufficient time to prevent UAT failure (sudden pressure relay [SPR] actuated). UAT may have had preexisting vulnerability, or the backup protection (breaker 52/20) was not optimally set to protect the UAT from excessive let-through current. Bus 4 transferred from the UAT to the SUT and fault cleared by cross-tie breaker 52/19 protective overcurrent device. <u>**Second fault:**</u> **Primary:** An attempted generator lockout reset resulted in a second HEAF event (UAT SPR signal still present and lockout re-actuated). Power (from the SAT) again flowed through the stuck 52/24 breaker, feeding the cable fault until the stuck 52/24 breaker thermally failed and breached the rear switchgear cabinet. **Secondary:** Backup/bus-tie breaker 52/19 cleared the fault (second time) via TOC (51) relay.

4.4 HEAF Events Where Currents Were Too Low for Isolation by Protective Devices

Table 4-5 document two low-voltage HEAF events where the fault current was too low to be isolated by the primary protective device.

Table 4-5
Two out of 23 HEAF events where currents were too low for protective device operation

Event ID	Date	Location	Summary	Damage
50935	6/7/2011	Load center: supply breaker (Class 1E, 480 VAC)	HEAF duration: 41 s. Fault originated at the bus supply circuit breaker copper stab connections (line side) and propagated to phases A and B of the main bus bars. The fault lasted approximately 41 s. Operators had to manually open the 4160 VAC bus supply circuit breaker upstream of the faulted breaker to deenergize the 1B4A bus [54]. The data from FEDB 50935 event was reviewed, and the fault current ranged from 1.5 kA to 4.8 kA. It was concluded that the circuit breaker did not trip earlier than 41 s because the low arcing fault current was significantly lower than the setting of the TOC (51) relay located on the upstream 4160V circuit breaker feed to the load center transformer.	Major damage to 480V incoming breaker and breaker cubicle in 480V load center due to high-resistance connection at breaker stabs
434	8/2/1984	Load center: supply breaker (480 VAC)	HEAF duration: unknown. Sequence of events: 1. The first relay sensed fault current between No. 4 SST and 480 VAC load center and tripped breaker. a. Because the fault was on the breaker's incoming side, the system continued to feed the fault. 2. The second relay between the No. 1 and No. 4 SSTs sensed the fault; however, the fault cleared itself by melting the connection between the circuit breaker and the incoming cables.	Damage localized to load center

5

HIGH ENERGY ARCING FAULT IGNITION FREQUENCY AND SUPPRESSION RATE

This section identifies the following:

- HEAF ignition source bins
- The counting guidance for apportioning generic frequencies to individual equipment
- The generic ignition frequency for each HEAF bin
- The HEAF manual non-suppression rate

5.1 HEAF Ignition Source Definitions

NUREG/CR-6850, Supplement 1, [2] defined four ignition source bins to capture the range of HEAF experience. No unique HEAF ignition sources were added based on this research. However, this research split Bin 16.1 into two bins (now Bins 16.1-1 and 16.1-2).

Switchgear and Load Centers

<u>16.a HEAF for LV electrical cabinets (480–1000V):</u> HEAFs associated with load centers.

<u>16.b HEAF for MV electrical cabinets (above 1000V):</u> HEAFs associated with switchgear.

Electrical cabinets can also have thermal fires, which are treated separately from the HEAF failure mode. NUREG/CR-6850, Supplement 1, which clarified several aspects of the HEAF modeling, states “the intent of the HEAF analysis (per Appendix M of EPRI 1011989, NUREG/CR-6850), is the capture of ‘higher-consequence’ events that may have a *substantive impact outside the cabinet of origin*. Other arc fault events (e.g., events that did not lead to an impact outside the originated panel) are already treated via the general electrical panel fire frequency, and this treatment need not be adjusted. Only the ‘higher-consequence’ events are under question.” The industry has observed events that resulted in an arc blast in which the originating cubicle experienced pressure effects. The duration of these events is typically under 2 s, and they have not resulted in an ensuing fire. These events are screened from the HEAF analysis, which captures higher-consequence events that include a blast and a fire. Additionally, arc flash events are not counted toward Bins 16.a and 16.b ignition frequencies.

Bus Ducts

<u>16.1-1 Segmented (non-segregated) bus ducts:</u> HEAFs associated with segmented bus ducts located in Zone BDUAT and Zone BDSAT.

<u>16.1-2 Segmented (non-segregated) bus ducts:</u> HEAFs associated with segmented bus ducts located in Zone BD1, Zone BD2, and Zone LVBD.

NUREG/CR-6850, Supplement 1, [2] categorized bus ducts into one of four types (the fourth identified as iso-phase bus ducts in Bin 16.2). Category 1 (non-segmented or continuous bus duct HEAFs) are typically treated with the end device and Category 3 (cable ducts) are not in scope of the HEAF analysis. The treatment of Category 2 (segmented bus ducts) is the focus of NUREG/CR-6850, Supplement 1, as outlined by the following:

> A bus duct where the bus bars are made up of multiple sections bolted together at regular intervals (transition points). Here, the bus bars are contained within open-ended sections of metal covers that are bolted together to form a continuous grounded enclosure running the full distance between termination points. Segmented bus ducts are used in cases where the required lengths and/or geometries make the use of NSBD impractical.

Applying the guidance in this report splits Bin 16.1 into two generic fire ignition frequency bins for NSBD based on the generic HEAF zones. This separation is made to better match the observations in the operating experience; most NSBD HEAFs occur in Zones BDUAT and BDSAT. It is also recognized that the length of NSBD in various zones may differ among the industry. Therefore, the development of a specific generic ignition frequency for NSBD in Zones BDUAT and BDSAT limits the opportunity of inappropriately biasing the ignition frequency should a bulk of the NSBD length be located in other zones.

16.2 Iso-phase bus ducts: A bus duct where the bus bars for each phase are separately enclosed in their own protective housing (segregated bus ducts). The primary use of iso-phase buses is generally limited to the bus work connecting the main generator to the main and auxiliary transformers.

5.2 Ignition Source Counting Guidance for HEAFs

As noted in NUREG/CR-6850 [1] and the Supplement [2], switchgear, load centers, and bus bars/ducts with energies of 440 VAC and greater are subject to HEAFs. This section provides updated counting guidance for the HEAF ignition sources.

5.2.1 Bin 16.a: HEAFs for LV Panels (480–1000 VAC)

5.2.1.1 Insights from Operating Experience

In NUREG/CR-6850, HEAF counting guidance for HEAFs directed the analyst to count by vertical section, and each vertical section has an equal likelihood of ignition. The two LV HEAF events are reviewed to determine the location within the switchgear and the subcomponent. As shown in Table 5-1, the events occurred within the supply cubicle of the load center. Load centers have at least one and potentially two supply cubicles throughout the switchgear. The revised counting guidance in Section 5.2.1.2 more accurately apportions the 16.a frequency (as the operating experience does not support equal weight to vertical sections).

Table 5-1
Location of load center HEAFs

FEDB ID	Date	Bin	Supply or load	Fault location
434	08/02/1984	16.a	Supply	Breaker
50935	06/07/2011	16.a	Supply	Breaker

No load center main bus bar compartment HEAF events have occurred in U.S. operating history. The only two LV HEAFs occurred at the circuit breaker copper stab connections.

Testing a major U.S. load center brand failed to achieve a sustainable arc at 480 VAC when initiated at the bus bars inside the main bus or runback compartments. Two separate test programs [7,10] produced similar results in that the arc that initiated at the main bus bars either self-extinguished prematurely or experienced chaotic arc migration in nine out of nine tests. A bus arc could be sustained at 600 VAC, but only in a limited location in the main bus compartment. At other locations, the arc self-extinguished in three out of the five 600 VAC bus bar tests. Insights into physical construction and test experience about the difficulty in sustaining an arc include the following:

- If no barrier impedes arc travel, the magnetic forces will propel the arc to the ends of the bus bars, where the arc elongates until the arc length exceeds the ability to sustain and it self-extinguishes.
- If the arc encounters a barrier, the arc travel is impeded, and the rapid ionization of trapped gases can sustain the arc.
- Internationally designed and constructed tests that could successfully sustain a 480 VAC arc in the main bus compartment have one of the following characteristics:
  - The main bus bars were enclosed in a confined space.
  - Multiple barriers existed in the main bus bar compartment, with at least one barrier that would impede the direction of arc travel away from the source before reaching the end of the main bus bars.
- The three major U.S. load center manufacturers construct their main bus compartments similarly with respect to (1) significant free volume and (2) absence of barriers that would impede arc travel.

The LV EDS is stepped down from the MV system by a load center transformer. In most cases, each load center has one transformer. In a few cases, an MV branch circuit may feed two or three load centers.

In the typical electrical arrangement, the transformer secondary circuit breaker is also the load center supply circuit breaker. There may be cases where there is no secondary breaker (the load center supply circuit breaker is the same as the load center transformer upstream MV circuit breaker). The transformer also has a primary-side circuit breaker. Assuming that a failure in the load center also disables the supply circuit breaker (so that it does not open under faulted conditions), the demand would be placed on the load center's transformer primary-side circuit breaker to interrupt the fault.

Because most load centers have a dedicated transformer, there are no coordination requirements between the transformer primary and load center supply circuit breakers in the TOC region. In most cases, the load center supply circuit breaker is set to operate faster than the transformer primary circuit breaker, but in a few cases, the transformer primary circuit breaker may be faster (or may be the only circuit breaker). Nonetheless, the load center transformer primary circuit breaker may be considered a backup to a stuck load center supply circuit breaker.

Therefore, HEAFs in load centers (480 VAC and 600 VAC) should only be postulated in the supply circuit breaker cubicles given that:

- The presence of instantaneous TOC (50) relays limit the fault duration downstream of the load center supply breakers.
- The two load center HEAF events occurred in the load center supply circuit breaker.
- Experimental testing has consistently shown it is difficult to maintain an arc below the supply breaker in U.S. load center configurations and designs. The main bus bar compartment is a much larger compartment of free volume, creating challenging conditions for the development of a long duration arc.
- The general power distribution arrangement of U.S. NPPs, which has the following characteristics:
    - The supply breaker in a load center will limit the fault current and duration of a fault on and below the bus bars to levels lower than what is sufficient to create HEAF-level consequences.
    - Is not susceptible to generator-fed faults.

5.2.1.2 Fire PRA Counting Guidance for Load Centers

Counting Bin 16.a load centers (also referred to as LV switchgear) differs from the counting guidance for Bin 15 electrical cabinets (which is per vertical section) and the HEAF counting guidance in NUREG/CR-6850 [1]. Bin 16.a includes load centers at typical nominal system voltage ranging from 480 VAC to 1000 VAC but also includes system voltage down to 440 VAC.

For ignition frequency apportionment, only count the load center supply breakers for HEAF susceptibility. Based on the discussions in Section 3.11.2 and Section 4.4, the most likely location of load center HEAFs is in the supply circuit breaker. The remaining locations have the following characteristics:

- The presence of instantaneous TOC (51) relays limit the fault duration downstream of the load center supply breakers.
- The main bus bar compartment is a much larger compartment of free volume, creating challenging conditions for the development and sustainability of a long duration arc.
- Given a fault at the load center bus supply circuit breaker, it is theoretically possible that the arcing fault current may be too low for proper detection and timely isolation by the TOC (51) relay associated with the upstream load center's medium voltage primary circuit breaker. Nonetheless, the resulting arc energy is expected to be below the HEAF threshold.

Figure 5-1 shows three supply breakers in red. Under the new counting guidance, the fire PRA count for this load center is three.

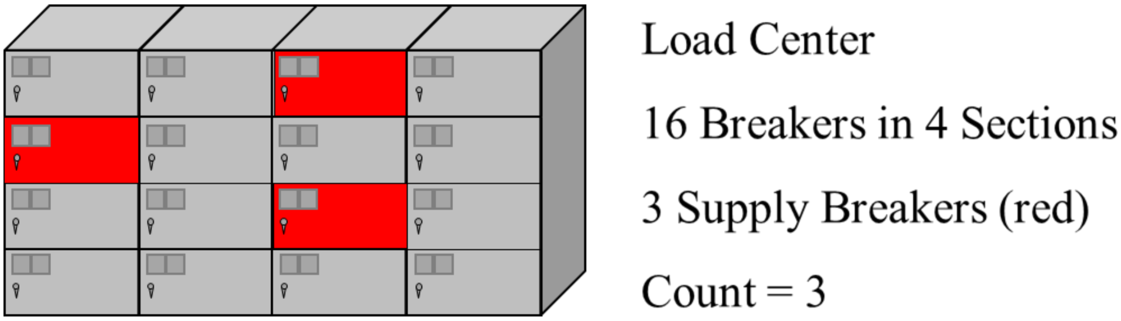


Figure 5-1
Counting of Bin 16.a load centers (modified from Figure 3-1 in Supplement 1 to NUREG/CR-6850)

Some configurations may not have a supply circuit breaker located between the step-down transformer's secondary side and the main bus bar of a load center (see Figure 5-2). If the load center does not have supply circuit breaker, do not count it as a HEAF (Bin 16.a) ignition source. The reported load center HEAFs occurred on the supply circuit breaker stabs. In conclusion, the analyst should not count or assign a ZOI for load centers that do not have supply circuit breakers.

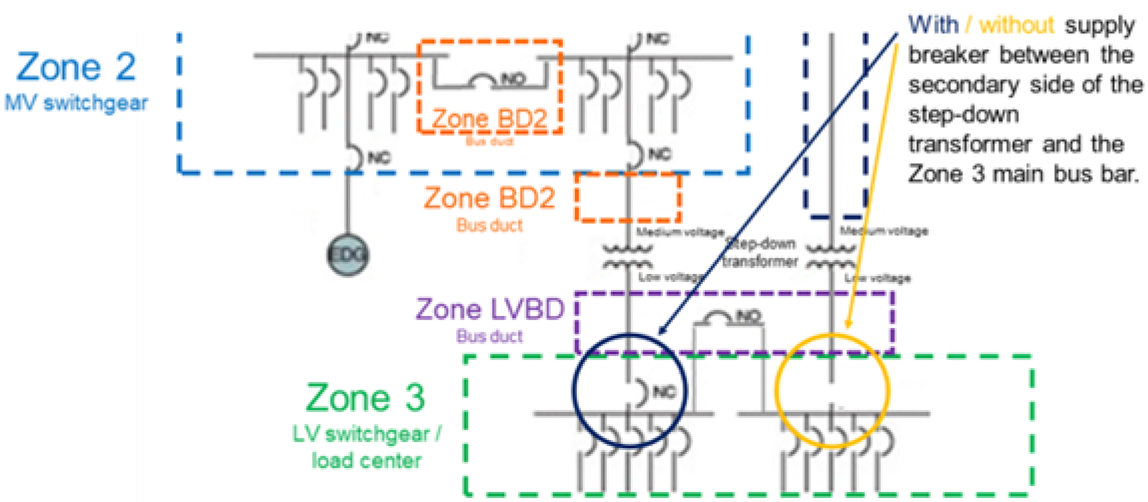


Figure 5-2
Load center with and without a supply circuit breaker between the Zone 2 main bus bar and the step-down transformer's secondary side

Motor control centers (MCCs) should not be counted as HEAF ignition sources in Bin 16.a. In general, MCCs are not directly connected to a step-down transformer and are instead connected through an intermediary load center that provides an extra level of protection and less available fault current. Appendix B discusses this further. NUREG/CR-6850, Supplement 1 [2] (FAQ 06-0017) identified that only MCCs with switchgear used to directly operate equipment such as a load center should be counted as a HEAF source. This statement's general intent was that HEAFs should be considered in LV switchgear or, in other words, MCCs with equipment (loads) operated by LVPCBs are load centers. Some MCCs use LVPCBs for the supply breaker and molded case circuit breakers (MCCBs) for loads. The working group concluded that these should be considered MCCs (and not load centers) because equipment is not directly operated by the switchgear. MCC arc flashes are treated in FAQ 14-009 [34].

5.2.2 Bin 16.b: HEAFs for MV Panels (>1000 VAC)

5.2.2.1 Insights from Operating Experience

In NUREG/CR-6850 [1], the counting guidance for HEAFs directed the analyst to count by vertical section, and each vertical section has an equal likelihood of ignition. The seven switchgear HEAF events were reviewed to determine the fault location within the switchgear and the subcomponent. MV switchgear typically has a primary supply and a backup supply circuit breaker (although other arrangements may exist). Section 5.2.2.2 recommends revised counting guidance to more accurately apportion the switchgear frequency because the operating experience does not support equal weight to vertical sections.

Table 5-2
Location of MV switchgear HEAFs

FEDB ID	Date	Bin	Switchgear Location	Subcomponent
732	7/6/1988	16.b	Load	Main bus bar
947	1/3/1989	16.b	Supply	Breaker
74	6/10/1995	16.b	Supply	Breaker
106	2/3/2001	16.b	Supply	Breaker
112	8/3/2001	16.b	Supply	Breaker
50910 – Event 1	3/28/2010	16.b	Supply	Primary cable connection
50910 – Event 2	3/28/2010	16.b	Load*	Breaker

*The breaker where the fault occurred was supplying power to a stub-bus (location of initial HEAF event).

As shown in Table 5-2, the supply circuit breaker cubicle is a likely fault location because of the following:

- Supply circuit breaker protective settings must be selectively coordinated with all load circuit breakers within the switchgear assembly. Because load circuit breakers are set to instantaneously trip for load short circuit faults (typically 0.05 s or 50 ms); supply circuit breakers do not generally have an instantaneous protection setting to maintain coordination. Instead, supply circuit breakers have a region referred to as TOC (51) or breaker short time delay. This delay could be set as high at 4 s (240 cycles), which results in a let-through energy that can be up to 80 times higher for a supply circuit breaker than for a load circuit breaker.
- Arc faults have been recorded for load breakers; however, due to the instantaneous trip protection (50), these faults are cleared rapidly and the energy does not exceed that of a typical arc flash and does not rise to the energy level of a HEAF.

5.2.2.2 Fire PRA Counting Guidance for Medium Voltage Switchgear

As shown in Table 5-2, MV switchgear events mostly occur in the supply section of the switchgear. Because the operating experience (biased to supply sections) does not accurately reflect the counting (by individual vertical section), this methodology recommends that MV switchgear should be counted by entire switchgear bank and not by individual vertical section.

To summarize, for ignition frequency apportioning, the counting of MV switchgear is based on the number of switchgear: the entire bank is counted as one. Figure 5-3 provides an example. Because the switchgear's physical and electrical functions may differ, the plant one-line diagram should be reviewed to assist in defining switchgear banks. In some cases, the switchgear physically appears as a single bank, but electrically functions as two adjacent banks (i.e., the main bus bars of each bank are separated). If the banks are electrically separated but appear as one, they should be counted individually.

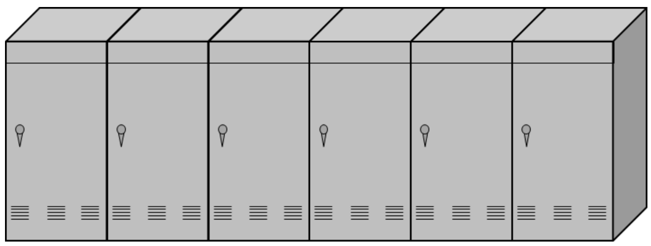


Figure 5-3
Counting of Bin 16.b MV switchgear (modified from Figure 3-1 in Supplement 1 to NUREG/CR-6850)

The change from counting by vertical section to counting an entire bank of switchgear is necessary to properly apportion the ignition frequency when detailed modeling is required. NUREG/CR-6850 [1] evenly apportioned the ignition frequency per vertical section. However, reviewing the operating experience shows that HEAFs in MV switchgear are most likely to occur in the supply section(s). Although not necessary during the counting stage, identifying the supply section(s) may be beneficial for detailed analysis.

5.2.2.3 MV Switchgear Weighting Factor

In addition to the observation of HEAFs within switchgear, observations are also based on the switchgear's location within the EDS. In Section 3, different fault zone progressions were described for Zone 1 switchgear (fed directly from the auxiliary power transformers) and Zone 2 (fed through an intermediate Zone 1 bus). For lineups fed from the UAT, Zone 1 is more likely to experience a generator-fed fault than Zone 2. A generator-fed fault in Zone 1 occurs when the switchgear bus supply circuit breaker fails to open. To experience a generator-fed fault in Zone 2, both the Zone 2 supply circuit breaker and the Zone 1 supply circuit breaker must fail to open. Per working group discussions, this physical arrangement supports the conclusion that HEAFs are more likely to occur in Zone 1 than Zone 2. To account for this difference, a zone weighting factor is applied to shift the frequency of switchgear banks to bias Zone 1, with less frequency apportioned to Zone 2.

To determine the factor, the MV switchgear HEAF operating experience was reviewed and is shown in Table 5-3. For each event, the normal power alignment in the EDS and the power flow during the event were categorized. For example, the location where FEDB 732 occurred is normally in a Zone 1 alignment. However, when attempting to reenergize the switchgear, an alternate power source was aligned that more closely resembled a Zone 2 alignment (fed through an intermediate bus). The working group considered these alternate lineups during the expert panel discussions and concluded that the switchgear zones should not change based on off-normal plant alignments (e.g., the analyst should not have to model Zone 1 and Zone 2 configurations for a single switchgear). Because the fire PRA models events as starting from standard operating conditions (i.e., the fire event disrupts the plant's normal operation), the normal plant configuration should be expected during the initiating event. Therefore, the fault zone associated with a normal alignment is used for the weighting factor. Subsequently, the guidance for the analyst is to use the normal alignment when assigning switchgear into either Zone 1 or Zone 2.

Table 5-3
MV switchgear fault zone alignment and alignment during HEAF

FEDB	Date	Bin	Supply or Load Section	Fault Zone with a Normal Alignment	Fault Zone During HEAF Event
732	7/6/1988	16.b	Load	Zone 1*	Zone 2*
947	1/3/1989	16.b	Supply	Zone 1	Zone 1
74	6/10/1995	16.b	Supply	Zone 1	Zone 1
106	2/3/2001	16.b	Supply	Zone 1	Zone 1
112	8/3/2001	16.b	Supply	Zone 1	Zone 1
50910 – Event 1	3/28/2010	16.b	Supply	Zone 2	Zone 2
50910 – Event 2	3/28/2010	16.b	Load	Zone 1^	Zone 2^

* Assignment based on the EDS alignment of the original failure, which was Zone 1 (UAT fed). The fault location did not move, and the fault was still located in Zone 1. However, as part of the post-trip recovery procedural actions, operations attempted to reenergize the bus from an alternate power source, which was a switchgear in Zone 2 fed from the SAT.

^ 50910 Event 2 physically occurred in Zone 1 with respect to normal plant alignment from the UAT but was operating in a Zone 2 alignment (from the SUT at the time).

From this review, 86% (six out of seven) of the events occurred in Zone 1, and 14% occurred in Zone 2. The potential for a Zone 1 MV switchgear arcing fault to escalate to a HEAF over that of a Zone 2 arcing fault is due to the following:

- Zone 1 MV switchgear is typically where the automatic/manual fast bus transfer schemes reside. Fast bus transfers are an electrical transient that require precise timing coordination of multiple circuit breakers and buses. Faults are more likely to occur as a direct result of this type of switching, as shown in four out of the seven MV switchgear HEAF events. Zone 2 MV switchgear EDS alignment normally follows the upstream Zone 1 MV switchgear and does not require circuit breaker operation during Zone 1 MV switchgear bus transfer operations. Even when Zone 2 MV switchgear manual bus transfers are performed, less energy is being switched.
- Zone 1 MV switchgear fed from the UAT does not have backup fault interruption. Failure of the Zone 1 MV switchgear supply circuit breaker exposes the bus to a generator-fed fault because of the decaying residual energy from the generator that cannot be isolated.
    - This is not the case for the same Zone 1 MV switchgear fed from the SAT because backup interruption capability with the SAT primary switchyard circuit breakers can be credited, including defense-in-depth, and high-speed switchyard breaker failure protection.

- An extra breaker is available from Zone 1 MV switchgear that may be relied upon to clear a downstream Zone 2 MV switchgear fault before it develops into a HEAF fed by the auxiliary power transformers.

To implement this frequency shifting, the steps to identify switchgear and apportion (and conserve) the frequency are the following:

1. Use the station one-line electrical diagram to identify MV switchgear (greater than 1000V) within the fire PRA global analysis boundary.
2. Identify whether the MV switchgear is directly fed from the auxiliary power transformers (primary side of the transformer is connected to the main generator or to the switchyard) or fed through an intermediate bus. Classify switchgear as either Zone 1 or Zone 2 based on the following definitions:
    a. Zone 1: MV switchgear fed directly from the auxiliary power transformers (SAT, UAT, or equivalent)
    b. Zone 2: MV switchgear fed from an intermediate bus (via Zone 1)
3. Start with the apportioned plant-wide frequency for Bin 16.b of 1.98E-03 from Table 5-8. Based on the previous calculation, 86% of the frequency is apportioned to Zone 1 and the remaining 14% to Zone 2. If Zone 2 does not have MV switchgear, then use the entire frequency for Zone 1. The sub-frequencies are as follows:
    a. Zone 1: 1.98E-03(0.86) = 1.70E-03
    b. Zone 2: 1.98E-03(0.14) = 2.77E-04
4. Using the sub-frequency value and the counts for Zone 1 and Zone 2 switchgear, apportion the sub-frequencies among the plant-specific Zone 1 and Zone 2 counts. This is shown by the following:
    a. $\lambda_{\text{Zone 1 switchgear bank}}$: 1.70E-03/count of Zone 1 switchgear banks
    b. $\lambda_{\text{Zone 2 switchgear bank}}$: 2.77E-04/count of Zone 2 switchgear banks
5. Use the apportioned frequencies as the scenario frequencies for the scenario definition (either screening or configuration-specific) in Section 8.

5.2.3 Bin 16.1-1 and 16.1-2: HEAFs for NSBD

Counting of Bins 16.1-1 and 16.1-2, NSBD generally follows the counting guidance in FAQ 07-0035 (Section 7 of Supplement 1 to NUREG/CR-6850 [2]). Consistent with NUREG/CR-6850, Supplement 1 [2], because NSBD (category 1) and cable ducts (category 3) have no transition points other than the termination at the end device, treatment of bus duct faults independent from the treatment of fires for the end device is not required. That is, arc faults for categories 1 and 3 of bus ducts are inherently included in the treatment of the end device and no further treatment is needed.

Section 5.2.3.1 (for known transition points) and Section 5.2.3.2 (for unknown transition points) summarize the two counting practices.

5.2.3.1 For Known Transition Points

The counting of segmented bus ducts is based on the total number of transition points, which may be identified by external visual inspection or based on plant electrical construction drawings. Although transition points may not be generally known, certain locations may point to the presence of a transition point. For example, geometric factors such as a horizontal direction change (making a flat or vertical turn) or changes in elevation (a step) suggest the presence of a transition point.

Reviewing operating experience also highlighted the potential for a HEAF to occur in outdoor locations where environmental access to the bus bar insulation—such as ventilation openings, mechanical hatches, or external wall penetrations (e.g., yard-to-turbine-building penetration)—occurs and could allow accelerated degradation of the bus bar insulation.

For known transition points, the analysis should look for fire PRA targets (i.e., fire PRA equipment and cables) within the ZOI at the transition points and postulate scenarios consistent with Supplement 1 to NUREG/CR-6850 [2]. For outdoor locations with features that may allow degradation of the bus bar insulation (e.g., vents, hatches, and wall penetrations), fire PRA targets near these features should be captured and included with scenarios structured around the nearest transition points or alternatively considered as transition points. Openings, such as vents, drains, or hatches located inside buildings (protected from weather elements) are not expected to increase the likelihood that the bus bar will degrade and do not need to be included in a scenario. For counting purposes vents, hatches, and wall penetrations on outdoor NSBD do not need to be counted as transition points for the purposes of counting segmented bus ducts. The fire PRA targets located in the ZOI of one of these locations should be included in a scenario involving the closest transition point.

5.2.3.2 For Unknown Transition Points

The counting of segmented bus ducts is based on the total length of the segmented bus duct within the bus duct bin (either 16.1-1 or 16.1-2). A per-linear-foot frequency can then be estimated by dividing the plant-wide fire frequency by the total length of segmented bus duct in the plant.

Scenarios should be postulated at any point along the duct length where potential fire PRA targets fall within the ZOI. Developing fire scenarios would then depend on the relative length of bus duct for which an identified target set lies within the bus duct ZOI.

Supplement 1 to NUREG/CR-6850 [2] states that when determining the frequency associated with a specific scenario in which the transition points cannot be located, the following may be used:

> *A lower limit to the assumed fire frequency for any given fire scenario is also applied. That is, if the length of bus duct for which the identified target(s) fall within the zone of influence is less than 12 linear feet, then a minimum length of 12 feet should be assumed. This lower bound is based on the assumption that, lacking specific information on segment lengths, a nominal segment length of 12 feet should be assumed. Any single scenario is then assigned a fire frequency equivalent to that associated with one bus bar segment 12 feet in length (i.e., equivalent to one nominal transition point).*

5.2.3.3 Using Both Apportionment Methodologies

Both the known transition point and the unknown transition point method may be used in the same analysis if the frequency is conserved within the respective NSBD bin. For example, assume transition points are not known for the bus ducts in Bin 16.1-1 (Zone BDUAT and Zone BDSAT). For Bin 16.1-1, the scenario frequency is apportioned based on the linear foot. For Bin 16.1-1, the total linear foot calculation should only include the length of bus duct associated with BDUAT and BDSAT. At the same plant, the transition points for Bin 16.1-2 (Zones BD1, BD2, and LVBD) are known. Within Bin 16.1-2, the frequency can be apportioned using the known transition points. In summary, the analyst may choose different apportioning strategies for Bins 16.1-1 and 16.1-2. Supplement 1 to NUREG/CR-6850 [2] identifies the following refinement which may still be utilized if the unknown transition point method is used for one of the bins:

> *Note that in either approach, the analysis can always be refined by examining the bus duct to determine if one or more transition points actually lie within the applicable bus duct segment. If no transition points are identified within that particular duct section, then a fault scenario need not be postulated and the scenario "goes away." If one or more transition points are identified within a particular duct section, then the analysis can be refined based on the known locations (i.e., both the fire frequency and the impacted target set may be refined once transition points are identified).*

5.2.3.4 Continuous (Non-Segmented) Bus Ducts and Cable Ducts

As noted in FAQ 07-0035 [2], HEAFs are not postulated along the length of continuous bus duct and cable ducts because they lack transition points, and HEAF events are inherently included in the treatment of the end device. Typically, continuous bus ducts are limited in length. The intent of separating segmented bus ducts from NSBD was to eliminate the need to postulate HEAFs on short sections of bus duct (e.g., bus duct connecting two nearby load centers) where targets would already be captured within the ZOI of the end device.

5.2.3.5 DC Bus Ducts

LV bus duct may also be present in main generator static excitation systems for distributing DC field excitation current to the generator rotor (field). The bus duct may either be segregated or non-segregated. Unlike AC systems in which impedance dictates the fault level, excitation system current is limited by the firing capability of the excitation system silicon-controlled rectifiers (SCR) to about 150% of rated, full-load current. The DC excitation system is also ungrounded and continuously monitored by a field ground detector. Only conductor-to-conductor arcing faults are credible. Voltage regulator/excitation systems have multiple levels of limiters and fast-acting protection to prevent catastrophic failures: the current limiters act before protection (trip), which is likely part of the reason that no reported voltage regulator/excitation failures have escalated to a HEAF (including DC bus ducts).

From an energy perspective, rated excitation system conditions for a large nuclear plant are approximately 600 VDC at 5200 ADC. Even if an arcing event were to occur in a large excitation system, the resulting energy would be limited to 2.9 MJ/m^2 (or less) per second, as calculated:

375 V × (5,200 × 1.5) = 2.9 MJ/m^2, where:

- 375 V = arc voltage (conductor to conductor)
- 5200 ADC = rated current at full load
- 1.5 = 150% current limit from SCRs (full firing)

Due to the low arc energy, low-voltage dc bus ducts should not be counted as HEAF ignition sources.

5.2.4 Bin 16.2: HEAFs for Iso-Phase Bus Ducts

Counting of Bin 16.2, iso-phase bus ducts, continues to follow the counting guidance in FAQ 07-0035 [2]:

> *For iso-phase bus ducts, there should generally be one iso-phase bus per unit (an iso-phase bus includes all three phases). If there is more than one iso-phase bus, simply count the total number of iso-phase buses per unit.*

5.2.5 Generic Frequency Apportioning—Ignition Source Weighting Factor

NUREG/CR-6850 [1] identifies the ignition source weighting factor, W_{IS}, as the fraction of the ignition source type in a specific compartment or scenario relative to the total population.

5.2.5.1 Load Centers

As noted in Section 5.2.1.2, only load center supply breakers are counted for Bin 16.a.

As an example, consider a NPP with 16 load center supply breakers. To determine the ignition source weighting factor, consider the configuration of three load centers in a single fire compartment as follows:

- Load center with ten vertical sections (two supply breakers)
- Load center with six vertical sections (two supply breakers)
- Load center with four vertical sections (one supply breaker)

The ignition source weighting factors for the load centers are calculated in Table 5-4. Based on the locations in the plant EDS, the supply breaker is the only potential location for a HEAF. Load center cubicles or other metering equipment are not counted.

Table 5-4
Example of load center ignition source weighting factors

Load Center Configuration	Ignition Source Weighting Factor, W_{IS}	Discussion
10 vertical sections, 2 supply breakers	0.125	Two supply breakers over a total plant population of 16 load center supply breakers
6 vertical sections, 2 supply breakers	0.125	Two supply breakers over a total plant population of 16 load center supply breakers
4 vertical sections, 1 supply breaker	0.0625	One supply breaker over a total plant population of 16 load center supply breakers

5.2.5.2 Medium Voltage Switchgear

MV switchgear is apportioned following the methodology in Section 5.2.2.2, which counts each MV switchgear bank in Zone 1 and Zone 2. When the count in each zone is known, use the MV switchgear weighting factor to determine the switchgear bank frequencies. As a reminder, MV switchgear HEAFs are no longer counted by vertical section.

For example, consider an NPP with 12 MV switchgear. From a review of the plant one-line diagram, the switchgear count in Zone 1 is five and the count in Zone 2 is seven.

The ignition source weighting factor for the MV switchgear is calculated in Table 5-5.

Table 5-5
MV switchgear bank frequency calculation

Location of switchgear	Bin 16.b generic frequency with Zone Weighting Factor	Total count of switchgear within zone	Switchgear bank frequency (/year)
Zone 1	1.98E-03(0.86) = 1.7E-03	5	3.40E-04
Zone 2	1.98E-03(0.14) = 2.77E-04	7	3.95E-05

5.2.5.3 Non-Segregated Bus Ducts

Segmented Bus Duct with Known Transition Points

When the transition points are known, the NSBD frequencies (Bins 16.1-1 and 16.1-2) can be apportioned by transition points. Fire PRA targets in outdoor locations with a propensity to allow bus bar insulation to degrade from environmental factors should be captured and included with the scenarios structured around the nearest transition points or alternatively treated the same as transition points. Example 1 and Figure 5-4 describe scenario selection for the known transition point method.

Segmented Bus Ducts with Unknown Transition Points

When the transition points are not known, the NSBD frequencies (Bins 16.1-1 and 16.1-2) are apportioned by linear foot, and the fault location is not limited to a transition point or locations with a propensity to allow the bus bar insulation to degrade but may occur at any point along the bus length. Ultimately, scenario development depends on the relative length of bus duct where a target may be impacted by the HEAF ZOI. Per Supplement 1 to NUREG/CR-6850, there are two approaches:

- <u>Analysis approach 1</u>: Potential fire PRA targets are located within the ZOI for a significant length of duct (greater than the nominal assumed segment length of 12 ft). An estimate of the scenario fire frequency can be determined by multiplying the following:
    - The respective bus duct bin frequency (either 16.1-1 or 16.1-2), and
    - The ratio of the duct length of duct (in linear feet) where scenario targets lie within the ZOI to the total length of segmented bus duct in the bin.
- <u>Analysis approach 2</u>: A target set is identified that lies within the ZOI for a limited portion of bus duct that is less than the nominal assumed segment length of 12 ft. An initial analysis should assume that a fault occurs within the bus duct segment where fire PRA targets might be impacted, regardless of length. The fire frequency assigned to the scenario is the minimum fire frequency value calculated based on a minimum 12 ft length of duct.

Example 2 and Figure 5-6 describe scenario selection for the unknown transition point method. In this example, the transition points are not obvious, and the counting and scenario development are based on the total NBSD length in linear feet within the bin.

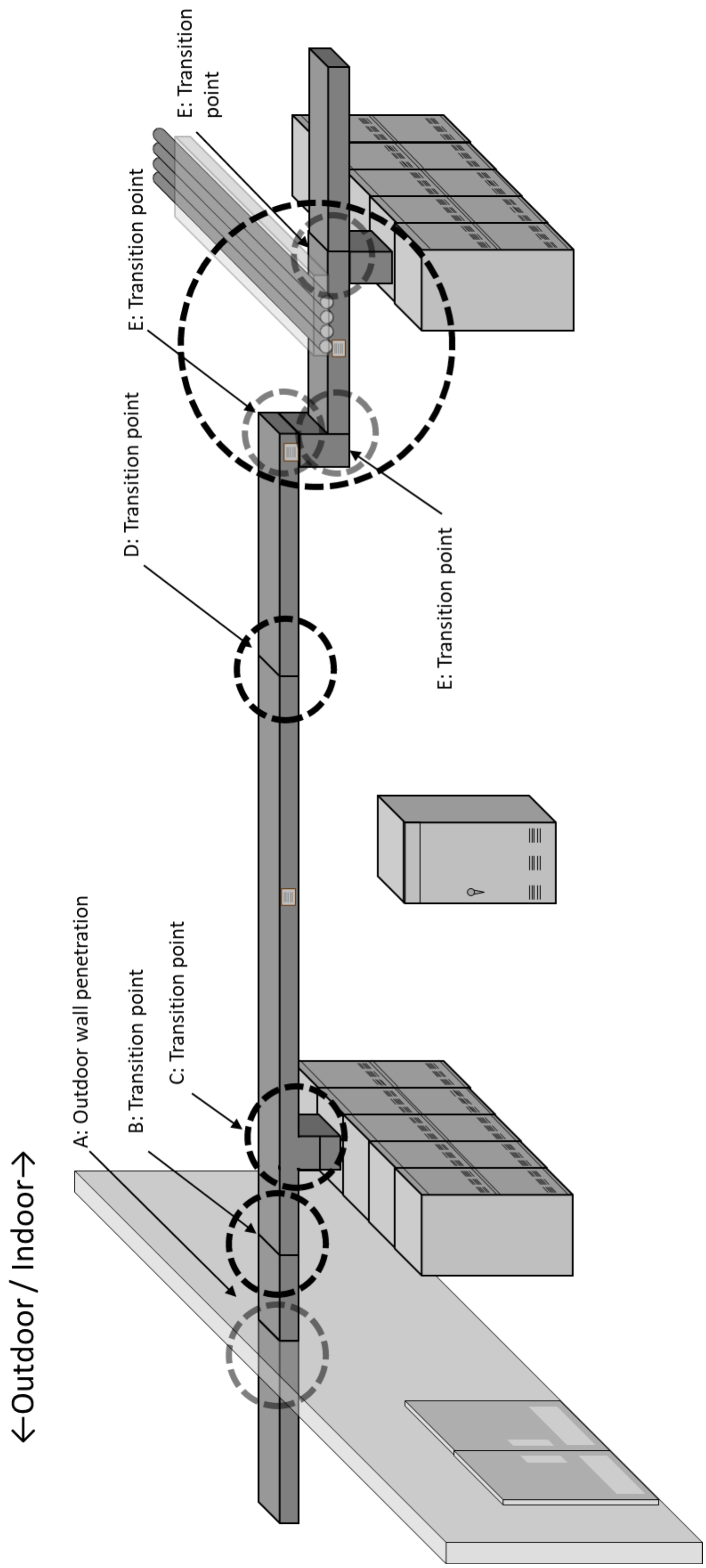


Figure 5-4
Counting of NSBDs (not to scale)

Example 1 – Segmented Bus Duct with Known Transition Points

The counting and scenario development for the NSBD in Figure 5-4 are the following:

- Operating experience highlights the potential for a HEAF to occur where an NSBD penetrates a wall to the outdoors (point A). If fire PRA targets are located within the ZOI for an NSBD near this location (targets either inside or outdoors), the targets should be included within the scenario associated with transition point B or alternatively a count of 1 should be attributed to this location (it is treated as a transition point) with a fire scenario considered.
- Transition point B is located between the wall and the farthest left switchgear. A count of one should be attributed to this transition point, and a scenario that damages the farthest-left switchgear should be considered.
- As Figure 5-5 shows and per FAQ 07-0035 [2], end termination points are counted with the end device (in this instance, a switchgear) and not with the NSBD. However, transition point C is above the switchgear, but outside the switchgear ZOI. In this instance (transition point is outside the ZOI of the switchgear), this transition should be considered similar to other transition points.
- A vent is located on the NSBD between transition points C and D. Scenarios at vents are not developed for NSBDs in indoor locations. Fire PRA targets and/or scenarios need only be identified for vents, drains, or hatches on NSBD located outdoors.
- No fire PRA targets are located within the ZOI of transition point D. However, the bus duct itself may be a fire PRA target.
- Multiple transition points are located in close proximity above the right switchgear. The cable tray located above the switchgear is within the ZOIs of all the nearby transition points. Therefore, consistent with the guidance, the close transition points may be counted and grouped as a count of three.

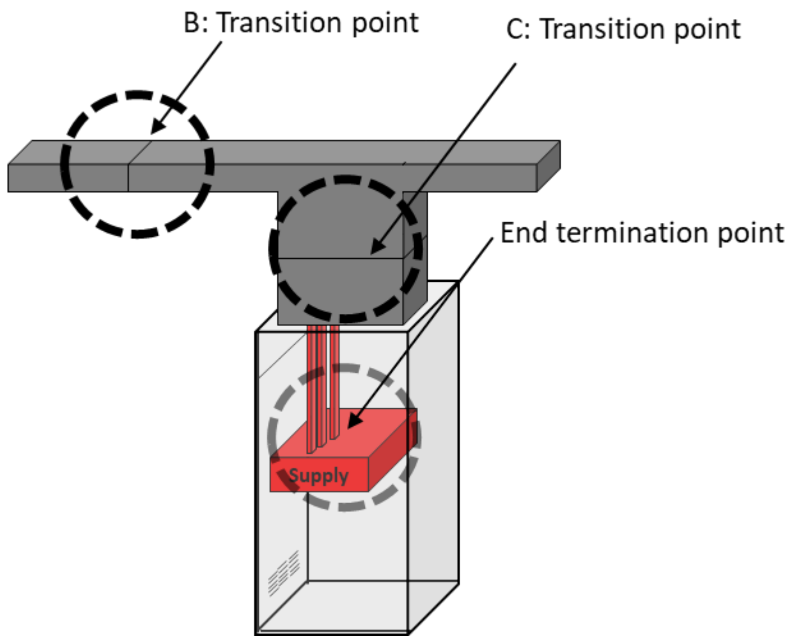


Figure 5-5
Transition point C from segmented bus duct with known transition points

Example 2 – Segmented Bus Duct with Unknown Transition Points

Consider the length of NSBD in Figure 5-6. In this example, the transition points are not obvious, and the counting and scenario development is based on the total linear feet of NSBD.

The counting and scenario development of the NSBD sections in Figure 5-6 are the following:

- Section A of the NSBD runs above a fire PRA target cable tray for a length of approximately 50 ft. Following approach 1, the scenario should use the ratio of duct length that could impact the fire PRA target (cable tray underneath the NSBD). Therefore, a scenario should be developed using the ratio of 50 ft to the total linear foot length of bus duct within the bin.
- Section B of the NSBD runs over a fire PRA target (switchgear). The switchgear underneath Section B is the only fire PRA target or secondary combustible within the NSBD ZOI. Following approach 2, this scenario should use the ratio of a minimum 12 ft length of bus duct to the total linear foot length of bus duct within the bin.
- Section C of the NSBD runs over a fire PRA target (electrical cabinet). The electrical cabinet underneath section C is the only fire PRA target or secondary combustible within the NSBD ZOI. Following approach 2, this scenario should use a ratio of a minimum 12 ft length of bus duct to the total linear foot length of bus duct within the bin.
- Similar to section B, section D of the NSBD runs over a fire PRA target (switchgear). The switchgear underneath section D is the only fire PRA target or secondary combustible within the NSBD ZOI. Following approach 2, this scenario should use a ratio of a minimum 12 ft length of bus duct to the total linear foot length of bus duct within the bin.

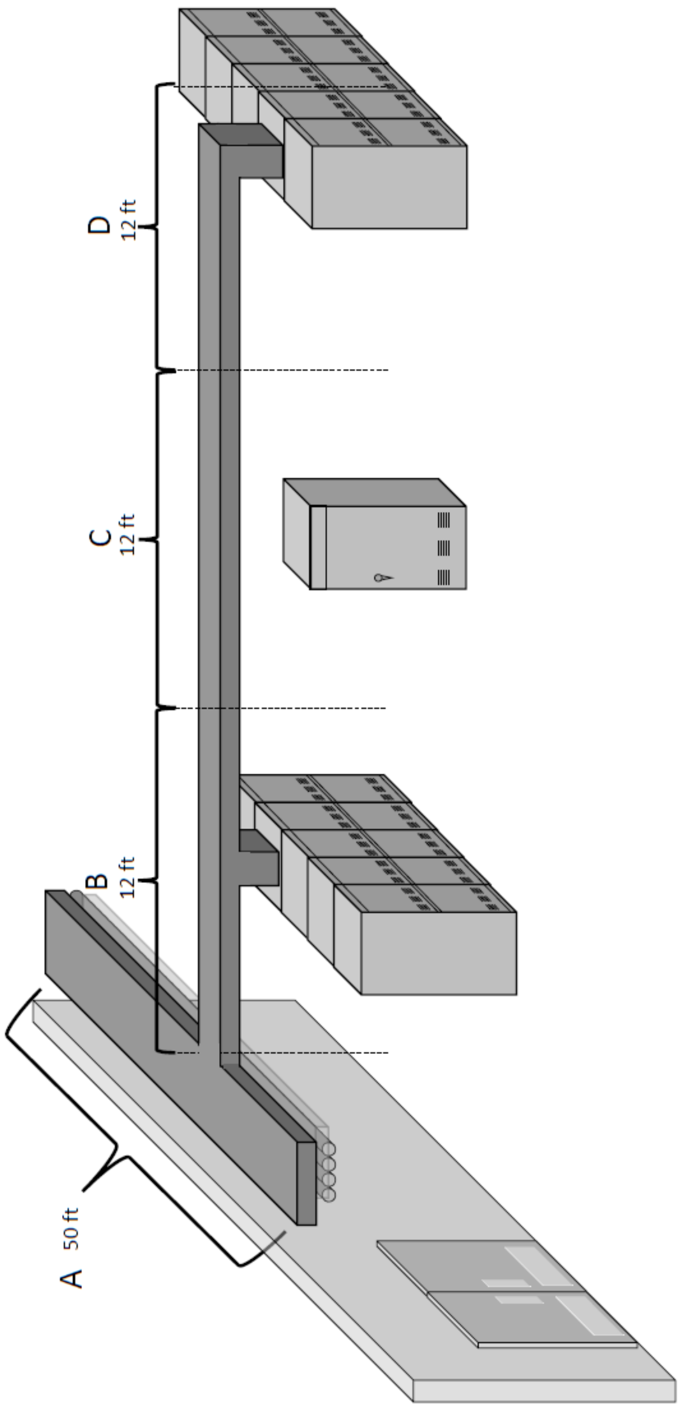


Figure 5-6
Counting of NSBDs with unknown transition points (not to scale)

5.3 HEAF Ignition Frequencies

This report updates the ignition frequencies from NUREG-2169 [35] for the HEAF-related bins. After the publication of NUREG-2169, EPRI collected and classified the fire event data available in the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS) database through 2014. This is documented in EPRI 3002005302 [33]. Although the fire event categorization is complete through 2014, an additional search to obtain operating experience through 2021 was performed and included in this effort. Similar to the assumption in NUREG-2169 [35], HEAF events are likely to be reported to the NRC, which minimizes the chances of missing events in the frequency analysis.

Fire events assigned to the HEAF ignition source bins are reviewed against the following definitions:

- Arc flash: An event in which damage is contained within the confines of the component of origin. Minor damage and minimal bus bar degradation occur, and the event does not result in an ensuing fire.
- Arc blast: An event in which damage is contained within the confines of the component of origin. The initiating equipment may be damaged through pressure-rise effects, but does not result in an ensuing fire.
- HEAF: An event in which the component of origin is damaged and breached, with the potential to spread to the surrounding equipment. Pressure-rise effects may damage the initiating equipment. HEAFs in switchgear and load centers are accompanied by an ensuing fire. However, no ensuing fire is necessary for a bus duct event to be considered a HEAF.

Appendix E of RIL 2022-09/EPRI 3002025123 [16] provides a detailed review of test data and operating experience regarding the pressure-rise effects associated with arc blasts and HEAFs. Because events classified as arc flashes and arc blasts do not result in an ensuing fire, they are not counted in the HEAF ignition frequency or non-suppression rates for switchgear and load centers. Arc blasts are counted for the bus duct frequency and non-suppression rates with an understanding that, similar to cabinets, bus ducts do not commonly contain combustible material (such as insulation or wiring material). Counts are tallied for each HEAF-related ignition source bin. As a result of this review, some events previously classified as HEAFs in NUREG-2169 [35] and FAQ 17-0013 [36] were reclassified into other bins. Table 5-6 shows the counts for each time period. Table A-1 outlines a more detailed summary of each HEAF event, and Table A-2 provides the PRA classification summary.

Table 5-6
HEAF PRA counts per time period

Bin	Location	Ignition Source	Power Modes	Fire PRA counts		
				1981–1999	2000–2009	2010–2021
16.a	Plant-wide components	HEAF for low voltage electrical cabinets (480–1000V)	AA	1	0	1
16.b	Plant-wide components	HEAF for medium voltage electrical cabinets (>1000V)	AA	3	2	2
16.1-1	Plant-wide components	HEAF for segmented bus ducts (Zone BDUAT and Zone BDSAT)	AA	3	3	3
16.1-2	Plant-wide components	HEAF for segmented bus ducts (Zones BD1, BD2, and LVBD)	AA	0	0	2
16.2	Plant-wide components	HEAF for iso-phase bus ducts	AA	1	1	1

The periods for event counting in Table 5-6 differ from the periods in NUREG-2169 [35]. In NUREG-2169, the time periods used to determine the bin frequency was driven by the number of events that occurred from 2000 to 2009. Events with a count of fewer than 2.5 events were considered sparse, and calculation included events from 1990 to 2009. Bins with 2.5 or more fire events were considered non-sparse, and calculation included the most recent time period (2000-2009). Both sparse and non-sparse events use the legacy period in NUREG-2169 (1968–1989) as a diffuse prior to inform frequency calculations. The frequency calculation continues to differentiate between sparse and non-sparse bins. If 2.5 or more events occurred within the latest time period (2010–2021), only that period is used as the update period for the Bayesian analysis used to calculate the generic fire ignition frequency. When fewer than 2.5 events occurred between 2010 and 2021, the update period is expanded an additional ten years to 2000–2021. The update periods are shifted to capture the most recent decade of operating experience and to accurately consider industry trends.

Additionally, the prior period now considers 1981–1999. The 1968–1980 data is sunset. The decision to shift the prior period's starting year to 1981 resulted from the adoption of Appendix R to 10 CFR 50. This represents a shift in the industry that may have propagated impacts into the frequency of fire events. In addition, older data is often less robust and may be inconsistent about reporting elements needed for proper fire event classification. For these reasons, the oldest events in the analysis are no longer carried. Although the period has shifted, the development of the prior follows the method used in NUREG-2169 [35] and continues to be very diffuse, introducing limited bias into the analysis, which continues to be significantly driven by the data in the update periods. The 1990s data is included in the prior because it is no longer within the 20-year update period.

Table 5-7 lists the number of reactor years for each time period. Table 5-8 presents the updated HEAF frequency distributions for each bin.

Table 5-7
Reactor years for fire ignition frequency update

	1981–1999	2000–2009	2010–2021
Reactor years (all)	1889	1040	1195

Table 5-8
Fire ignition frequency distribution for HEAF ignition sources

Bin	Location	Ignition Source	Power Modes	Period	Mean	Median	5th percentile	95th percentile	Mu	Sigma	EF
16.a	Plant-wide components	HEAF for low voltage electrical cabinets (480–1000V)	AA	2000–2021	5.32E-04	1.26E-04	4.67E-07	1.69E-03	-8.78	1.58	13.40
16.b	Plant-wide components	HEAF for medium voltage electrical cabinets (>1000V)	AA	2000–2021	1.98E-03	2.20E-04	3.59E-07	6.90E-03	-8.42	2.10	31.39
16.1-1	Plant-wide components	HEAF for segmented bus ducts (Zones BDUAT and BDSAT)	AA	2010–2021	2.61E-03	1.06E-03	6.31E-06	8.28E-03	-6.73	1.25	7.84
16.1-2	Plant-wide components	HEAF for segmented bus ducts (Zones BD1, BD2, and BDLV)	AA	2000–2021	8.98E-04	1.73E-04	2.11E-07	2.95E-03	-8.50	1.72	17.01
16.2	Plant-wide components	HEAF for iso-phase bus ducts	AA	2000–2021	1.01E-03	2.81E-04	7.59E-07	3.28E-03	-8.01	1.49	11.66

The mean frequencies for bin 16.a (HEAF for low-voltage electrical cabinets) and bin 16.2 (HEAF for iso-phase bus ducts) increased from the mean values in NUREG-2169 [35]. The mean frequencies for bins 16.a and 16.2 have increased by 250% and 71%, respectively. The significant increase in bin 16.a is driven by the limited number of fire events in the industry experience in NUREG-2169 and an event that occurred post NUREG-2169 (the impact of adding or removing a single event is more apparent). However, the frequency for bin 16.a is low (second lowest following Bin 1 – batteries). The frequency for bin 16.b has decreased by 7%. Splitting the segmented bus duct frequency results in an increase in frequency by 137% for bin 16.1-1 and a decrease of 18% for bin 16.1-2 from the previous combined bin 16.1 mean.

5.3.1 Generator Circuit Breaker

A generator circuit breaker (GCB) is a specially designed circuit breaker installed between the main generator and interconnected transformers (GSU and UAT). The GCB is physically integrated within the interconnected iso-phase bus duct system at operating voltages ranging from 17 kV to 25 kV, and therefore must be able to interrupt large fault currents reaching 200 kA (or more). As a result of their high short-circuit current-interrupting rating, they are designed, constructed, and operated differently than MV circuit breakers and high-voltage switchyard circuit breakers. IEEE Standard C37.013 [24] governs GCB design and testing.

The GCB design arose from the increased size of electric generating stations and facility requirements to prevent interruption of power to station auxiliaries in the event of a station trip or generator fault. In this case, power from the switchyard back-feeds the auxiliary power system through the GSU and UAT without the need for bus transfers when the generator trips or is shut down. In addition to their operational flexibility, GCBs can prevent main generator coast-down energy from feeding faults elsewhere on the auxiliary power system if the fault is detected within the GCB zone of protection (e.g., the UAT, Zone 1 switchgear bus supply circuit breakers, and associated non-segregated bus).

Less than 20% of U.S. NPPs utilize GCBs when they align their EDS to the generator via the UAT at power. The remaining U.S. NPPs are unit-connected designs without the benefit of GCBs. Sections 8 and 9 cover crediting the GCB in scenarios where a GCB can reduce the frequency of generator-fed faults in the following locations:

- The portion of the iso-phase bus duct (Bin 16.2) downstream of the GCB. The portion of the IPBD upstream of the GCB should not credit the GCB factor because the GCB is physically located downstream of the faulted location and cannot interrupt.
- Zone BDUAT (non-segregated bus ducts).
- The supply section of a Zone 1 MV switchgear fed from the UAT.

The Conseil International des Grands Réseaux Electriques (CIGRE) [37] performed a comprehensive survey that was used to develop reliability parameters using major failures for air blast, SF_6 pneumatic, and SF_6 hydromechanical spring operating GCB technologies. A major failure was defined as a switchgear or control gear failure that causes one or more of its fundamental functions to cease. The CIGRE study results use major failure data from more than 100 countries for a period of approximately 40 years. The data was heavily skewed toward pumped storage power generation, with only around 1.2% of the operational data coming from nuclear power generation.

Table 5-9 presents the reported major failures “on command,” or as commonly known in PRA, “on demand.”

Table 5-9
Generator circuit breaker major failures on command [37]

	Air blast	SF_6 with pneumatic operating system	SF_6 with hydromechanical spring operating mechanism
Major failures per 10,000 close commands	**0.344**	**0.032**	**0.020**
Does not close on command	*0.339*	*0.032*	*0.018*
Does not make the current	*0.006*	*0.000*	*0.002*
Major failures per 10,000 open commands	**0.006**	**0.028**	**0.004**
Does not open on command	*0.006*	*0.016*	*0.004*
Does not break the current	*0.000*	*0.012*	*0.000*
Major failure per cycle (failure per 10,000 cycles)	**3.5E-05**	**6.0E-06**	**2.4E-06**

The value of 3.5E-05 associated with the air-blast-type GCB bounds the failure results for the three different GCB technologies. Credit for the GCB interruption of the faulted conditions can be applied when the fault is within the GCB differential protection zone. This credit can be applied to the following fault zones:

- Iso-phase bus duct (Section 9.2.1). The portion of the IPBD upstream of the GCB should not credit the GCB factor because the GCB is physically located downstream of the faulted location and cannot interrupt.
- BDUAT (Section 9.2.2).
- Zone 1 supply section of MV switchgear (Section 8.5).

If the GCB operates as designed (1 - 3.5E-05), the GCB prevents the main generator coast-down energy from feeding a fault within the GCB zone of protection. The working group determined that plants with installed GCBs are expected to have a better than average performance as compared to plants without GCBs. Therefore, for an end state where the GCB is credited, the scenario frequency is not conserved, since the 1 – 3.5E-05 when applied to the branch end state does not result in HEAF-type consequences.

5.4 Updated HEAF Manual Non-Suppression Rate

Consistent with FAQ 17-0013 [36], the non-suppression time is defined as the time that the fire was extinguished or the time responding plant personnel, personnel discovering the fire, or the fire brigade reported the fire as under control.

For a HEAF event, suppression can only be credited for the ensuing fire following the energetic phase of the HEAF. Suppression is not credited during the energetic arcing fault phase of the overall event. Table A-2 details the events considered in the suppression rate.

A summary of the number of events, fire durations, and suppression rates are provided in Table 5-10 and shown graphically in Figure 5-7. The working group considered 15 events when determining the suppression rate, compared to 23 events considered in determining generic fire ignition frequency. The lower number of events counted for determining the suppression rate resulted from the inability to count events with no suppression time (self-extinguished), automatic suppression, or unknown suppression times.

Table 5-10
HEAF probability distribution for rate of fires suppressed per unit of time

Suppression Curve	Number of Events	Total Duration (min)	Rate of Fire Suppressed (λ)			
			Mean	5th Percentile	50th Percentile	95th Percentile
HEAF	15	576	0.026	0.016	0.025	0.038

Similar to NUREG-2169 [35], the 5th, 50th, and 95th percentiles for the suppression rate, λ, in Table 5-10 are calculated in using the Chi-square distribution in Equation 5-1.

$$P(x,v)/t_D/2$$ Equation 5-1

where $P(x,v)$ is the lower cumulative distribution function of the Chi-square distribution, *x* is the desired percentile, v is the number of degrees of freedom (equal to the number of events used in the suppression curve), and t_D is the total duration suppression time (in minutes) for the suppression curve.

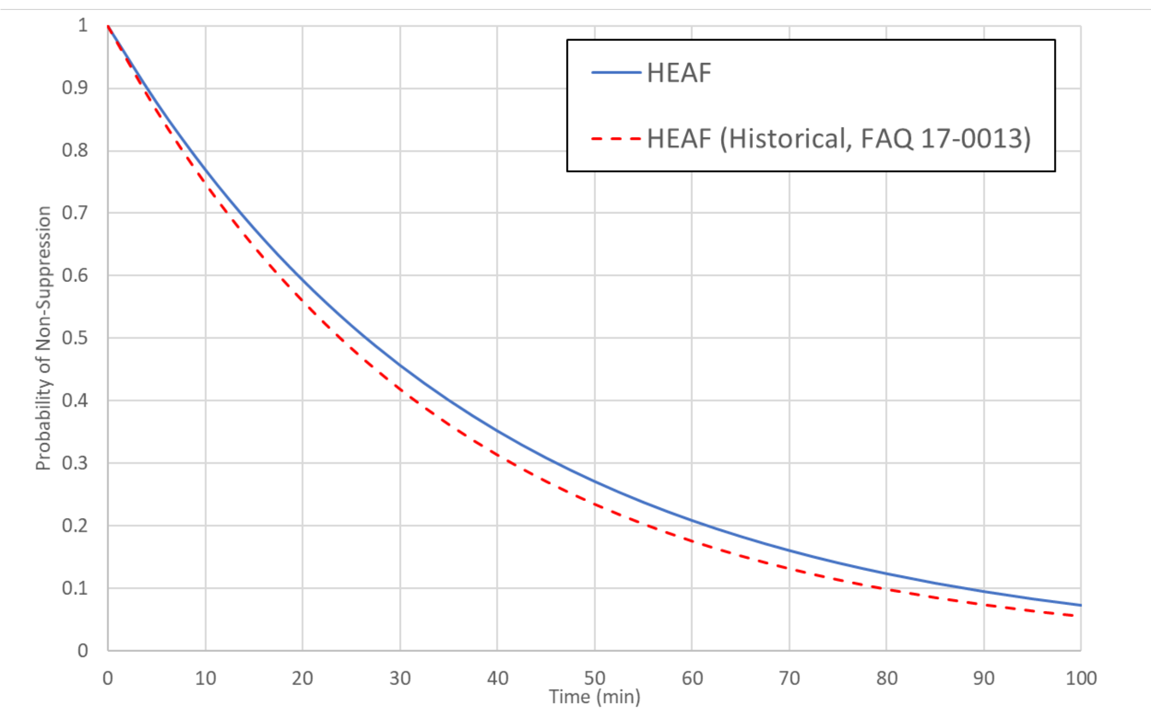


Figure 5-7
HEAF non-suppression curve plot: probability versus time available for suppression

6
HIGH ENERGY ARCING FAULT DAMAGE CRITERIA AND ZONE OF INFLUENCE

Section 6.1 documents potential failures aside from the energetic ZOI (e.g., electrical components that should be failed, survivability of structural elements). Section 6.2 documents quantitative HEAF-related failure thresholds. Section 6.3 provides a summary of the HEAF arc energy and associated end states. Section 6.4 describes the steps to determine FCTs. Sections 7, 8, and 9 characterize the energetic portion of the ZOI (combining the thresholds defined in Section 6.2 with the arc energies in Section 6.3 and the equipment-specific FCTs in Section 6.4). Section 6.5 provides guidance on modeling the post-HEAF ensuing fire.

6.1 Damage Characterization During the Energetic Phase

A HEAF event is modeled in two phases: the energetic phase and the ensuing fire. Figure 6-1 depicts the energetic phase damage ZOI for short and long FCTs. The ensuing fire will have a heat release rate equal to the 98th percentile peak value and will have a ZOI associated with the thermal radiation from the flames and from the fire plume. Figure 6-2 depicts a typical ensuing fire ZOI.

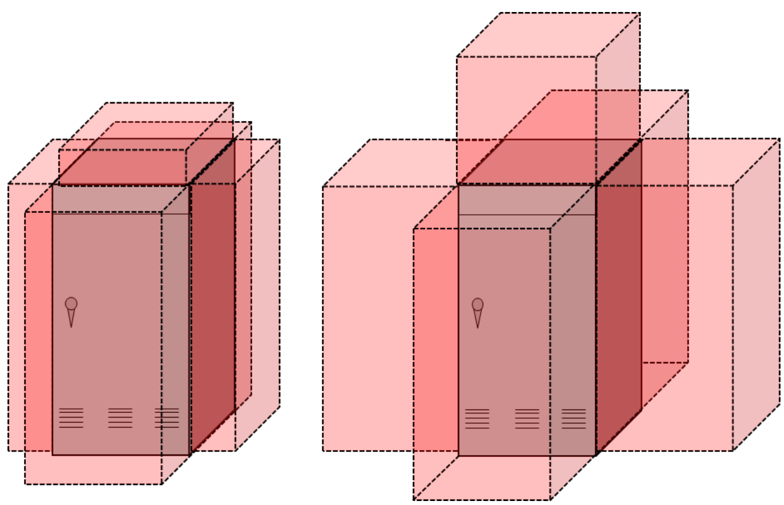


Figure 6-1
Energetic phase of HEAF ZOI. The left represents shorter FCTs, and the right represents longer FCTs. (Figures are not to scale, and ZOI is subject to the target fragilities and fault characteristics)

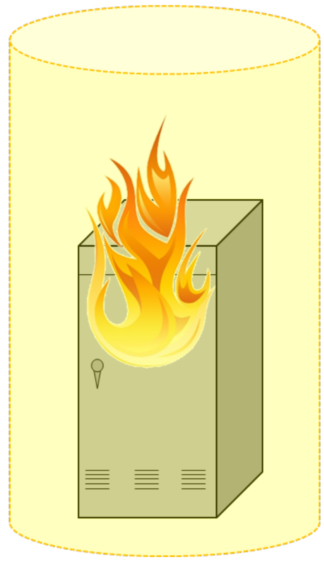


Figure 6-2
Post-HEAF ensuing fire ZOI. (The figure is not to scale; ZOI subject to analyst-developed fire with consideration for secondary combustibles)

The energetic phase and ensuing fire ZOI are not necessarily equal. For short FCTs, the ensuing fire ZOI may be larger than the energetic ZOI. For longer FCTs, some or all components of the energetic ZOI may be larger than the ensuing fire ZOI. An important distinction between the two ZOIs is that the ensuing fire ZOI may allocate frequencies to various target end states and incorporate suppression factors, whereas the energetic ZOI does not. Figure 6-3 provides a qualitative comparison of the energetic-phase and ensuing-fire phase ZOIs for short and long FCTs. Note that the ensuing fire ZOI may also expand beyond the initial HEAF ZOI if secondary combustibles are involved, if a damaging hot gas layer forms, or if adjacent vertical sections (see Section 6.5.1) are ignited.

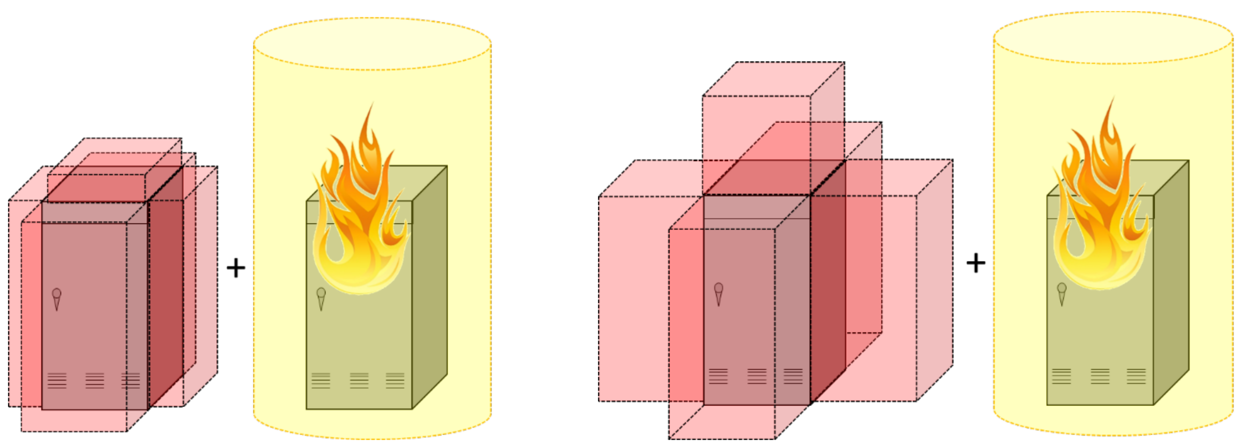


Figure 6-3
Energetic HEAF ZOI at short and long FCTs with ensuing fire (figures not to scale)

HEAFs in NSBDs are treated with two distinct components: the energetic phase and the waterfall. The energetic ZOI is determined using FDS results as performed for MV and LV switchgear. This energetic NSBD ZOI is applied along the bus duct at the location where the fault is postulated (see Figure 6-4). The waterfall component addresses the exposure to vulnerable equipment located below the bus duct where the fault is postulated (see Figure 6-4). The waterfall component accounts for heated parts of the bus duct, slag, and heated particles dropping onto equipment under the bus duct.

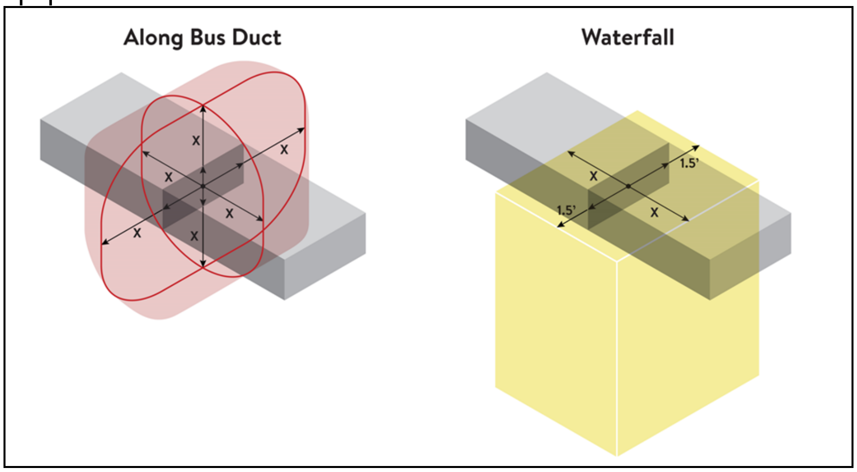


Figure 6-4
NSBD ZOI showing energetic (red shaded) and waterfall (yellow box) components

As identified in Figure 6-1 (for switchgear and load centers) the energetic ZOIs are squared and are extended from the corresponding enclosure faces. These are the regions around the enclosure where an arc plasma jet could be located due to ventilation openings, access doors, or breaches. The spaces outside these regions are not located within the arc plasma jet and the radiant view factor to the arc would be small given the arc is within the enclosure. The energetic ZOI for bus ducts (Figure 6-4) is rounded since breaches in the housing tend to occur on all sides resulting in minimal radiant obstruction between faces and potential exposure to the arc plasma jet. As the bus duct ZOIs are drawn and developed in this report they capture the 360° around the bus duct. For switchgear, the ZOI is intended to be squared based on the FDS results and the analyst should consider this difference in defining the energetic and ensuing fire ZOIs.

6.1.1 Switchgear and Load Centers

NUREG/CR-6850, Appendices M.4.2 and M.5, are updated to categorize the qualitative damage elements of HEAFs. For switchgear and load centers, consider the following:

- The initial arcing fault will cause destructive and unrecoverable failure of the faulting device (e.g., the feeder breaker cubicle), including the control and bus-bar sections.
- The next upstream overcurrent protection device in the power feed circuit leading to the initially faulting device will trip open, causing the loss of all components fed by that electrical bus. This fault may be recoverable if the initial faulting device can be isolated from the feeder circuit.
- Do not fail fixed structural elements, such as walls, floors, ceilings, and intact penetration seals (see Appendix E of RIL 2022-09/EPRI 3002025123 [16]). Do not fail large components

and purely mechanical components, such as large pumps, valves, major piping, fire sprinkler piping, non-soldered connected piping, or other large piping (1-in diameter or greater).

- The subsequent (ensuing) cabinet fire will continue to burn consistent with a fire intensity and severity described in Section 6.5.
- Unprotected cables—such as armored cables with exposed plastic covering, thermoset (TS) jacketed, and thermoplastic (TP) jacketed—that drop into the top of the panel will be ignited [15].
- The energetic phase occurs so quickly that neither automatic nor manual suppression systems can protect against damage and ignition within the energetic ZOI.
- The amount of smoke is expected to activate any smoke detection system in the area.
- Manual suppression by plant personnel and the fire brigade may be credited to control and prevent damage outside the initial energetic ZOI from ensuing fires. The HEAF suppression curve should be used.

6.1.2 Non-Segregated Bus Ducts

From NUREG/CR-6850, Supplement 1, the ZOI for bus ducts are unique from switchgear and load centers. Bus duct events generally involve a pool of molten metal and possible burning insulation material that forms within and then burns through the lower surface of the bus duct enclosure. This material spills out of the bus duct and may form a molten pool on the floor or objects below, may splatter onto other nearby surfaces, and may ignite and combust flammable materials contacted. The following bullets update the NSBD treatment from NUREG/CR-6850, Supplement 1 [2]:

- Assume that the effects of the bus duct fault are manifested at a transition point (the fault point). Recall that failures at the end-point terminations are captured under the end-point equipment.
- Switchgear, load centers, MCCs, and transformers powered by the bus duct are deenergized. Transfer to alternate power lineups is required for this equipment to be available.
- The following ZOI is assumed to originate from the edge of the bus duct enclosure at the assumed location of the transition point:
    - Assume that the initial arc fault will breach the bus duct enclosure during the energetic phase and will spread out from the edge of the bus duct in a rounded-corner square shape. Along the length of the bus duct, assume the bus bar and duct damage extends the length of the ZOI (from Table 9-2) in both directions from the initial fault location. Figure 6-4 and Figures 9-1 characterize this “along the bus duct” ZOI.
    - Assume that molten metal material will be ejected from the bottom of the bus duct below the fault point, encompassing the shape of a waterfall flowing 1.5 ft from the edge faces of the bus duct. Assume the waterfall extends the length of the ZOI (from Table 9-2) along the length of the bus duct in both directions from the initial fault location. Figure 6-4 and Figures 9-1 characterize this ZOI.
    - Assume that any exposed combustible or flammable material within the waterfall ZOI will be ignited by the molten slag. Combustible/flammable materials should not be

considered exposed if protected by a fire-rated raceway wrap, a conduit, or solid metal panels (e.g., a switchgear enclosure). Specific examples of the recommended treatment of exposed versus nonexposed materials are as follows:

- The solid metal top panels of an electrical cabinet will prevent ignition of the combustible/flammable materials inside the cabinet.
- For cabinets with ventilated tops or unsealed cable or conduit penetrations, molten material deposited on top of the panel will penetrate into the panel and ignite the contents if the openings are within the energetic ZOI.
- For electrical cabinet side panels or doors that include ventilation openings, molten material in the waterfall ZOI is not considered capable of penetrating horizontally into the electrical cabinet.
- Cables in conduit will not be ignited by molten materials deposited on the outer conduit surface if the open ends of the conduit are located outside the waterfall ZOI.
- Cables in trays that are equipped with unventilated steel covers will not be ignited by molten metals falling from above.
- Cables in open-top cable trays will be ignited if they are within the waterfall ZOI.
- The first solid surface encountered by the material ejected from the bus duct will truncate the waterfall ZOI along that line of travel. (Examples include where the ZOI intersects the floor, a sealed cabinet top, or a cable tray with a solid metal cover.) The waterfall ZOI does not extend through that surface to other targets or flammable material beyond. For stacked cable trays in which the first open-top cable tray is sufficiently filled, the first cable tray can be considered to also truncate the waterfall ZOI.

- Damage within the energetic ZOI occurs at time zero (concurrent with the initial fault), but secondary combustibles within the waterfall ZOI should be assumed to develop over time from a from a single point of ignition (e.g., a cable tray should be assumed to ignite at one point, not over its entire exposed length).
- Subsequent analysis of fire growth, fire detection, and fire suppression response follow the same practices applied to HEAFs for switchgear and load centers. In particular, the manual HEAF suppression curve is also applicable to bus duct faults.

6.2 Summary of HEAF-Related Failure Thresholds

Because of the simplicity of the model in NUREG/CR-6850 and Supplement 1, specific fragilities for targets exposed to a HEAF were not needed. Building off data from fragility testing documented in RIL 2021-09 [14], RIL 2022-01/EPRI 3002023400 [15] documents the working group's conclusions on fragilities for electrical cables. Additional PRA targets are discussed and documented in Appendix F. The following target fragility thresholds are established to define the energetic portion of the HEAF ZOIs:

- 15 MJ/m²
  - Electrical failure/damage of TP-jacketed[6] cables. This also includes TP-jacketed cables in conduits, cable trays (including any top/bottom cover), cable bus ducts, and cable wireways.
    - Regardless of raceway, these cables do not see sustained ignition during the energetic phase of the HEAF.
  - Damage to junction boxes with TP-jacketed cables (see Appendix F.3.1).
  - Damage to electrical equipment (e.g., PRA targets such as battery chargers, dry transformers, inverters, load centers, MCCs, and switchgear). This is a bounding target selection that can be refined; see the step-wise process in Appendix F.4.2 for full details.
    - In the detailed approach (which considers ventilation if more refinement is necessary) at 15 MJ/m^2, equipment with open ventilation (regardless of aluminum or metal enclosure) and equipment with limited ventilation and an aluminum enclosure are assumed failed.
  - Damage to aluminum-enclosed bus ducts.
  - Damage to copper instrument air piping with soldered joints.[7]

- 30 MJ/m²
  - Electrical failure/damage of TS-jacketed cables. This also includes TS cables in conduits and cable trays (including any top or bottom covers).
    - Regardless of raceway, the cables do not see sustained ignition during the energetic phase of the HEAF.
  - Damage to junction boxes with TS-jacketed cables (see Appendix F.3.1).
  - Damage to electrical equipment classified as limited ventilation, such as PRA targets that are closed (no vents), have vents with louvers or filters, or are not in the HEAF's sightline. See Appendix F.4.2 for more details.
  - Damage to steel-enclosed bus ducts.
  - Damage to steel instrument air piping.[8]

- 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, not ignited, and do not contribute to the fire load.

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[6] Consistent with guidance in the NFPA 805 FAQ 08-0053 Revision 1 close-out memo, ML121440155 [38], Kerite-FR insulated cable should be assumed damaged at thermoplastic thresholds.

[7] This item is not covered in RIL 2022-01/EPRI 3002023400 [15] but was discussed and agreed upon during the November 2021 working group meeting. The thermoplastic failure criteria were agreed upon as a suitable damage threshold in lieu of additional testing or operating experience.

[8] This item is not covered in RIL 2022-01/EPRI 3002023400 [15] but was discussed and agreed upon during the November 2021 working group meeting. Because steel instrument air piping would require a breach, the 30 MJ/m^2 piping was selected.

6.3 Introduction to HEAF Zone of Influence Evaluation

In Section 3.1, generic fault zones are developed to understand the potential arcing-fault durations for HEAF-susceptible equipment. The fault progressions in Section 3 outline the various durations associated with a fault in the HEAF-susceptible equipment.

Sections 7, 8, and 9 focus only on the end states expected to result in a HEAF; end states not expected to result in a HEAF are not postulated. Because the Bin 16 generic ignition frequencies are developed from HEAF operating experience, end states are not postulated from branches with successful protection-scheme operation that do not lead to fault durations for energy levels capable of causing a HEAF. This ensures that the methodology postulates only HEAF outcomes and not a thermal fire event that is captured with Bin 15. Additionally, some branches are combined to simplify the analysis when multiple end states produce similar outcomes. Finally, for MV switchgear and some NSBD fault zones, split fractions are introduced to apportion the scenario frequency to specific ZOIs when detailed evaluation is necessary.

6.3.1 Use of Fire Dynamics Simulator for Modeling the Energetic Portion of the HEAF ZOI

FDS [39,40], a computational fluid dynamics (CFD) software tool developed by NIST, was used to model HEAF events in MV switchgear, LV switchgear, and non-segregated bus ducts.

- Simulations in MV switchgear include both vertical- and horizontal-lift circuit breaker configurations.
  - For vertical-lift circuit breakers, the FDS model geometry is based on the GE Magne-Blast metal-clad switchgear.
  - For horizontal-lift circuit breakers, the FDS model geometry is based on the ABB ITE metal-clad switchgear.
- The FDS model geometry for load center HEAFs is based on the GE AKD metal-clad switchgear.
- The FDS model geometry for NSBD HEAFs uses common bus duct configurations (straight, tee, and elbow) with a single bus-duct metal thickness of 0.125 in. This thickness corresponds to that of commonly used aluminum sheet and 11-gauge steel.

FDS simulations were benchmarked against full-scale testing (MV switchgear and NSBD) or operating experience (NSBD and load centers). The MV switchgear benchmarking is used to establish bias and uncertainty of FDS model predictions for HEAF. The full details of these simulations and results are documented in RIL 2022-09/EPRI 3002025123 [16].

The FDS simulations for MV switchgear characterized the HEAFs using an arc power profile. Construction of an arc power profile to represent typical plant conditions is discussed next.

During the energetic phase of the HEAF, the power of the arc can be defined in terms of voltage and current. For MV systems, the arc voltage is the voltage drop across the arc, which is dictated by the geometry and spacing of the bus bars and enclosure and is significantly less voltage than the system voltage. Through testing, data analysis, and modeling discussed in Appendix A of RIL 2022-09/EPRI 3002025123 [16], the arc voltage is sufficiently consistent and representative for all MV levels. This arc voltage value is $650V_{L\text{-}L}$[9] for 4.16 kV, 6.9 kV, and 13.8 kV systems. Similarly, the arc voltage for LV systems (480 V and 600 V) is $375V_{L\text{-}L}$.

Sufficient data from actual MV HEAF events at NPPs revealed arcing fault currents that ranged from 28 kA to 32 kA for a stiff current. For the purpose of determining the arc power, an average of 30 kA was chosen as representative of the NPPs. The current profile for generator-fed faults is based on operating experience and is modeled as fault current starting at 20 kA and decaying exponentially over time.

The remaining component to the arc power equation is to include the √3 to represent the three-phase system. Therefore, arc power is defined by Equation 6-1:

$$\text{Arc Power (Watts)} = V_{\text{arc}(\text{L}-\text{L})} \cdot I_{arc} \cdot \sqrt{3} \qquad \text{Equation 6-1}$$

The arc energy is a time-based profile that results in the integrated energy delivered by the arc and may be expressed as in Equation 6-2:

$$\text{Arc Energy (Joules)} = W_{arc\ power} \cdot T_{arc} \qquad \text{Equation 6-2}$$

The arc energy profile uses Equations 6-1 and 6-2 to calculate the total integrated energy of a HEAF. The profile (time) may either be fixed arcing fault current over time or an exponentially decaying current profile representative of a generator-fed fault. To illustrate, a simple fixed arcing fault current of a 2 s duration (i.e., FCT) is used to calculate the total energy of the arc:

$$Arc\ energy\ = 650V_{L-L}\ \cdot 30{,}000A\ \cdot \sqrt{3}\ \cdot 2_{seconds} =\ 68\ MJ$$

For additional background information on the arc energy profiles see Appendix A of RIL 2022-09/EPRI 3002025123 [16].

6.3.1.1 Medium-Voltage Switchgear and Non-Segregated Bus Ducts

The working group considered a constant-current arc power profile and a generator-fed arc profile. The constant-current arc duration ranged from 2–5 s, consistent with the timing in Section 3. Testing demonstrated that arc faults in MV switchgear under a 2 s duration do not have sufficient energy to reach HEAF thresholds. A minimum threshold of 2 s is sufficient to bound arc faults at 2 s and under. Several 1 s duration HEAFs were considered for NSBDs to assess the effect of shorter duration arcs on aluminum enclosures. Generator-fed faults were evaluated using the same arc voltage of $650V_{L\text{-}L}$ as the constant-current arcs but with a current that decayed exponentially with time. The decay duration of 15 s is based on the timing in

[9] $V_{L\text{-}L}$ represents phase-to-phase arc voltage. Phase-to-phase arc fault testing is the predominant industry standard (i.e., IEEE Std C37.20.7 [41]). In addition, NRC open box testing (RIL 2021-18 [42]) shows that phase-to-phase and phase-to-ground faults rapidly develop into three-phase faults. Due to the wide variability of reduced fault current in resistance grounded systems, phase-to-ground fault testing is not used.

Section 3 and Section 4. Generator-fed faults are evaluated with and without an initial constant-current arc fault of variable duration.

The total arc energy is the arc power profile integrated over time. For constant-current arcs, this energy is the power multiplied by the duration. For generator-fed faults, the total arc energy includes any constant-current part plus the generator-fed power profile integrated over time. The range of arc energies considered was 68–300 MJ and 34–300 MJ for NSBDs. Section 5 and Appendix A of the FDS ZOI report [16] detail the power profiles and calculation details for MV switchgear and non-segregated bus duct HEAFs.

6.3.1.2 Load Centers

The arc power profile for load centers (also known as LV switchgear) is determined using operating experience, as described in Section 4. The power profile and total arc energy from FEDB 50935 was determined using the available line-to-line voltage and current data for the event. The profile was simplified by characterizing the data in two constant-current arc stages. The first stage lasted for 20 s and had an approximate average current of 5.85 kA. The second stage lasted 21 s and had an approximate average current of 2.75 kA. The line-to-line voltage for both stages was $375V_{L\text{-}L}$. The power profile was then determined using Equation 6-1. The total arc energy for the LV switchgear HEAFs was 90 MJ in all baseline cases. Section 5 and Appendix A of the FDS ZOI report [16] presents the power profiles and calculation details for load centers.

6.3.2 Summary of HEAF End States

ZOIs are developed for load centers, MV switchgear, and bus ducts. At a high level, the end states considered include the following:

- Generator fed with differential protection (87): This end state is used for fault locations within the transformer zone of differential protection for generator-fed faults. This fault energy decays to zero over 15 s to simulate the coast-down from a turbine-generator trip (modeled based on FDS runs for 0 stiff/15 s decay). Figure 6-5 shows the classic generator-fed fault for Zone 1 MV switchgear (fault in or around the circuit breaker stabs rendering the Zone 1 bus supply breaker unable to clear the fault).
    - The total energy release is 132 MJ.

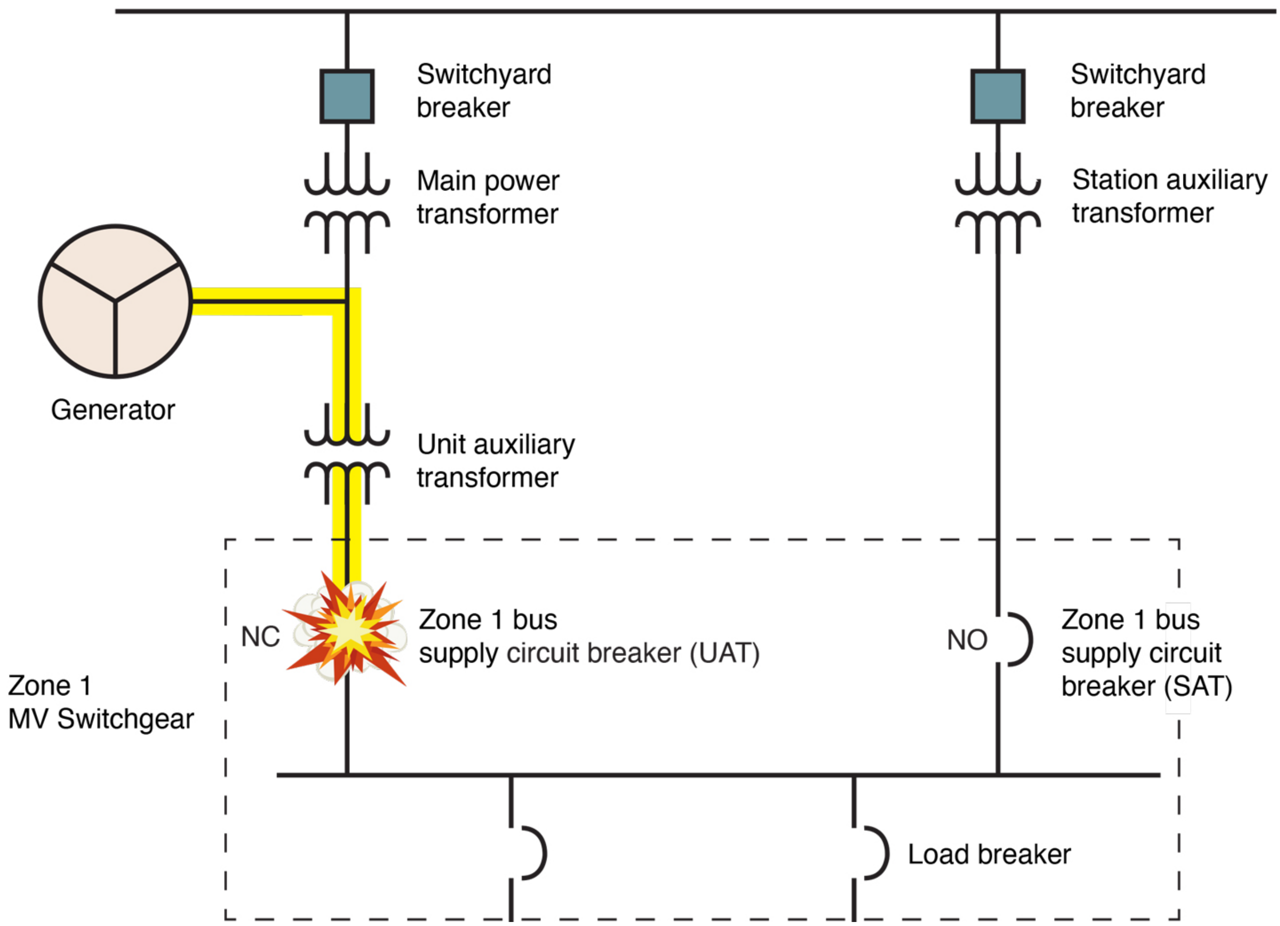


Figure 6-5
Conceptual drawing of a generator-fed fault with stuck Zone 1 bus supply circuit breaker

- Generator fed outside the differential protection zone (87): This end state is used for energy feeding the fault from the generator via the UAT outside the transformer zone of differential protection (87). For these scenarios, the UAT backup protection (TOC [51] relay) is credited. This end state is modeled with a stiff or constant-energy portion prior to a decay (generator-fed fault). Figure 6-6 show an example of a generator fed fault in the Zone 2 supply breaker. Figure 6-6 shows the lowest point in the EDS that is potentially susceptible to a generator-fed fault. As the fault point moves upward through the EDS, fewer independent failures are necessary to expose the faulted location to a generator-fed fault.

  The stiff or constant current time regimes for outside the differential protection zone include the following:

  - 0–0.5 s: modeled based on FDS runs for 0 stiff/15 s decay.
    - Total energy: 132 MJ
  - 0.51–2 s: interpolation is based on FDS runs 0 stiff/15 s decay and 3 stiff/15 s decay
    - Total energy: 200 MJ
  - 2.01–3 s: modeled based on FDS runs for 3 s/15 s decay
    - Total energy: 233 MJ
  - Greater than 3 s: modeled based on FDS runs for 5 stiff/15 s decay
    - Total energy: 300 MJ

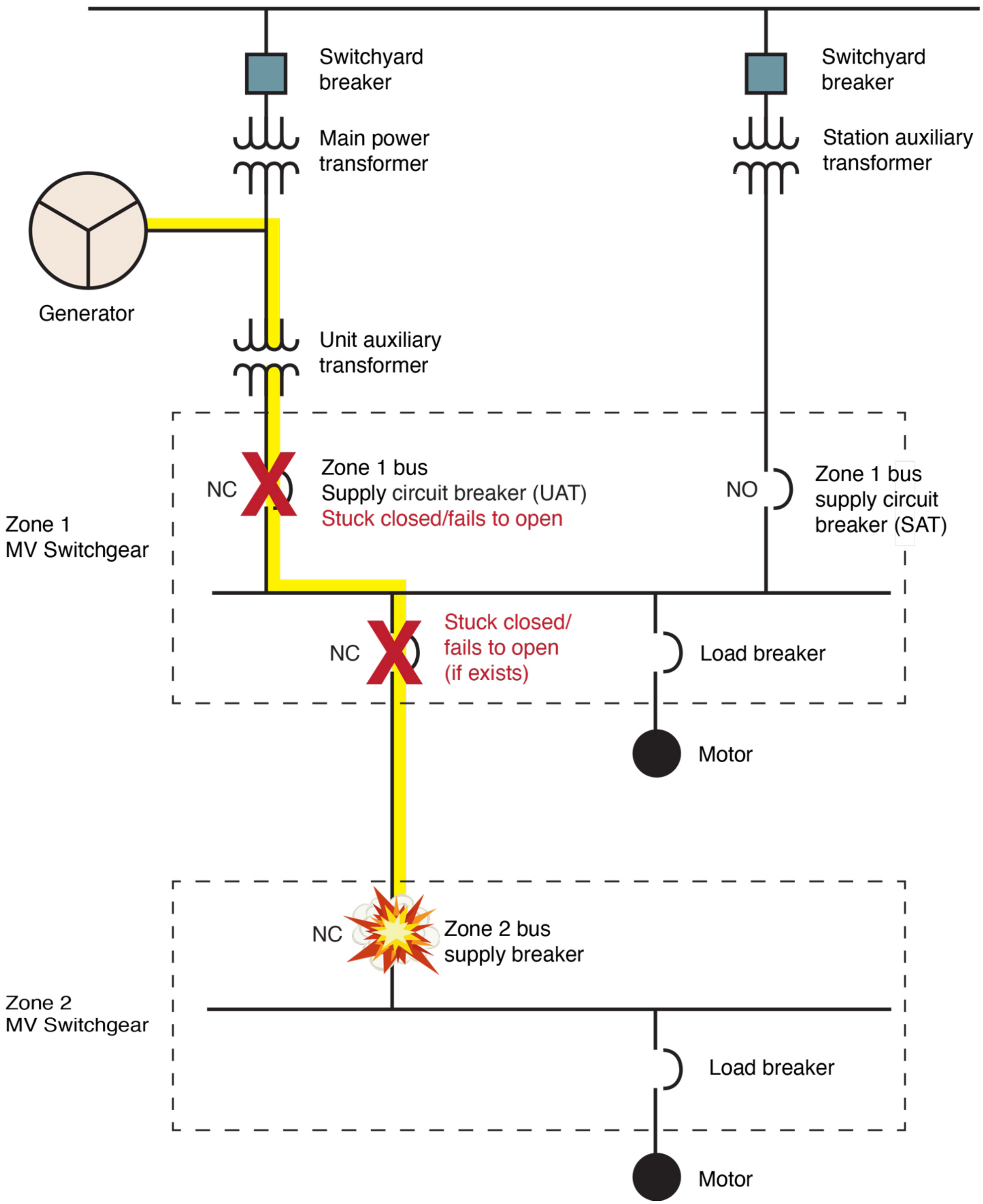


Figure 6-6
Example of a generator-fed fault (fault on Zone 2 with at least three independent failures)

- SAT: This end state is used for energy feeding the fault fed from the SAT. Although the SAT has differential protection (87), if this is successful, a HEAF does not occur. A conservative assumption in modeling SAT faults is that differential protection (87) has failed and backup protection (TOC [51] relay) is credited. This ZOI is modeled as a stiff source with no decay portion. Figure 6-7 shows a fault on the Zone 1 MV switchgear bus supply breaker fed by the SAT.

  The time regimes for the SAT are:

  - 0–2 s: modeled based on 2 s stiff FDS runs
    - Total energy: 68 MJ
  - 2.01–3 s: modeled based on 3 s stiff FDS runs
    - Total energy: 101 MJ
  - 3–4 s: interpolation is based on 3 and 5 s stiff FDS runs
    - Total energy: 135 MJ
  - Greater than 4 s: modeled based on 5 s stiff FDS runs
    - Total energy: 169 MJ

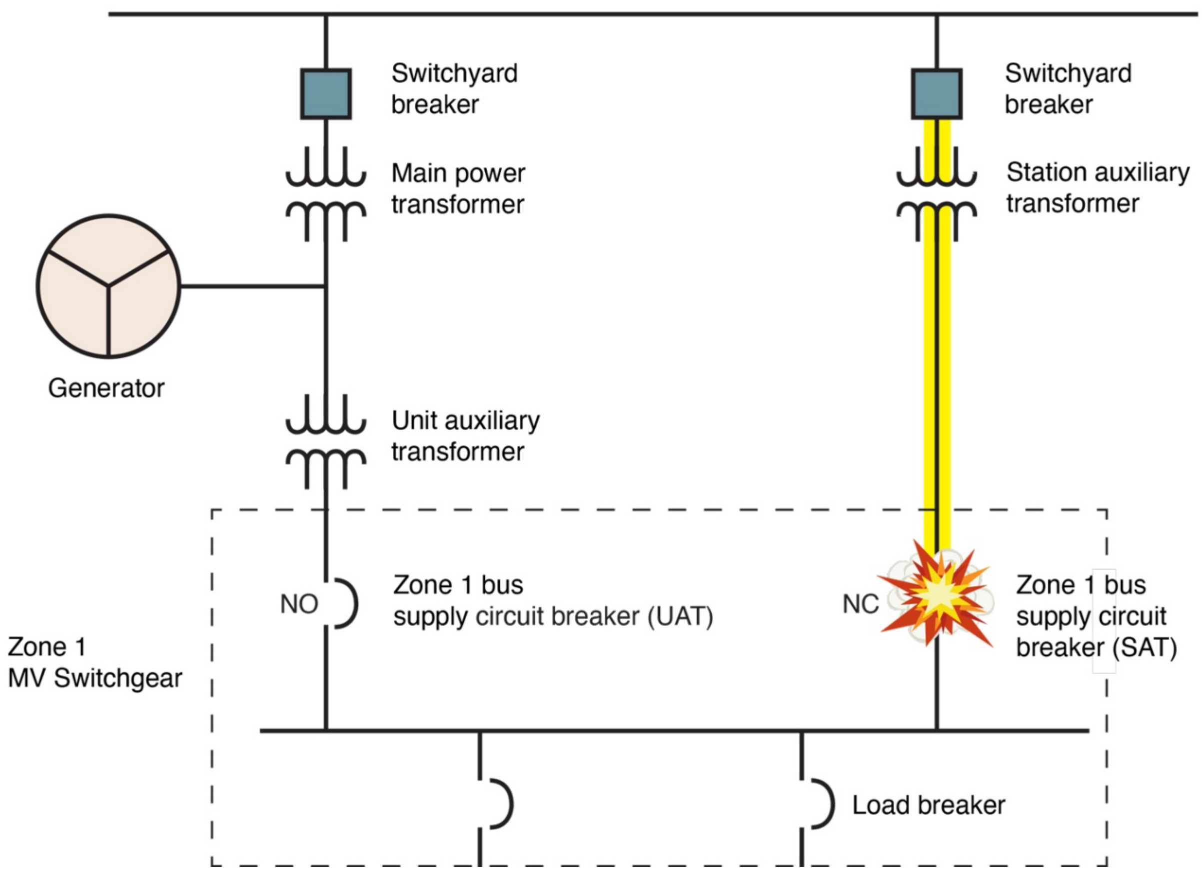


Figure 6-7
SAT-fed fault

Supply breaker limited (SBL): This is an end state for HEAFs that do not rely on the auxiliary power transformer fault protection to clear a fault. In an SBL HEAF, the upstream supply circuit breaker successfully interrupts the fault, which prevents the fault from cascading further up the MV EDS to the auxiliary power transformer backup protection scheme. This includes the following:

- Zone 1 main bus bar and load faults interrupted by the Zone 1 bus supply circuit breaker
- A Zone BD1 fault interrupted by the Zone 1 supply circuit breaker
- A Zone 2 bus supply circuit breaker fault interrupted by the Zone 1 bus supply circuit breaker
- A Zone 2 main bus bar and load faults interrupted by the Zone 2 bus supply circuit breaker.
- A Zone 2 main bus bar and load faults interrupted by the Zone 1 load circuit breaker with overcurrent protection
- A Zone BD2 fault interrupted by the Zone 2 bus supply circuit breaker

Two generic/default durations of SBL end states are modeled: the Zone 1 bus supply breaker interrupting at 4 s and the Zone 2 bus supply breaker interrupting at 2 s. The timing for each was determined by an aggregate review of NPP plant protection and coordination calculations summarized in Table 3-2.

Figure 6-8, Figure 6-9, and Figure 6-10 show potential SBL variations for Zone 1 and Zone 2 MV switchgear. Figure 6-8 shows a fault point on the main bus (yellow) or on the load breaker (pink) that is successfully cleared by the Zone 1 bus supply circuit breaker. Figure 6-9 shows a fault point on the Zone 2 bus supply circuit breaker that is interrupted by the Zone 1 bus supply circuit breaker. Figure 6-10 shows a fault point on the main bus (yellow) or on the load breaker (pink) that is successfully cleared by the Zone 2 bus supply circuit breaker.

  - SBL 4 s (conceptually shown in Figure 6-8 and Figure 6-9). Four seconds is chosen as an upper limit of the time required for a Zone 1 switchgear supply circuit breaker to interrupt a downstream fault (either in Zone 1 or as selectively coordinated with the Zone 2 supply circuit breaker). This interpolation is based on 3 and 5 s stiff source FDS runs.
    - Total energy: 135 MJ
  - SBL 3 s. A refinement option if the analyst determines the Zone 1 supply breaker FCT is between 2.01 and 3 seconds. This refinement can also be used for Zone 2 if the Zone 1 switchgear has a load circuit breaker with overcurrent protection (see Section 8.6.1 and 8.6.2). From the FDS simulations, this was modeled based on 3 s stiff source runs.
    - Total energy: 101 MJ

- SBL 2 s (conceptually shown in Figure 6-10). Two seconds is chosen as an upper limit of the time required for the Zone 2 switchgear supply circuit breaker to operate given a downstream fault. This end state can also be used as a refinement if the Zone 1 switchgear supply breaker can interrupt at 2 seconds or quicker. This refinement can also be used for Zone 2 if the Zone 1 switchgear has a load circuit breaker with overcurrent protection (see Sections 8.6.1 and 8.6.2). From the FDS simulations, this was modeled based on 2 s stiff source runs.
    - Total energy: 68 MJ

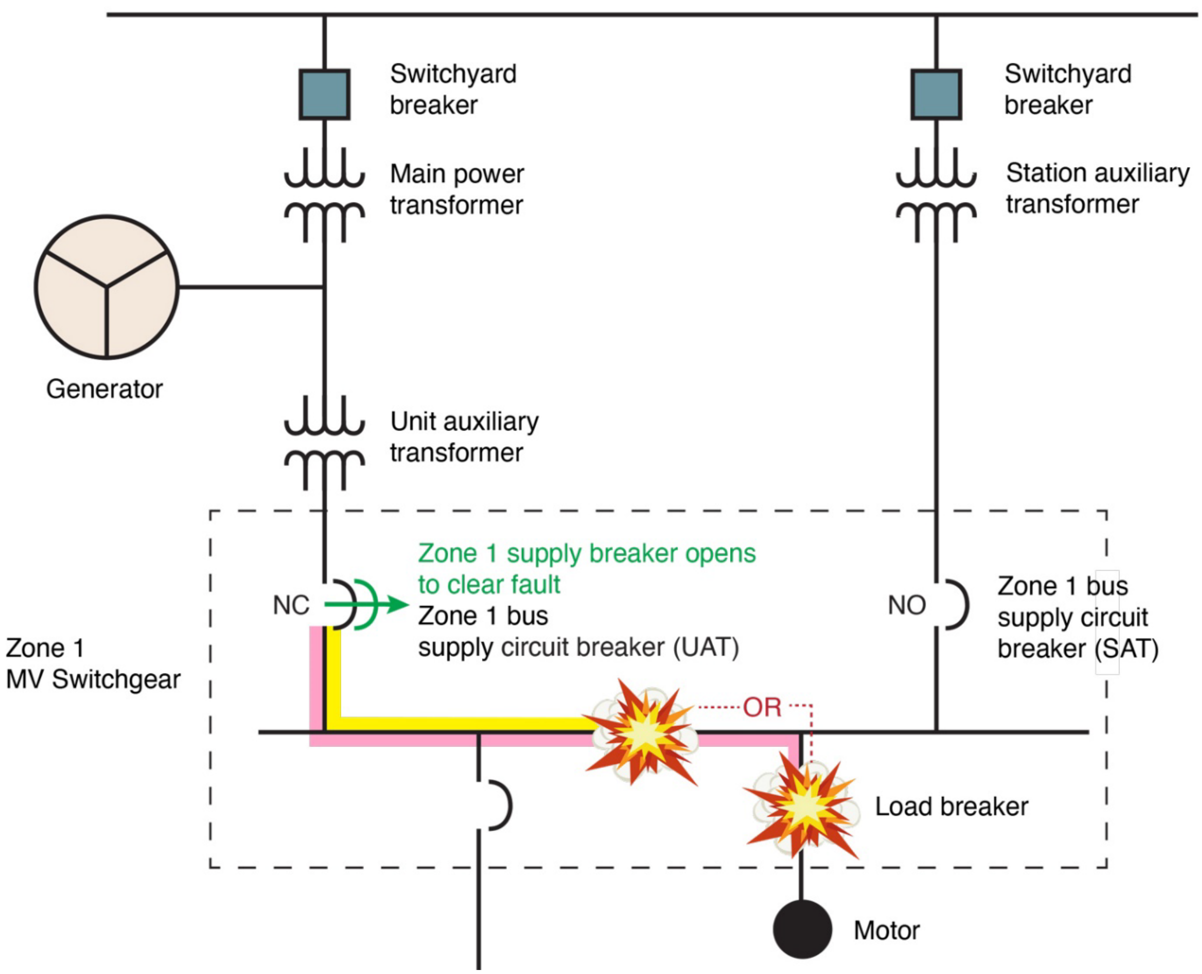


Figure 6-8
Fault on Zone 1 MV switchgear interrupted by Zone 1 bus supply circuit breaker (SBL fault interrupted by bus supply circuit breaker)

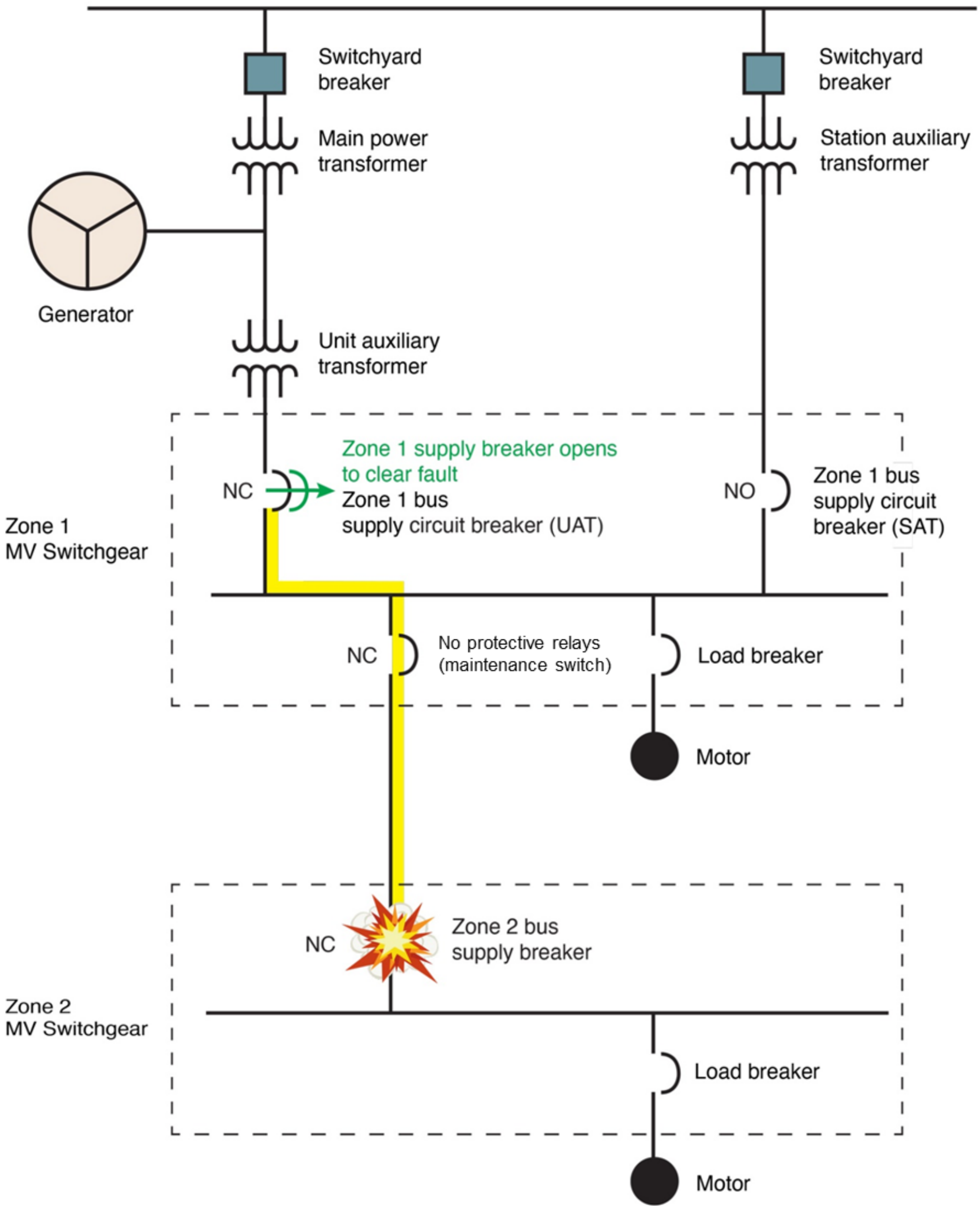


Figure 6-9
Zone 2 circuit breaker fault interrupted by Zone 1 bus supply circuit breaker (SBL fault interrupted by Zone 1 bus supply circuit breaker)

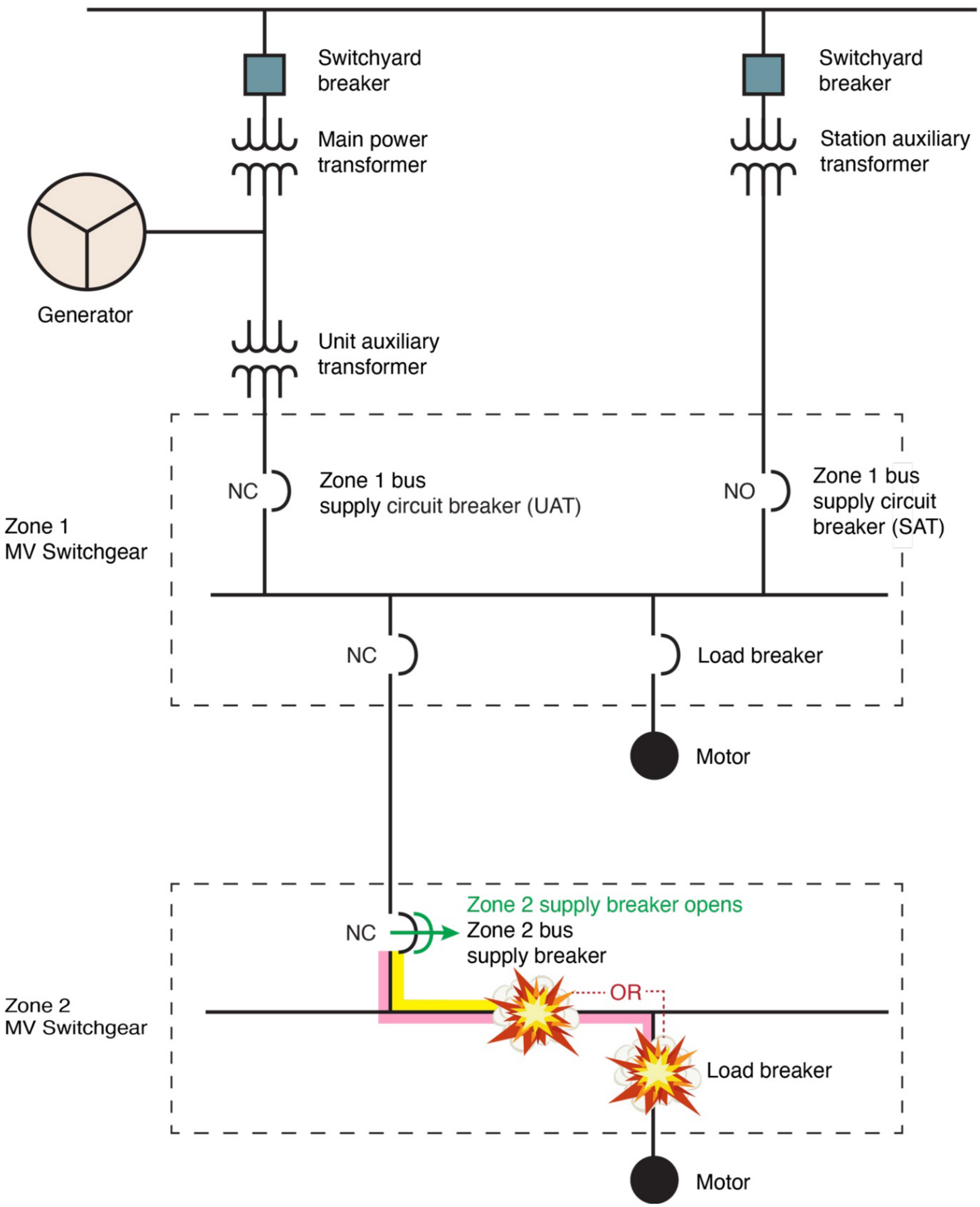


Figure 6-10
Fault on Zone 2 MV switchgear interrupted by Zone 2 bus supply circuit breaker (SBL fault interrupted by bus supply circuit breaker)

Stiff energy (constant-current arcing faults) is attributed to classical short circuits that are fed by an infinite source limited by the impedance of the upstream transformer(s). These faults are of constant current until interrupted by the EDS protection scheme (e.g., differential [instantaneous] or TOC relays), which define the duration of constant-current arcing faults. For conservatism, the fault location in electrical studies is modelled as a zero-impedance fault (commonly referred to as a bolted fault). However, not all faults are zero-impedance and are referred to as arcing faults. For MV systems, the fault-current magnitude is typically 85% of a bolted fault. Nonetheless, they are still considered a constant-current arcing fault stiff source for the fault duration.

Instantaneous protections systems will limit fault duration such that the energy will not rise to the level of a HEAF (typically within cycles). On the other hand, depending on the FCT of the TOC protection system, the let-through energy can achieve that of a HEAF (typically within one or more seconds depending on the equipment).

6.4 How to Determine Fault Clearing Timing

Development of the EDS fault zones in Section 3 introduces the concept of a FCT based on an NPP's protection and coordination calculation protection scheme settings to limit the arcing fault energy to below the maximum observed in the industry (Figure 3-3, Figure 3-4, and Table 3-2). The FCTs important to the HEAF analysis include the following:

- Zone 1 MV switchgear stuck bus supply circuit breaker with interruption by the upstream transformer backup TOC (51) device. This is the auxiliary power transformer's protection speed of operation. Section 3.2.1 describes the UAT transformer protection and FCT range, and Section 3.2.2 describes the SAT protection and FCT range. This FCT represents how long a fault outside the differential (or instantaneous) protection (87) of the auxiliary power transformer would take to trip the generator and/or the switchyard breakers. This FCT applies to the following fault zones:
    - UAT-fed scenarios in Zone 1 load/main bus bar and Zones 2, BD1, and BD2
    - SAT-fed scenarios in Zones 1, 2, BDSAT, BD1, and BD2

  This FCT is calculated for each auxiliary power transformer (UAT or SAT), and the same FCT is used for all downstream zones powered by that auxiliary power transformer. Section 6.4.1 describes the steps to determine this FCT.

- Zone 1 MV switchgear bus supply circuit breaker. Described in Section 3.2.3, this FCT is the speed in which the switchgear supply circuit breaker will operate given a downstream stuck circuit breaker. Section 6.4.2 describes the steps to determine this FCT.
    - This is used in determining a refined FCT for the SBL of the Zone 1, Zone BD1, or Zone 2 bus supply circuit breaker if the bounding 4 s ZOI requires refinement. This step is not necessary if using the default/generic SBL fault duration is acceptable.

The FCTs related to the Zone 1 MV switchgear stuck bus supply circuit breaker backup protection was provided by U.S. industry during the industry-wide survey regarding HEAFs with the presence of aluminum. The high-level results of the survey are documented in EPRI 3002020692 [43], and Figure 3-3 and Figure 3-4 reproduce the plots of the FCT ranges.

Note 1: When determining the FCTs, accounting for relay sensing time (e.g., 0.5 cycles) and circuit breaker interrupting time (3-8 cycles) is not necessary since these durations are negligibly short compared to the HEAF durations of concern.

Note 2: In the early stages of the project, proof of concept used three-phase bolted (zero impedance) faults for medium voltage. IEEE 1584 [25] shows that medium voltage arc faults are consistently around 85% of the three-phase bolted (zero impedance) fault (this is also supported by HEAF OE). Since the objective is to ensure all the energy is accounted for in the ZOI determination, use of three-phase bolted fault at the available short-circuit current (ASC) is considered acceptable. This is due to the design of inverse time overcurrent relays (51) as the total integrated energy is slightly less (or the same) given a 15% reduction in fault current, even though the FCT is slightly increased for an arc fault by approximately 0.1 to 0.2 seconds. This was verified against four NPP medium voltage protection and coordination calculations. The only exception would be for known station design vulnerabilities where the time overcurrent (51) relays are not optimally set (that is, FCTs are in excess of 5 seconds at the ASC). In these cases, the arc fault current using IEEE 1584 may need to be used for FCT determination.

6.4.1 Zone 1 Medium Voltage Switchgear Bus Supply Circuit Breaker Backup Protection (Stuck Breaker)

When the Zone 1 switchgear bus supply circuit breaker is unable to clear the fault (i.e., stuck breaker), the next level of upstream protection must interrupt the fault. This next-level upstream protection is typically the auxiliary power transformer SAT or UAT TOC protection (e.g., transformer primary side [51] or a 51G, 51N relay). The instantaneous SAT or UAT differential protection (87) is not credited because the fault is considered to be outside the differential (87) protection zone or assumed to be failed along with the bus supply circuit breaker.

To determine the FCTs, perform the following steps:

1. Using the station one-line diagrams, identify Zone 1 MV switchgear and associated upstream power transformers (UAT and/or SAT).
    a. Zone 1 switchgear typically has two power supplies (bus supply circuit breakers): one for normal alignment at power and a second supply typically used during shutdown or when the normal supply transformer is taken out for maintenance. The analyst must consider both supplies for the screening level (selecting the most bounding configuration [highest energy]) or configuration-specific ZOIs (both normal and secondary supplies).
2. For each Zone 1 MV switchgear, identify the normal and secondary bus supply circuit breakers and trace upstream to the respective power transformer (either UAT or SAT). (Output circuit breakers of emergency diesel generators [EDG] are not in scope because they are treated as load breakers in the HEAF analysis).
3. Obtain the associated TCC curve(s) from the station protection and coordination calculations for each Zone 1 MV switchgear/power transformer lineup (UAT and/or SAT).
4. Obtain the ASC at each Zone 1 MV switchgear. ASC may be provided on the TCC curve or determined from a separate station short-circuit current calculation.
    a. Caution: Some TCC curve plots display the short-circuit withstand rating of the switchgear as the ASC, which may be higher than actual. Use the calculated ASC when determining the FCT for Zone 1 MV switchgear bus supply circuit breakers.
    b. If multiple ASC values are provided (e.g., normal, LOCA, or EDG surveillance), select the ASC associated with Mode 1 normal operation.

   c. If the secondary alignment has a different ASC value, that value is needed for the secondary Zone 1 MV switchgear alignment.

5. Identify the TOC (51) relay curve associated with the power transformer (UAT or SAT) feeding the Zone 1 MV switchgear bus supply circuit breaker.
6. Identify the ASC on the horizontal axis and draw a straight line upwards until it intersects with the transformer's 51 TOC relay. Ensure that the TCC plot has the same voltage as the Zone 1 MV switchgear; if not, the ASC must be normalized to the plot voltage.
7. At the intersection of the 51 TOC relay and the ASC, draw a horizontal line to the left to determine the FCT from the vertical axis (time).
8. Repeat for the secondary Zone 1 MV switchgear/power transformer alignment.

In summary, the FCTs are located where the transformer TOC protection (51 relay) curve intersects with the ASC. Figures 3-3 and 3-4 show the ranges of FCTs for U.S. NPPs. Example 1 shows the FCT calculated for a SAT 51 relay.

Example 1:

This example uses the TCC curve in Figure 6-11.

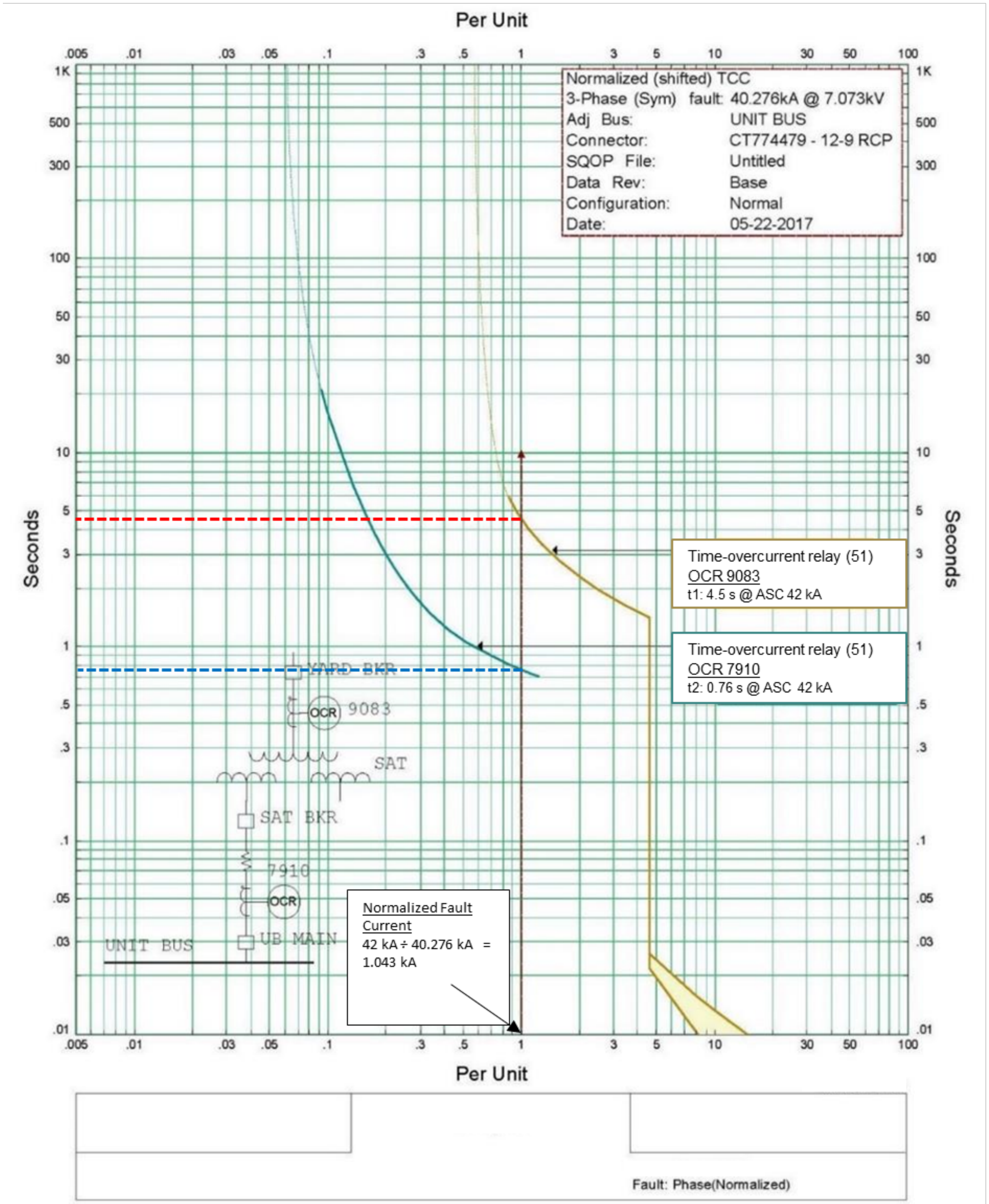


Figure 6-11
Example 1 TCC curve

- The available fault current has been normalized to 1.0 per unit (i.e., 40.276 kA = 1.0 per unit on the SAT secondary at a voltage of 7.073 kV).
    - Fault current: 1.043 units × 40.276 kA/unit = 42 kA (brown vertical line on Figure 6-11)
- The TOC (51) relay of interest is 9083 (yellow curve on Figure 6-11), which trips the SAT circuit breaker.
    - In some cases, if no SAT breaker exists, this relay will trip only the switchyard breakers on the primary side of the transformer (similar for UAT, plus generator trip).
- The point at which the SAT circuit breaker and/or switchyard circuit breakers will trip open is 4.5 s on the TCC curve. See the horizontal dashed red line on Figure 6-11.

6.4.2 Zone 1 MV Switchgear – SBL FCT

In HEAF scenarios where the fault originates in or downstream of the load circuit breaker of the Zone 1 MV switchgear and a failure occurs that prevents the load circuit breaker from opening on demand (e.g., stuck breaker), then the MV switchgear bus supply circuit breaker will trip open on a TOC (51) relay. In addition, a fault on the main bus bar with an operable supply breaker will also clear the fault on a TOC (51) relay.

The FCT is limited by how fast the supply breaker will trip open. Section 3.2.3 summarizes a review performed for a sample of United States NPPs, and an upper bound of 4 s was determined for the time it takes for the Zone 1 MV switchgear bus supply circuit breaker to operate. The default/generic ZOI for a SBL fault requiring the opening of the Zone 1 bus supply circuit breaker is based off an FCT of 4 seconds.

Recognizing that 4 s may be on the higher end, this section provides the analyst with the steps necessary to determine the Zone 1 bus supply breaker FCT. This step is optional because the upper end of the FCT is used as a default/generic selection in the ZOI tables in Sections 8 and 9. If the Zone 1 supply breaker FCT is 3 s or less, less energetic SBL ZOIs can be used in Sections 8 and 9 if more refinement is necessary. To determine the FCT, follow steps 1 through 8 in Section 6.4.1 with one exception. In step 5, instead of identifying the TOC (51) relay associated with the UAT or SAT, identify the Zone 1 MV switchgear bus supply circuit breaker TOC (51) relay. The FCT is where the switchgear supply circuit breaker TOC protection (51) relay curve intersects with the ASC.

Example 2 shows the FCT calculated for the normal supply circuit breaker of the MV switchgear.

Example 2:

This example uses the TCC curve in Figure 6-11.

- The available fault current has been normalized to 1.0 per unit (representing 40.276 kA at 7.073 kV).
    - Fault current: 42 kA (brown vertical line on Figure 6-11).
- The TOC (51) relay of interest is 7910 (blue curve on Figure 6-11) that trips the UB MAIN circuit breaker.
- The point at which the UB MAIN circuit breaker will trip open is shown as 0.76 s on the TCC curve. See the horizontal dashed blue line on Figure 6-11.

6.4.3 EDS Designs with ESF Transformer Between Zone 1 and Zone 2 Switchgear

Approximately 15% of the US NPP EDS designs utilize an additional step-down transformer from 13.8kV to 4.16kV to serve the Class 1E buses and some BOP buses (larger BOP loads remain at the higher 13.8kV voltage). These are typically called an ESF transformer (or similar). For some NPPs, this design choice was preferred over 3-winding auxiliary power transformers with two separate voltage levels (e.g., Zone 1 is 13.8kV and Zone 2 is 4.16kV).

Zone 2 faults where the bus supply circuit breaker to the switchgear is stuck would rely on the ESF transformer time overcurrent (51) backup protection (primary side). Similar to auxiliary power transformers, the ESF transformer time overcurrent protection is expected to be set to protect the ESF transformer from excessive let-through current duration within approximately 4 seconds (or less). This is supported by the EPRI survey results [43].

If refinement is necessary, the FCT of the ESF transformer primary supply circuit breaker can be determined similarly as was done for the UAT or SAT backup up time overcurrent FCT determination given the following considerations.

The first consideration is that the available short circuit (ASC) current on the secondary side of the ESF transformer will be less than the ASC current to primary side due to the transformer impedance. The second consideration is that the primary and secondary ASC current must be normalized to one base voltage when working with the time-current-characteristic (TCC) curves. This information is typically available in one of two ways (note: 13.8kV/4.16kV ESF transformer used in the following example):

1. Protection and coordination calculation TCC curves directly display both ASC currents on the horizonal x-axis of the graphs (normalized to one voltage base, e.g., 13.8kV):
    - ASC current at the 13.8kV bus feeding the primary side of the ESF transformer
    - ASC current at the 4.16kV bus fed from the secondary of the ESF transformer.

    The ASC at the 4.16kV is then used to determine the ESF transformer primary supply circuit breaker FCT from the time overcurrent (51) relay curve.

2. The ASC current at the primary and secondary voltage side of the step-down transformer is not shown on the TCC curve and may have to be obtained from a separate short circuit calculation. One of the short circuit currents then has to be normalized to the base voltage level that the TCC curve is set at. For example:
    - TCC curve voltage scale is normalized at 13.8kV. That is, the bottom x-axis current scale is based on 13.8kV system voltage. If the short circuit calculation provides the 4.16kV bus ASC current as 30,000A, this current has to be normalized to 13.8kV as follows:
        - 4.16kV ASC current converted to 13.8kV base is multiplied by the ratio of (4.16kV/13.8kV)
        - That is 4.16kV ASC on a 13.8kV base = 9,043A (30,000A * (4.16/13.8))
    - Then 9,043A is used when determining the FCT of the ESF primary side circuit breaker (via the overcurrent relay (51) curve) for a stuck Zone 2, 4.16kV bus supply circuit breaker.

6.5 Post-HEAF Ensuing Fire (Switchgear and Load Centers Only)

HEAFs have two distinct phases: the energetic fault and the post-HEAF ensuing fire.

Immediately following the energetic blast, the ensuing fire has a heat release rate (HRR) equal to the 98th percentile associated with switchgear and load centers. From NUREG-2178, Volume 1 [44], the 98th percentile HRR is 170 kW. For detailed fire modeling, the fire begins immediately following the arcing fault at t = 0 (e.g., at the start of the fire scenario). The ensuing fire timing is modeled as:

- Growth period: 0 min (none)
- Steady-burning period: 8 min
- Decay period: 19 min

The HRR timing profile is shown in Figure 6-12.

The elevation (location) of the ensuing fire should be modeled following existing practices as described in Supplement 1 to NUREG/CR-6850 [2] considering the expected condition of the load center or switchgear post-HEAF, with one exception. The exception to this is for load center supply circuit breakers that are modeled at lower elevations (B, C, E or F in Table 7-1). Since the elevation of the HEAF is physically located in the middle or lower portions of the load center, the post-HEAF ensuing fire can also be postulated lower. As described in Section 6.5.1.1, breaches in load centers are minimal and not expected to substantially alter the cabinet construction beyond the immediate cubicle barrier.

For the ensuing fire, do not credit obstructions in either the vertical or horizontal directions. The arcing phase of the HEAF can damage (e.g., open) faces with external ZOIs (top, back, front, sides). Because of the breach of the cabinet, do not use the obstructed plume in the methodologies from NUREG-2178, Volume 1 [44], or obstructed radiation in NUREG-2178, Volume 2 [45], for the post-HEAF fire ZOI.

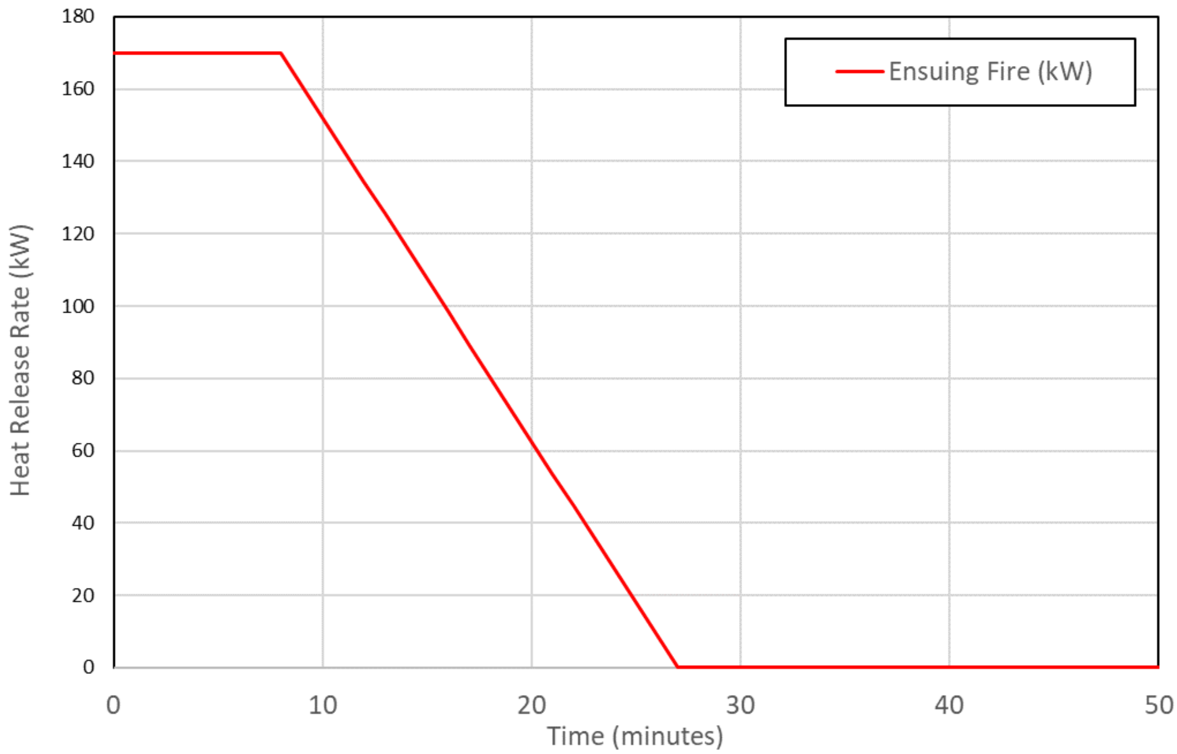


Figure 6-12
Post-HEAF ensuing fire HRR timing profile

As concluded in RIL 2022-01/EPRI 3002023400 [15], the HEAF's arcing phase will not ignite secondary combustibles or cable targets external to the source switchgear or load center. Secondary combustibles can be ignited from the post-HEAF ensuing thermal fire. The existing guidance for determining the ignition and modeling of secondary combustibles due to fire are described in the following references:

- FAQ 16-0011 [46] for bulk cable tray ignition that may occur during the following conditions:
    - Flame impingement
    - Plume temperature of 932°F (500°C)
    - Radiant heat flux of 25 kW/m^2
- NUREG/CR-6850 [1] and NUREG/CR-7010 [47] for spread and propagation

6.5.1 Fire Spread Between Adjacent Cabinets

Fire spread to switchgear vertical sections that are adjacent to where the HEAF initiated is postulated under certain conditions due to the potential for the arc to breach the shared boundary. A breach in the shared boundary could allow the HEAF and ensuing fire to expose the combustible contents of an adjacent section to an energy flux high enough to sustain ignition. A detailed methodology is provided to determine the fire spread potential to adjacent switchgear vertical sections.

6.5.1.1 Applicability

Fire spread to an adjacent section is postulated for MV switchgear HEAFs with an arc energy greater than 101 MJ for vertical sections separated by a single steel barrier (i.e., single wall construction) or greater than 202 MJ for vertical sections separated by two steel barriers (i.e., double wall construction).[10] The basis for this is as follows:

- Physical testing of low voltage switchgear (load center) HEAFs indicates that enclosure breaches are minimal [10]. Arc migration was observed in several experiments, which would reduce the possibility of enclosure breach because the most intense heat fluxes at the enclosure boundary are not in a fixed location [10].
- The bounding arc energy for load centers HEAFs is 90 MJ [16]. FDS simulations of arcs at different locations predict relatively small breaches that develop near the end of the arcing period at the bounding arc energy [16].
- Physical testing of MV switchgear show that short duration arcs (2 s) result in minimal enclosure side breaches. Longer duration arcs (4 s) can result in large breaches [6]. A 4 s stiff arc is characterized with a 135 MJ energy.
- FDS simulations of stiff and generator fed arcs at different locations in MV switchgear show that side breaches initiate around 1.8 – 2 s, consistent with observations from physical testing [6, 16]. Breaches are predicted to grow in size as the arc continues and for arcs greater than 3 s, side breaches could approach 5% of the wall area [6, 16]. The energy required to breach the enclosure boundary at a fixed location is a linear function of the enclosure boundary thickness. The FDS simulations and physical testing of MV switchgear involve vertical sections with one steel barrier (i.e., single wall construction). Configurations separated by two steel barriers (one corresponding to each vertical section [i.e., double wall construction]), will require twice as much energy to create a significant breach as the single wall construction sections. Given the threshold arc energy for a significant single wall breach is 101 MJ for single wall construction, the threshold energy for a double wall breach is 202 MJ.

6.5.1.2 Medium Voltage Switchgear Combustible Fuel Configuration

MV switchgear vertical sections have several distinct sub-compartments with different combustible materials and different combustible fuel load. The most relevant sub-compartments for characterizing fire spread involves the following:

- The meter and relay cubicle, which is located near the top front of the switchgear and contains the highest concentration of small diameter cables and synthetic insulated switchboard (SIS) wiring, terminal blocks, control relays, etc.
- The balance of the switchgear vertical section, including the primary cable compartment, the rear riser compartment, the main bus bar compartment, and the circuit breaker stabs.

[10] Some MV switchgear across the industry are constructed in a modular fashion, where each vertical section is constructed and installed to form the switchgear bank. This creates two layers of steel with an air gap between them (i.e., double wall construction).

Figures 6-13 depicts the location of the sub-compartments within a vertical-lift style circuit breaker MV switchgear vertical section. Figures 6-14 and 6-15 depict the locations of the sub-compartments for horizontal draw-out style circuit breakers.

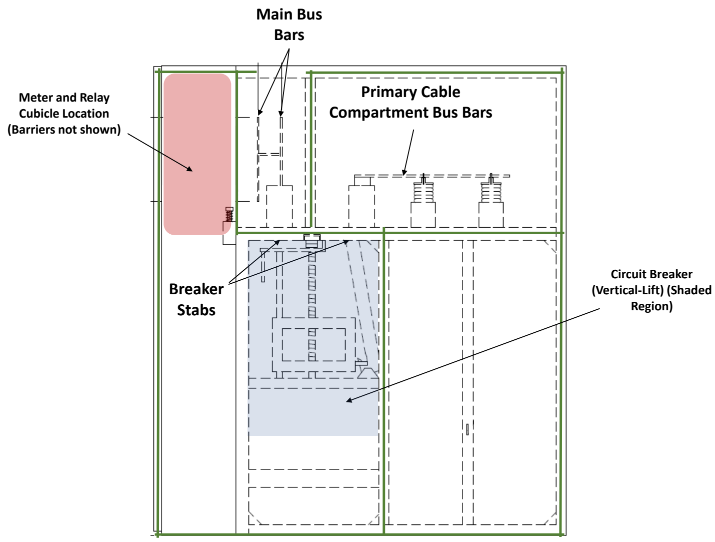


Figure 6-13
Internal configuration of the GE Magne-Blast vertical-lift style circuit breaker MV switchgear

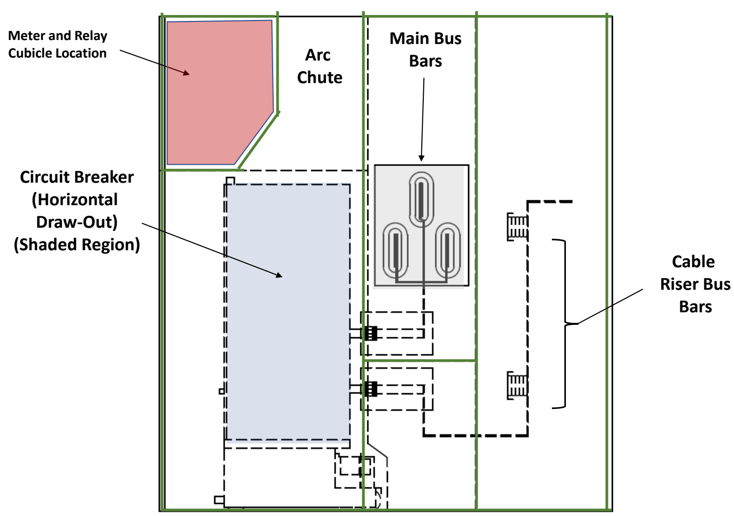


Figure 6-14
Internal configuration of the ABB/ITE HK horizontal draw-out style circuit breaker MV switchgear

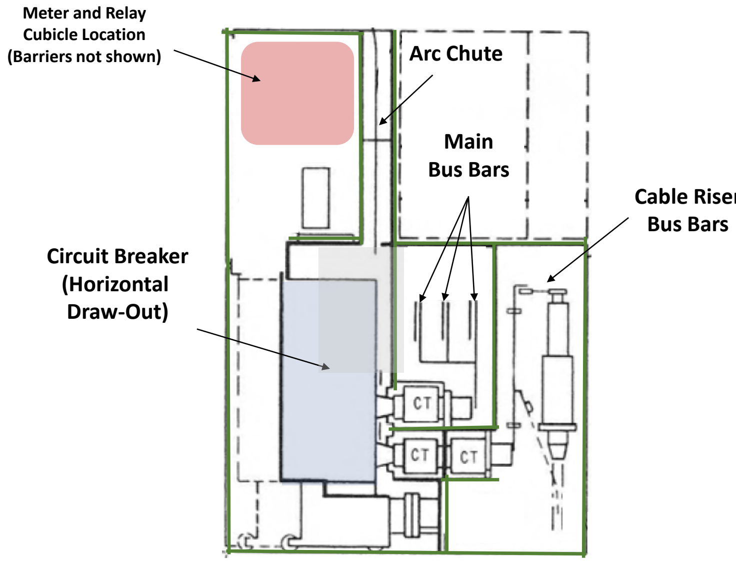


Figure 6-15
Internal configuration of the Westinghouse DH-P horizontal draw-out style circuit breaker MV switchgear

The largest fuel load concentration within the switchgear vertical section is in the meter and relay cubicle. Figures 6-16 and Figure 3-9 in [48] show examples of the fuel loading within these cubicles for vertical-lift style breaker and a horizontal draw-out style breaker switchgear.

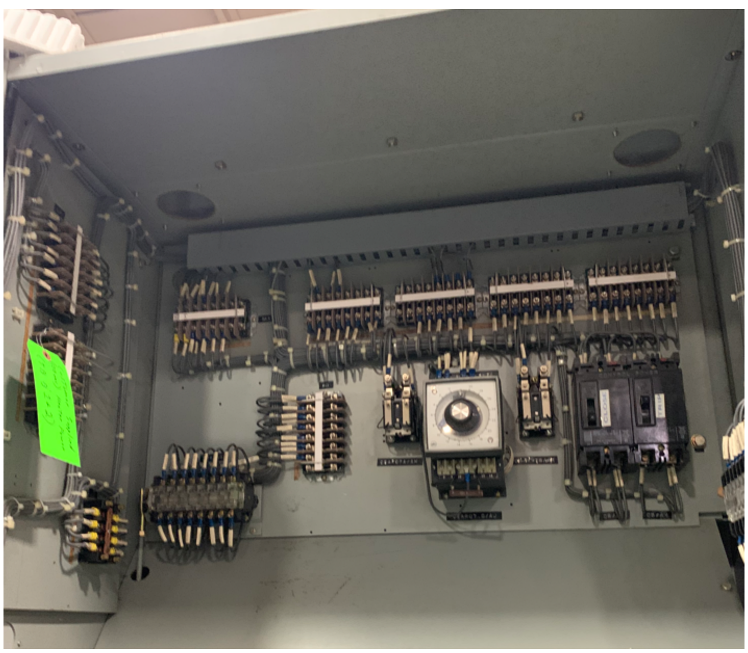


Figure 6-16
Meter and relay cubicle for a horizontal-lift style breaker MV switchgear

The fuel load in the remaining sections of the switchgear is very low and consists of materials associated with the breaker itself, several large diameter power cables, and a small quantity of small diameter cable and SIS wiring. Figures 6-17 and 6-18 depict examples of the fuel load within these areas of a typical MV switchgear.

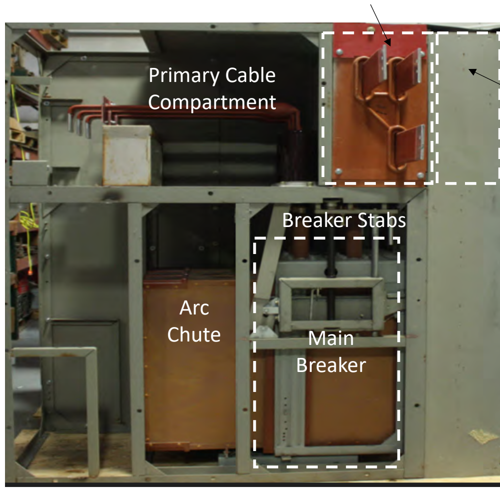


Figure 6-17
Fuel loading in the GE Magne-Blast vertical-lift style breaker MV switchgear (side view with breaker removed)

Figure 6-18
Fuel loading in the Magne-Blast vertical-lift style breaker medium voltage switchgear (front view with breaker in rack) [3]

The fuel load for switchgear is generically characterized as 'low' or 'very low' per Section 4.2.2.7 of NUREG-2178 Volume 2 [45]. Figures 6-16 through 6-18 show that most of the fuel within a switchgear vertical section is concentrated in the meter and relay cubicle, which is located at the top front of the switchgear. The fuel load in other areas is generally consistent with a 'very low' fuel load as described in NUREG-2178 Volume 1 [44].

Combustible materials outside the meter and relay cubicle are primarily small amounts of power cables, located in various sub-compartments and the main breaker itself, which is located in the breaker compartment. Although the breaker has a larger thermal inertia and contains a significant quantity of metal, there are combustible resins and components within the breaker that have been observed to ignite [7]. The fire elevation for a breaker fire is between the base and mid-height of the switchgear for both vertical and horizontal switchgear.

6.5.1.3 Generic Event Tree for Adjacent Switchgear Vertical Section Fire Spread

For HEAF energies that spread, an event tree is developed to characterize the probability of fire spread to adjacent switchgear vertical sections and given the fire spread, the probability that the meter and relay cubicle is involved. The end states considered in the event tree are summarized in Table 6-1. Note that fire spread is not modeled for arc energies of 101 MJ or lower for single wall construction and 202 MJ or lower for double wall construction as described in Section 6.5.1.1.

Fire spread to the meter and relay cubicle is assumed for a 300 MJ arc energy for both single and double wall construction.

In summary, the fire spread probability for end state arc energies of 132 MJ, 135 MJ, 169 MJ, 200 MJ, and 233 MJ for single wall construction and 233 MJ for double wall construction is determined using the fire spread event tree.

Table 6-1
Fire spread end states for MV switchgear HEAFs

Stiff duration (s)	Is the stiff followed by a generator-fed fault?	Arc energy (MJ)	End state	
			Single wall construction	Double wall construction
2	No	68	No fire spread	No fire spread
3	No	101	No fire spread	No fire spread
4	No	135	Use fire spread event tree (Figure 6-19)	No fire spread
5	No	169	Use fire spread event tree (Figure 6-19)	No fire spread
0	Yes	132	Use fire spread event tree (Figure 6-19)	No fire spread
2	Yes	200	Use fire spread event tree (Figure 6-19)	No fire spread
3	Yes	233	Use fire spread event tree (Figure 6-19)	Use fire spread event tree (Figure 6-19)
5	Yes	300	Fire spread to meter and relay cubicle (Figure 6-20)	Fire spread to meter and relay cubicle (Figure 6-20)

Figure 6-19 depicts the event tree for single and double wall construction end states. The probability of fire spread is based on operational experience for MV switchgear HEAFs in Table 5-2 and assumptions on the number of available propagation pathways. The split fractions and parameters for the event tree are as follows:

- Based on the events in Table 5-2, 14% of the MV switchgear HEAFs originate in the main bus bar, 14% originate in the primary cable compartment bus bar, and the remaining 72% originate at the main breaker. Of the seven events listed in Table 5-2 one occurred at the main bus bar, one occurred in the primary cable compartment bus bar, and five occurred at the main breaker.
- Only HEAFs that originate in the main bus bar are judged to be capable of involving the meter and relay cubicle of an adjacent vertical section of switchgear. HEAFs at the main bus bar are closest to the adjacent meter and relay cubicle and have the fewest barriers to breach to penetrate this cubicle. HEAFs that originate in the primary cable compartment bus bar or at the main breaker do not have a direct breach path into the meter and relay cubicle of the adjacent switchgear vertical section. A breach to the adjacent breaker cubicle igniting SIS control wiring that spreads to the meter and relay cubicle is judged implausible and does not need to be postulated.
- The fraction of HEAFs that could involve an adjacent vertical section’s meter and relay cubicle given a HEAF at the main bus bar is determined from the number of available breach directions. The arc will typically attach to the cubicle boundary in one or two points

along the same axis: left and right, top and bottom, or back and front. Assuming equal likelihood of breach among all directions, only one of these three directional pairs leads to a breach of the adjacent meter and relay cubicle resulting in a split fraction of 0.33 for fire spread into an adjacent meter and relay cubicle.

Using the event tree in Figure 6-19, for HEAF energies that can breach (refer to Table 6-1), 5% of HEAFs are postulated to involve the meter and relay cubicle of an adjacent switchgear vertical section. The remaining 95% of HEAFs are not postulated to spread into the relay and meter cubicle but can spread to sparsely loaded sub-compartments of adjacent vertical sections. Because of the breach symmetry, the fire spread potential is the same for adjacent sections on either side of the HEAF vertical section (if there are adjacent switchgear vertical sections on both sides).

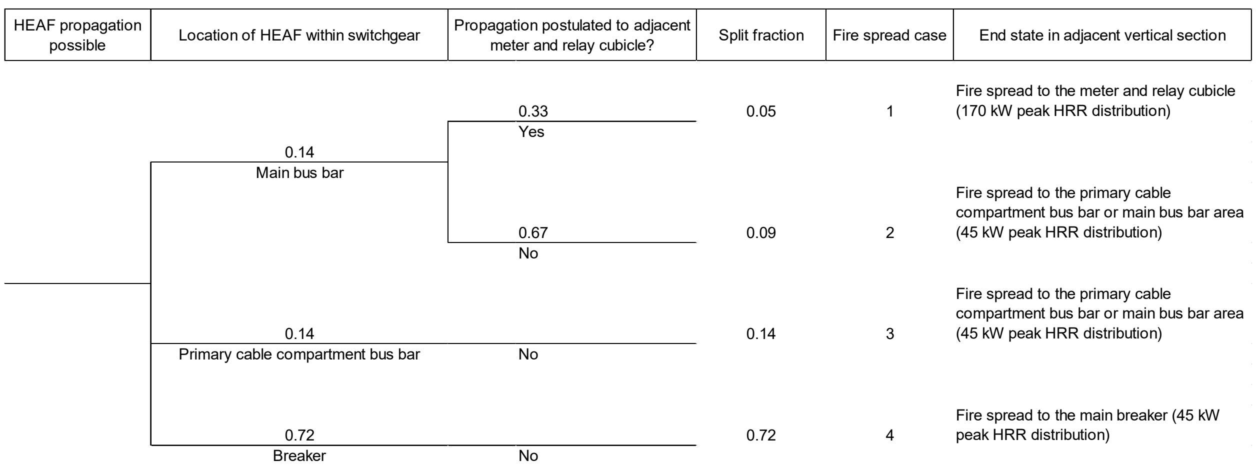


Figure 6-19
Generic fire spread event tree (use for single wall at energies of 132 – 233 MJ and for double wall energy of 233 MJ)

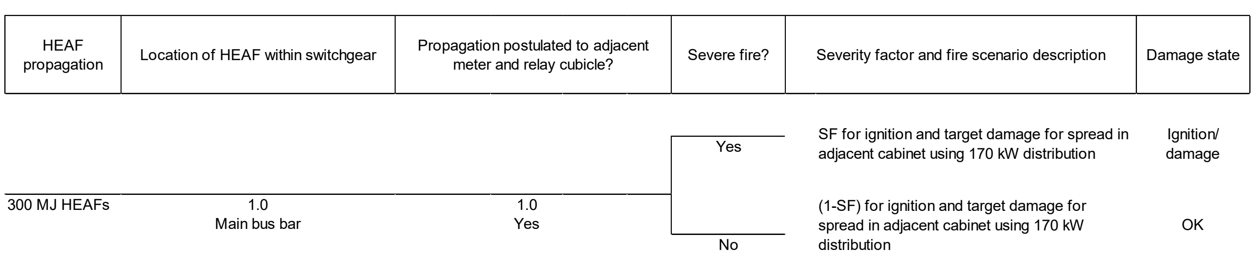
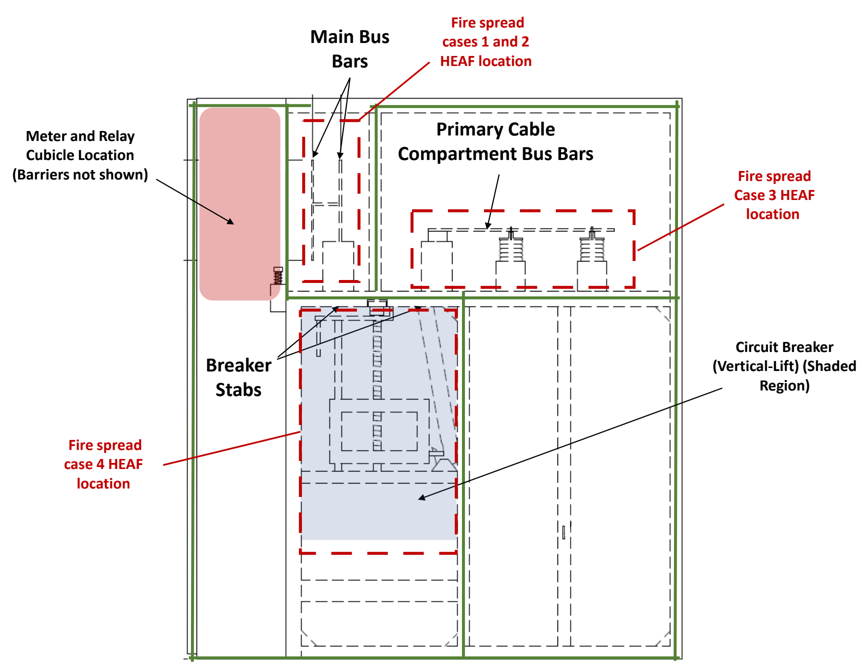


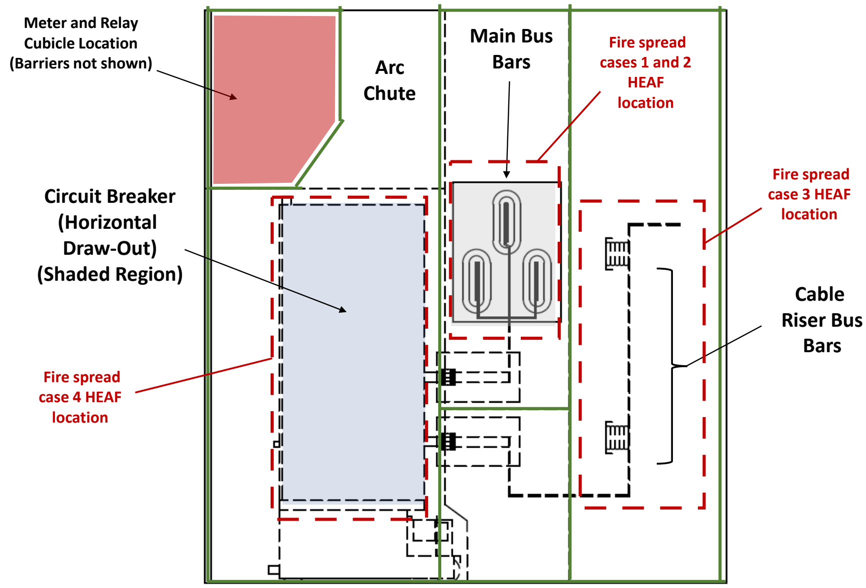
Figure 6-20
Fire modeling approach for 300 MJ HEAFs (assume fire spread case 1)

The four end states in Figure 6-19 and the end state in Figure 6-20 are used to develop overall HRR and ZOI guidance. These cases are as follows (see Figure 6-21):

- Fire spread case 1: the HEAF originates at the main bus bar and the fire propagates to the adjacent meter and relay cubicle.
    - This fire spread case also applies to the 300 MJ HEAFs since it is assumed these involve the meter and relay cubicle.
- Fire spread case 2: the HEAF originates at the main bus bar and has the ability to propagate to other adjacent compartments with a very low fuel load, but the fire does not propagate to the adjacent meter and relay cubicle.
- Fire spread case 3: the HEAF originates in the primary cable (or riser bus) compartment, but the fire does not propagate to the adjacent meter and relay cubicle.
- Fire spread case 4: the HEAF originates at the breaker and has the ability to propagate to other adjacent compartments with a very low fuel load, but does not propagate to the adjacent meter and relay cubicle.



Vertical-lift style circuit breaker



Horizontal draw-out style circuit breaker

Figure 6-21
HEAF locations for each fire spread case

6.5.1.4 Total Heat Release Rate for Fire Spread

The total HRR for the post-HEAF ensuing fire involves two components:

- The HRR of the initiating HEAF vertical section
- The HRR from one or two adjacent switchgear vertical sections, depending on whether there is one or two adjacent switchgear vertical sections physically located on either side of the initiating HEAF section

The HRR profile for the vertical section where the HEAF originated uses the 98th percentile peak HRR without a growth stage for switchgear and load centers (as previously described and depicted in Figure 6-12). The HRR profile for each adjacent switchgear vertical section depends on whether the meter and relay cubicle is involved or if the fire propagates to a cubicle with a very low fuel load. If the meter and relay cubicle is involved, the switchgear and load center HRR distribution with a 98th percentile peak HRR of 170 kW applies given most of the combustible contents are located in this cubicle. If the meter and relay cubicle is not involved, the HRR distribution for a medium volume enclosure with a very low fuel load applies, which has a 98th percentile peak HRR of 45 kW [45]. A medium volume is selected as representative of a switchgear sub-enclosure (primary cable compartment, main breaker compartment, main bus bar). A very low fuel load is selected based on the assessment provided in Section 6.5.1.2. Table 6-2 summarizes the gamma distribution parameters for HRR distributions applicable to adjacent MV switchgear fire spread.

Table 6-2
Gamma distribution parameters for fire types applicable to adjacent MV switchgear fire spread [45]

Meter and relay cubicle fire	Cable type	98th percentile peak heat release rate (kW)	Gamma distribution parameters	
			Shape parameter α	Shape parameter β
Yes	Thermoplastic	170	0.99	44
Yes	Thermoset/qualified thermoplastic	170	0.32	79
No	All	45	0.88	12

The overall HRR for a fire that propagates to one or two adjacent MV switchgear vertical sections is determined using the HRR gamma distributions for each adjacent vertical section in combination with the peak HRR for the vertical section where the HEAF originated. This is depicted generically in Figure 6-22.

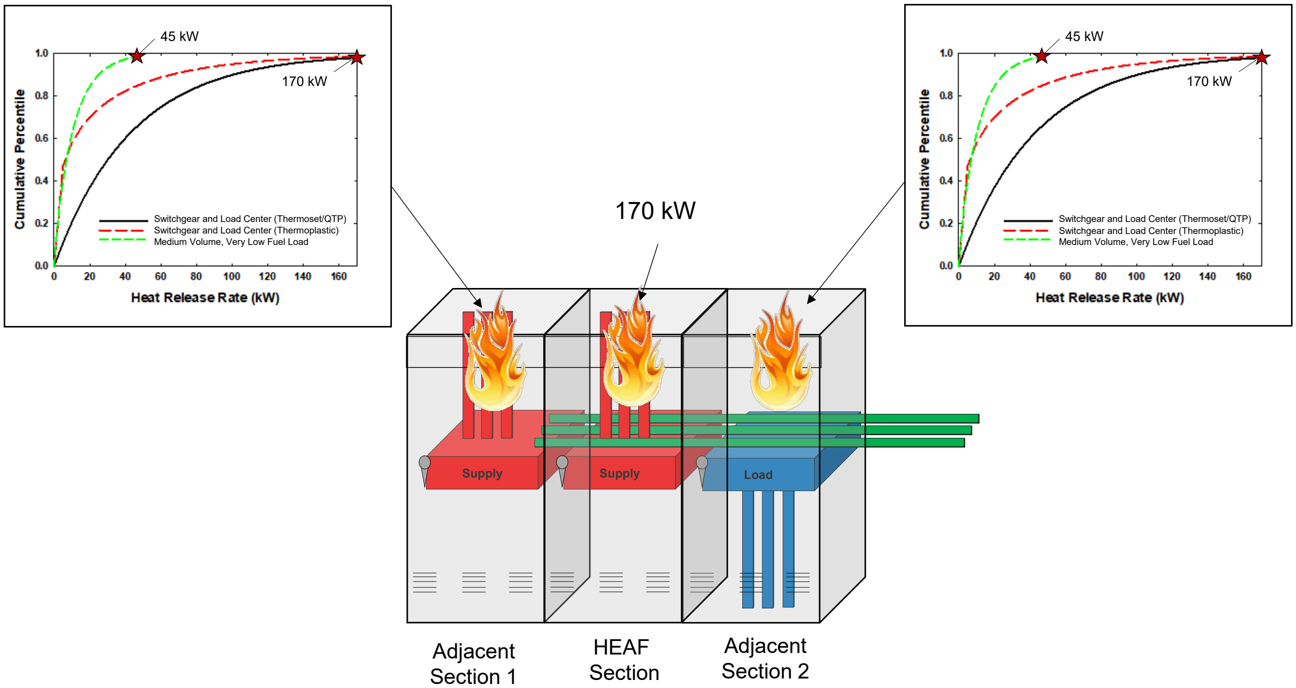


Figure 6-22
Peak HRRs for HEAF switchgear vertical sections

The switchgear vertical section with the HEAF has a peak HRR of 170 kW, regardless of the cable type. The HRR for each adjacent section depends on the cable type and the fire location (meter and relay cubicle or elsewhere). The peak HRR is a random variable with a cumulative distribution as shown in Figure 6-22. Because the HRRs for each adjacent section are random and independent, a Monte Carlo sampling method is applied to determine the cumulative HRR in one adjacent section and in two adjacent sections, with the peak HRR treated as a random parameter. A 25,000 sample size is used to develop a distribution function for the overall peak HRR for the HEAF vertical section plus one or two adjacent vertical sections. In addition, the Monte Carlo simulation is designed so that HRRs from adjacent cabinets are selected within the 98th percentiles of the distributions (i.e., values generated larger than the 98th percentile are set to the 98th percentile). The results are summarized in Table 6-3 for a single adjacent switchgear vertical section involved and Table 6-4 for two adjacent switchgear vertical sections involved. The 98th percentile heat release rate for fire spread case 1 is the same for electrical enclosures with thermoset/qualified thermoplastic cables and enclosures with thermoplastic cables when one adjacent vertical section is ignited. This is because the 98th percentile peak heat release rate for each is the same for each cable type and there is a single sample variable that converges to the 98th percentile. This is not true when there are two adjacent enclosures ignited because each adjacent section is a random variable and the gamma distributions are not the same for electrical enclosures with thermoset/qualified thermoplastic cables and enclosures with thermoplastic enclosures.

Table 6-3
Total HRR distribution parameters for a single adjacent vertical section ignited in combination with the HEAF vertical section

Parameter	Fire spread case 1 total HRR (thermoplastic cables) (kW)	Fire spread case 1 total HRR (thermoset/qualified thermoplastic cables) (kW)	Fire spread cases 2, 3, and 4 total HRR (kW)[1]
Mean HRR	212	194	181
Standard deviation	40	38	10
5th percentile HRR	172	170	170
Median HRR	200	177	177
95th percentile HRR	301	284	204
98th percentile HRR	340	340	215

[1]As shown in Table 6-2, the gamma distributions for medium-volume sections with a very low thermoset/qualified thermoplastic cable and thermoplastic cable fuel load are the same. Therefore, fire spread cases 2, 3, and 4 apply to all cable types.

Table 6-4
Total HRR distribution parameters for two adjacent vertical sections ignited in combination with the HEAF vertical section

Parameter	Fire spread case 1 total HRR (thermoplastic cables) (kW)	Fire spread case 1 total HRR (thermoset/qualified thermoplastic cables) (kW)	Fire spread cases 2, 3, and 4 total HRR (kW)[1]
Mean HRR	255	218	191
Standard deviation	56	53	15
5th percentile HRR	186	171	173
Median HRR	243	198	187
95th percentile HRR	365	340	220
98th percentile HRR	400	360	228

[1]As shown in Table 6-2, the gamma distributions for medium-volume sections with a very low thermoset/qualified thermoplastic cable and thermoplastic cable fuel load are the same. Therefore, fire spread cases 2, 3, and 4 apply to all cable types.

The resulting distribution functions versus severity factor are shown in Figure 6-23 for a single adjacent vertical section involved and Figure 6-24 for two adjacent vertical sections involved. It is noted that the peak HRR is not the simple sum of the 98th percentiles of the individual distributions. This is because an event generating the 98th percentile intensities on both adjacent switchgear vertical sections is highly unlikely given the assumption of independence in fire growth when propagating. For a single adjacent vertical section (used when the HEAF is postulated in the end section of the switchgear), the peak HRR percentiles may also be computed directly from the HEAF peak HRR (170 kW) plus the gamma distribution for a single adjacent vertical section.

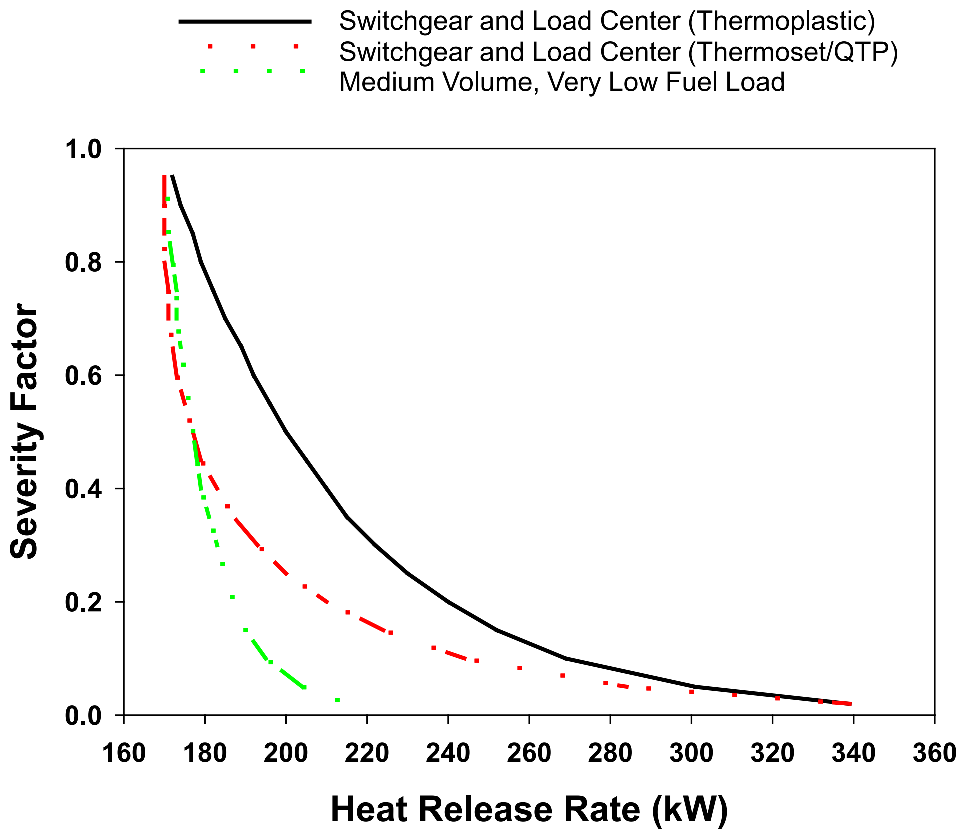


Figure 6-23
Total peak HRR distributions for a HEAF vertical section that ignites a single adjacent vertical section

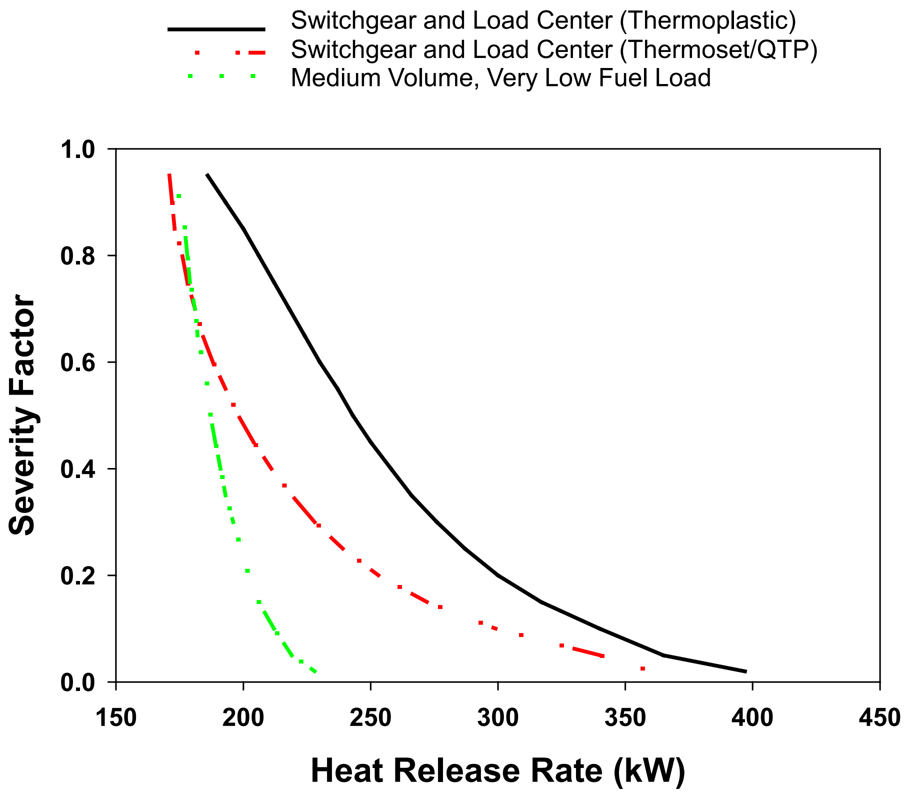


Figure 6-24
Total peak HRR distributions for a HEAF switchgear vertical section that ignites two adjacent vertical sections

The adjacent ignited switchgear vertical sections have a HRR growth, steady, and decay stage following a growing electrical enclosure fire [1, 49]:

- The growth stage is 12 minutes and is in proportion to time squared (t^2 profile)
- The steady burning stage at the peak HRR is 8 minutes
- The decay stage is linear and is 19 minutes

The overall HRR profile for the ensuing fire with one or two adjacent switchgear vertical sections includes the ensuing fire from the initiating HEAF vertical section as depicted in Figure 6-12 and the HRR profile for the adjacent vertical sections, which depends on the selected percentile. The HRR profiles for the 98th percentile overall HRR are shown in Figure 6-25 for a single adjacent vertical section ignited and Figure 6-26 for two adjacent vertical sections ignited. For simplicity and, noting that the total HRR is itself a new distribution function, the HRRs are determined using a 12 minute growth time to the total HRR starting from 170 kW, and the HRR of the initiating HEAF vertical section at time zero. The HRR profile then follows the standard HRR profile for growing electrical enclosure fires, with an 8 minute steady-state stage and a 19 minute linear decay stage. The hot gas layer analysis uses the total HRR and will typically select the 98th percentile, though other percentiles may be used in combination with the severity factor associated with the selected percentile.

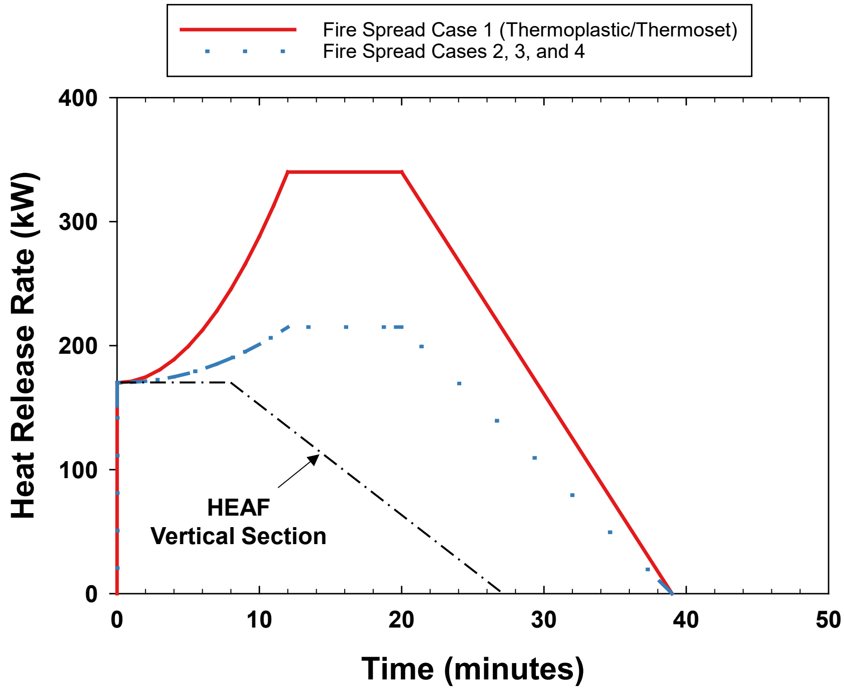


Figure 6-25
Total peak HRR profiles for a HEAF vertical section that ignites one adjacent vertical section

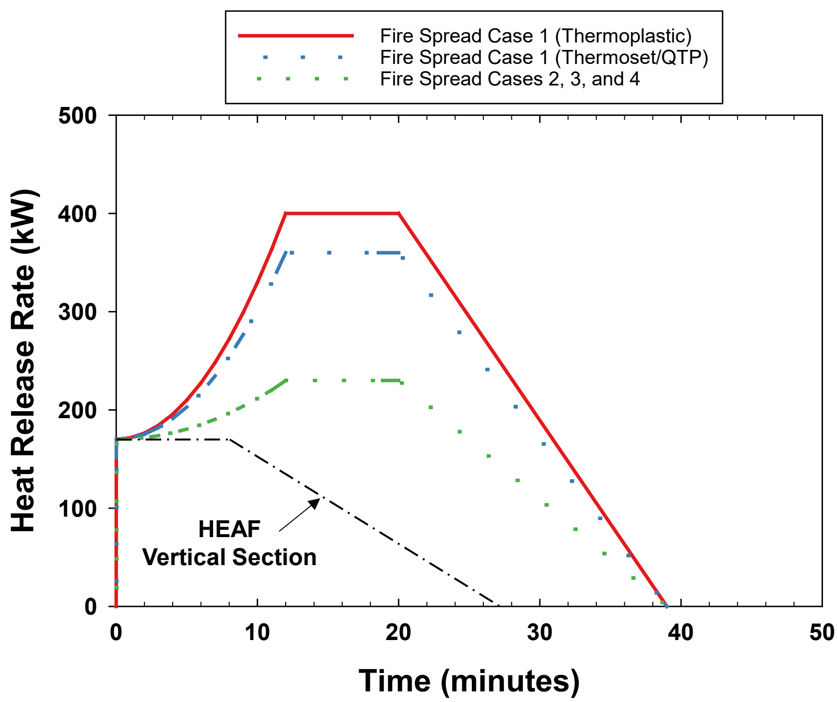


Figure 6-26
Total peak HRR profiles for a HEAF vertical section that ignites two adjacent vertical sections

6.5.1.5 Zone of Influence Calculation

The determination of the zones of influence (ZOI) above each ignited vertical section follows the guidance in NUREG/CR-6850 [1], NUREG/CR-6850 Supplement 1 [2], and NUREG-2178 Volume 2 [45] with the following updates:

- The ZOI for the initiating HEAF vertical section is 170 kW HRR with a fire base located 0.3 m below the top of the switchgear per NUREG/CR-6850 Supplement 1 [2] (see Figure 6-27).
- Fire spread case 1: The ZOI for an adjacent ignited vertical section that involves the meter and relay cubicle is determined using the switchgear and load center gamma distribution with a fire base located 0.3 m below the top of the switchgear vertical section (see Figure 6-28). For fire spread case 1 (which involves spread to the meter and relay cubicle) the 98th percentile peak HRR for each ignited adjacent section is 170 kW. If more detail is necessary the full switchgear HRR gamma distribution can be used for multi-point modeling.
- Fire spread cases 2 and 3: The ZOI for an adjacent ignited vertical section with the HEAF originating in the main bus bar or the primary cable compartment is determined using the medium volume enclosure with a very low fuel load gamma distribution. The 98th percentile peak HRR for each ignited adjacent section is 45 kW and the fire base height is 0.3 m below the top of the switchgear enclosure (see Figure 6-29). If more detail is necessary the medium enclosure with a very low fuel load HRR gamma distribution can be used for multi-point modeling.
- Fire spread case 4: The ZOI for an adjacent ignited section with the HEAF originating in the breaker is determined using a medium volume enclosure with a very low fuel load gamma distribution. The 98th percentile peak HRR for each ignited adjacent section is 45 kW and the fire base height is located at the switchgear mid-height, which accounts for the breaker compartment location in the switchgear (see Figure 6-30). If more detail is necessary the medium enclosure with a very low fuel load HRR gamma distribution can be used for multi-point modeling.

The ZOIs for the adjacent switchgear vertical sections are determined using the gamma distributions for each ignited switchgear vertical section. The total HRR is not necessarily equal to the sum of the ZOI assumed HRR for each individual switchgear vertical section because the HRR development within each section is independent. However, the ZOIs must be determined based on the characteristics of the individual switchgear vertical section or by using bounding assumptions.

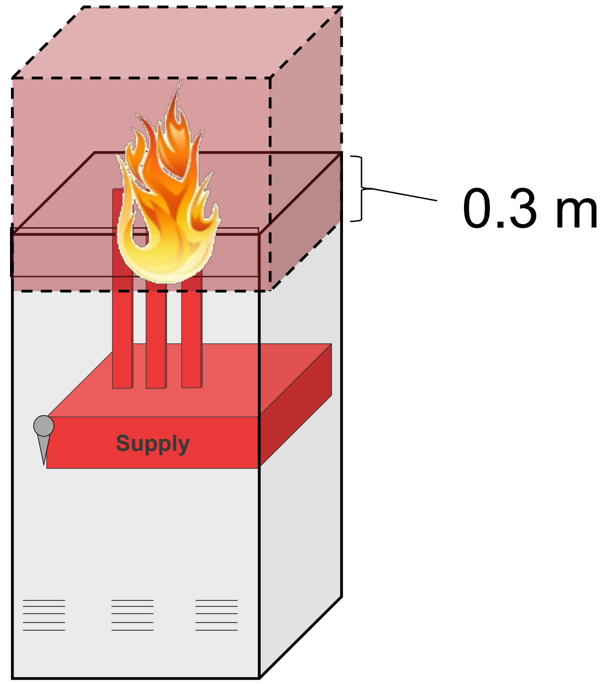


Figure 6-27
ZOI configuration for the vertical section with the HEAF

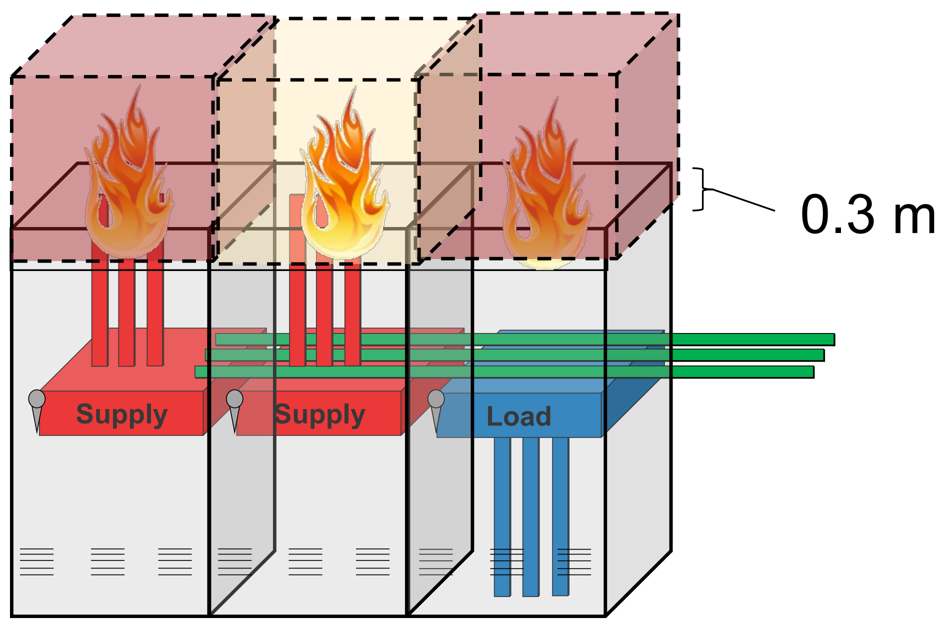


Figure 6-28
Fire spread case 1: ZOI configuration for the post-HEAF fire with spread to adjacent vertical section's meter and relay cubicle

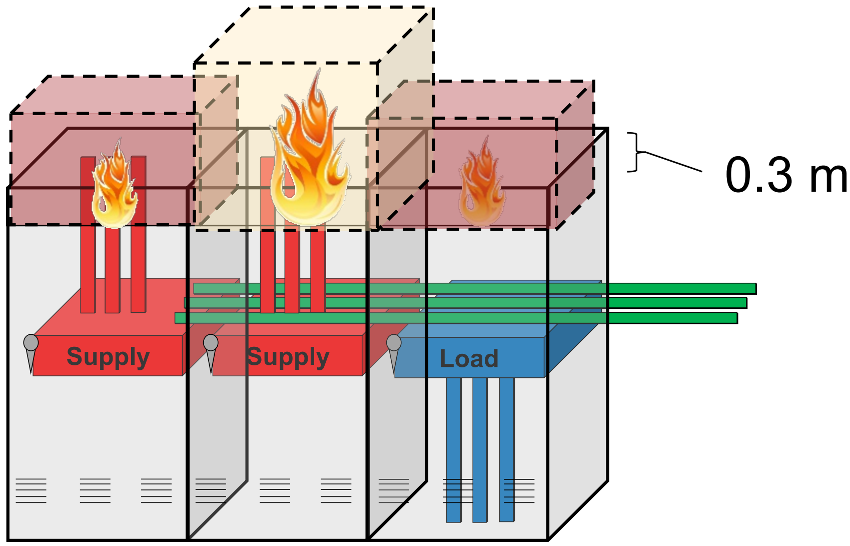


Figure 6-29
Fire spread cases 2 and 3: ZOI configuration for the post-HEAF fire with spread to adjacent vertical section's primary compartment bus bar or main bus bar

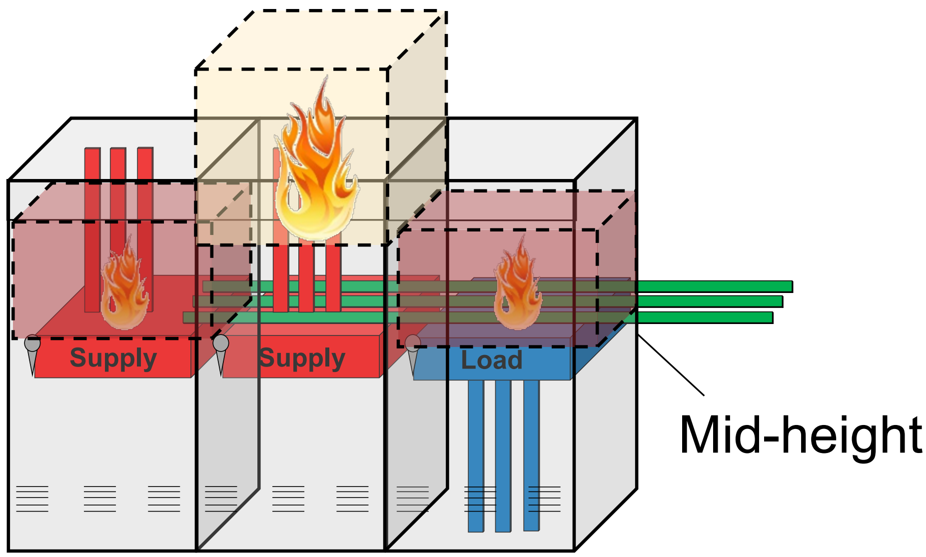


Figure 6-30
Fire spread case 4: ZOI configuration for the post-HEAF fire with spread to adjacent vertical section's breaker cubicle

The gamma distributions for the adjacent switchgear vertical sections may be used to develop a severe/non-severe split for each event tree end state shown in Figure 6-19. Figure 6-31 depicts the event tree and end states for adjacent switchgear vertical section(s) ignited by a HEAF for HEAF energies that result in postulated fire spread as identified in Table 6-1 (single wall configuration over 101 MJ and double wall construction over 202 MJ).

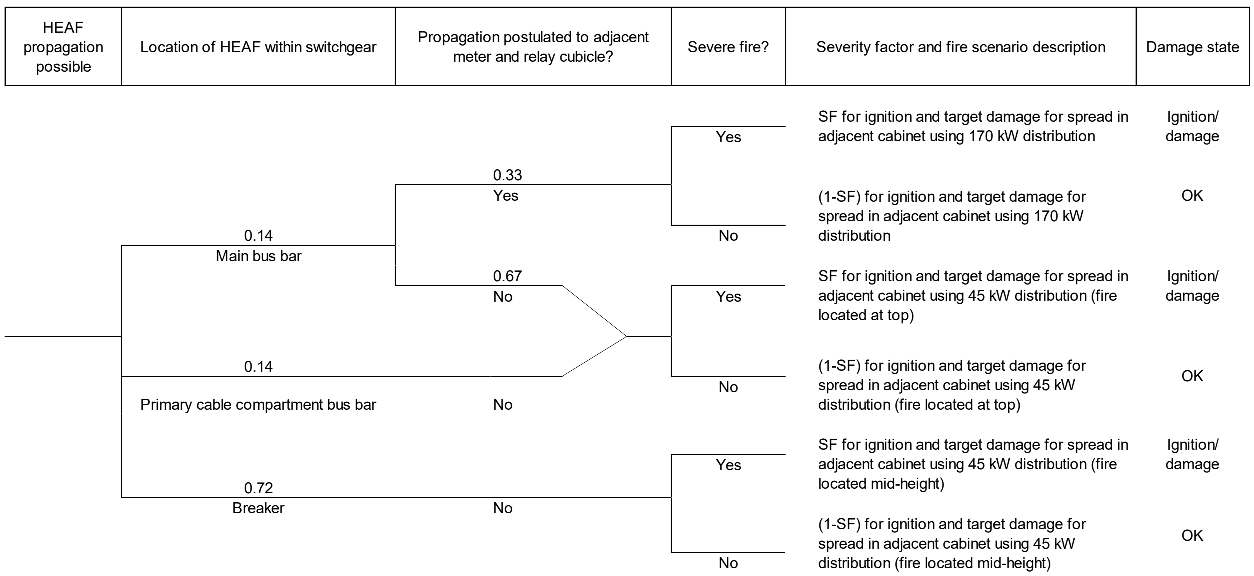


Figure 6-31
ZOI end states for adjacent switchgear vertical section ignited by a HEAF

6.5.1.6 Summary

Do not postulate fire propagation for the following cases:

- Load centers (LV switchgear)
- For MV switchgear with single wall construction at HEAF arc energies of 68 MJ and 101 MJ
- For MV switchgear with double wall construction at HEAF energies of 68 MJ, 101 MJ, 132 MJ, 135 MJ, 169 MJ, and 200 MJ

Assume fire propagation to the meter and relay cabinet for 300 MJ (fire spread case 1).

For the remaining energies (see list below), the analyst can use the fire spread event tree in Figure 6-19 to calculate the possibility of significant fire spread and fire propagation to adjacent vertical sections.

- Single wall: 132 MJ, 135 MJ, 169 MJ, 200 MJ, and 233 MJ
- Double wall: 233 MJ

The fire spread event tree is used to determine the end state frequencies for the post-HEAF fire HRR and for developing the different post-HEAF fire ZOIs and damage states for targets located outside the HEAF ZOI. The total HRR is characterized in terms of a gamma distribution that may be used to generate severity factors in the same way as typical electrical enclosure fire is modeled. For hot gas layer calculations, the total HRR should be analyzed as a single fire. When determining the ZOI, the fires in each switchgear vertical section (i.e., fire spread case 1, fire spread cases 2 and 3, and fire spread case 4) can be considered separately due to the change in physical location of the fire. A simple approach may be applied where the applicable 98th percentile HRR from either Table 6-3 of Table 6-4 is used initially. Depending on the risk contribution, refinements may be applied that use the distribution and severity factor for the respective end states. An example is provided in Appendix G.4.

7 HIGH ENERGY ARCING FAULTS IN LOAD CENTERS

7.1 Load Center HEAF Scenarios

HEAFs in load centers are modeled in two-phases, the energetic phase (analyzed in FDS and described in detail in this section) and the post-HEAF ensuing fire (discussed in Section 6.5). The combination of the energetic phase plus the ensuing fire determines the totality of the HEAF ZOI.

Because of the instantaneous trip protection (see Section 3.11), faults on the load side of the load circuit breaker are expected to clear rapidly (the energy is more typical of an arc flash). Thus, the LV HEAF frequency (Bin 16.a) is only apportioned to the load center supply circuit breakers (low-voltage circuit breakers that supply power from the load center transformer to the low-voltage switchgear), and no frequency is apportioned to load center load circuit breakers (circuit breakers that serves a load). Given the lack of U.S. operating experience, experimental testing evidence, and power distribution arrangements, faults downstream of the load center supply circuit breaker are more likely to result in an arc flash and not rise to the energy level of a HEAF.

Section 3.11.4 summarizes the fault locations and durations in Zone 3 (load centers). From the supply-side branch in Figure 3-23, the fault current being lower than the tripping threshold of the TOC (51) relay is the sole scenario (because no scenarios are postulated downstream of the supply circuit breaker). This scenario closely resembles FEDB 50935. The electrical data documented in the root cause analysis serves as the basis for the energy, fault currents, and duration.

7.2 Summary of FDS Cases and Insights for the Energetic Phase of Load Center HEAFs

As described in Section 6 and the FDS ZOI report [16], the working group developed FDS input files for LV switchgear types using an arc power profile derived from FEDB 50935. Based on the EPRI survey [43], the WG identified the different load center designs and geometries with aluminum, including those developed by ABB, GE, Westinghouse, Allis-Chalmers, Powell Nelson, LVME, and Sorgel. The working group selected the GE/ITE K Line design as a representative design for load centers (including copper and aluminum conductors) and used it as the basis for the geometry in the FDS analysis [16].

The FEDB 50935 arc power profile was idealized as two-stage constant arc power with a total arc energy of 90 MJ [16]. Two primary fault locations within the load centers were used to develop the energetic portion of the ZOIs as follows:

- Arc that originates at a middle-height compartment breaker and migrates to the bus bar compartment at the same height after 20 s and continues in this compartment for an additional 21 s.

- Arc that originates at a top compartment breaker and migrates to the bus bar compartment at the same height after 20 s and continues in this compartment for an additional 21 s.

Eight baseline cases use the FEDB 50935 arc power profile (with both aluminum and copper electrode material) to confirm that the ZOIs are applicable for other fault locations and bus compositions. These locations include the following:

- Top compartment circuit breaker
- Middle-height compartment circuit breaker
- Top compartment bus bar
- Middle compartment bus bar

In addition, 24 sensitivity cases were developed for aluminum and copper electrode materials using constant-duration arc power profiles ranging from 2 to 6 s, with total arc energies ranging from 28 to 84 MJ, to further confirm that energetic ZOIs determined from the baseline simulations are broadly applicable. The 6 s arc power profile roughly corresponds to the maximum arc energy estimated for FEDB 50935 (90 MJ) [16]. The shorter-duration arc profiles use the same power and result in a lower total energy.

The FDS results were used to develop energetic ZOIs for targets with 15 MJ/m² and 30 MJ/m² fragilities. For load center HEAFs, not all directions have an external ZOI (per Figure 7-1, FDS results show that load center HEAFs do not have front and back ZOIs. Appendix D provides the ZOIs for the baseline simulations.

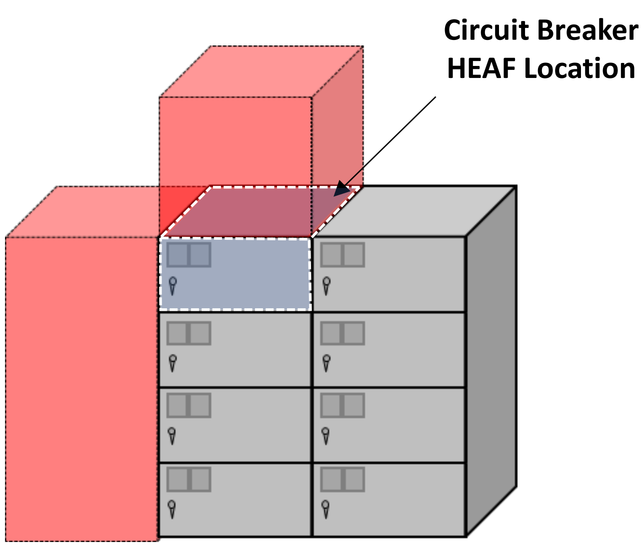


Figure 7-1
Load center depicting external HEAF ZOIs on the top and side (no back and front ZOIs)

The FDS ZOI report identified two significant findings that simplify the number of generic ZOIs required to characterize the HEAF hazard potential [16]:

- The bus-bar material composition does not have a significant effect on the ZOI. The ZOIs are within the uncertainty range for copper and aluminum bus-bar simulations for a given fault location, fault type, and fault energy. As a result, the ZOIs developed are independent of the bus bar material.
- The ZOI results are sensitive to the distance between the arc location and target and to the number of enclosure boundaries between the arc and the target.

Based on these observations, the working group developed ZOIs for load center supply circuit breakers based on location (end location and an internal location) and supply breaker elevation for 15 MJ/m² and 30 MJ/m² fragility targets. The ZOIs are applicable to all load center designs.

7.3 Energetic Zone of Influence for Load Centers (Zone 3)

Load center HEAFs are modeled with the fault initiated at load center supply circuit breakers. Scenario frequency for load centers is apportioned to each load center supply circuit breaker as described in Section 5.2.1.2 and Section 5.2.5.1. For example, in Figure 7-2, consider the red colored boxes (B and D) contain supply breakers. The assigned frequency for the load center is two over the total number of load center supply circuit breakers at the plant. The supply circuit breaker at location B has a scenario frequency of one out of the total number of load center supply circuit breakers at the plant with a ZOI corresponding to location B in Table 7-1. Similarly, the supply circuit breaker at location D also has a scenario frequency of one out of the total number of load center supply circuit breakers at the plant with a ZOI corresponding to location D in Table 7-1.

The FDS simulations show the arc only breaches the enclosure when both barriers and distance between the arc and the enclosure surface are limited. In Figure 7-2, a HEAF in supply circuit breaker B (located at the end of the load center) will breach the end of the enclosure; however, there are substantial barriers between the fault location and the front, back, and top. Similarly, a HEAF in supply circuit breaker D (located at the top of the cabinet) will breach the top of the enclosure, and is impeded by internal barriers on the sides, front, and back.

For load center supply circuit breaker HEAFs, four location dependent ZOIs are developed and reported in Table 7-1. The insights on the ZOIs are the following:

- A supply circuit breaker located at the top and the end of the load center has a ZOI externally in the horizontal and vertical directions (location A in Figure 7-2).
- A supply circuit breaker located at the middle or lower elevation and on the end of the load center has a ZOI only in the horizontal direction (location B or C in Figure 7-2).
- A supply circuit breaker in the top interior (at least one vertical section[11] on either side) has an external ZOI in the vertical (top) direction (location D in Figure 7-2).
- A supply circuit breaker in the middle or lower elevation and on the interior (at least one vertical section on either side) does not have a ZOI external to the switchgear (location E or F in Figure 7-2).

[11] The intent of this is to ensure there is an additional barrier and space in the footprint of the load center. This can be either a vertical section of load center circuit breakers, transformer enclosure, etc.

In addition to the energetic ZOIs, an ensuing fire is postulated at the supply circuit breaker. See Section 6.5 for modeling the ensuing fire. For load center supply circuit breakers that are modeled at lower elevations (B, C, E, or F in Table 7-1), the fire base can be located at the height of the load center supply breaker. Consistent with the conclusions in Section 6.5.1, the low-voltage HEAF energy of 90 MJ is below the threshold required to model fire propagation to adjacent vertical sections. Fire propagation to adjacent load center cubicles should not be postulated.

Table 7-1 reports the ZOIs in English units. Table E-1 reports the ZOIs in SI units. The ZOI dimensions should be applied from their respective faces as shown in Figure 7-2 and Figure 7-3. Figure 7-3 depicts the overhead view for locations where the supply circuit breaker is on the end of the load center and a second location where the supply circuit breaker is on the interior (e.g., at least one vertical section is on either end).

If the location of the supply circuit breaker is unknown, the ZOI should use the bounding location based on fire PRA targets (with horizontal and vertical ZOI components).

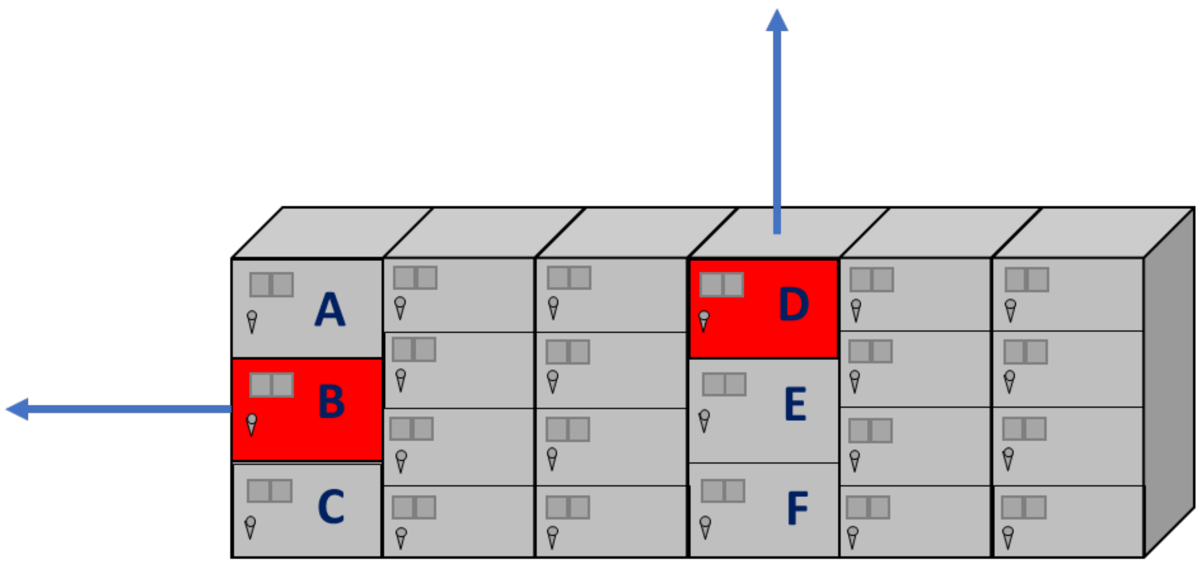


Figure 7-2
Load center supply circuit breaker locations

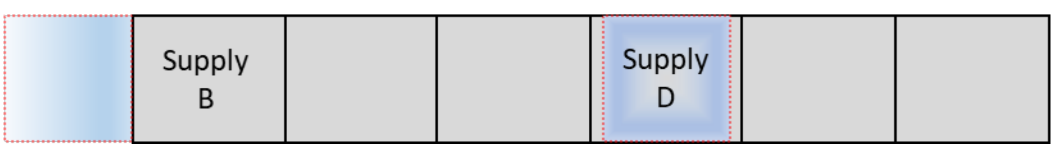


Figure 7-3
Overhead view of the load center energetic ZOIs

Table 7-1
Load center supply circuit breaker energetic ZOIs

Load Center Supply Circuit Breaker Location (from Figure 7-2) and Target Fragility	Arc Energy (MJ)	Back/Front	External Side (ft)	Top (ft)
A – end location, upper elevation: 15 MJ/m^2	90	None	2.5	2
A – end location, upper elevation: 30 MJ/m^2	90	None	1.5	1
B and C – end location, lower elevation: 15 MJ/m^2	90	None	2.5	None
B and C – end location, lower elevation: 30 MJ/m^2	90	None	1.5	None
D – interior, upper elevation: 15 MJ/m^2	90	None	None	2
D – interior, upper elevation: 30 MJ/m^2	90	None	None	1
E and F – interior, lower elevation: 15 MJ/m^2	90	None	None	None
E and F – interior, lower elevation: 30 MJ/m^2	90	None	None	None

8
HIGH ENERGY ARCING FAULTS IN MEDIUM VOLTAGE SWITCHGEAR

HEAFs in MV switchgear are modeled in two phases: the energetic phase (analyzed in FDS and described in detail in this section) and the post-HEAF ensuing fire (discussed in Section 6.5). The combination of the energetic phase plus the ensuing fire determines the totality of the HEAF ZOI.

Faults in MV switchgear (Bin 16.b) follow a graded approach that provides the analyst with a coarse screening approach as well as the flexibility to analyze using configuration-specific energetic ZOIs when more detail is necessary. The screening ZOIs are applied as a bounding dimension in the horizontal and vertical directions around the switchgear faces. When more detail is needed, configuration-specific ZOIs can be used in conjunction with the split fractions developed in Appendix C. These configuration-specific ZOIs are dependent on fault location, arc energy, and FCT. Dimensions are provided for the sides (left/right), front, back, and vertical (top). In certain configurations, such as vertical-lift circuit breakers, additional refinement on the sides (left/right) and the back is also provided.

8.1 Differences Between Zone 1 and Zone 2 MV HEAF Scenarios

Because Zone 1 is located directly downstream of an auxiliary power transformer and there is greater potential for a single point of failure on the Zone 1 bus supply circuit breaker, the faults occur more frequently in Zone 1 than in Zone 2. This is addressed in the frequency apportionment in Section 5.2.2.3, which shifts the frequency toward the Zone 1 switchgear.

In the configuration-specific approach, the split fractions in Zone 1 and Zone 2 are both heavily weighted toward the supply (both normal and secondary/alternate). Although the total split fractions (0.85 and 0.86 for Zone 1 and Zone 2, respectively) are biased toward the supply sections, different types of faults are expected in Zone 1 and Zone 2. Because fewer circuit breakers are located between the Zone 1 switchgear and the UAT, faults in Zone 1 are most likely fed directly from the UAT. In Zone 2, the Zone 1 supply circuit breaker provides some redundancy against faults fed from the UAT. Zone 2 is much more likely to have a supply breaker limited (SBL) fault. For scenarios where the Zone 1 supply circuit breaker can interrupt (Zone 1 main bus bar and loads and Zone 2), the supply circuit breaker fault is postulated at 4 s (as a conservative first estimate). For Zone 2 main bus bar and loads, the supply circuit breaker fault is postulated at 2 s (interrupted by the Zone 2 bus supply circuit breaker).

The supply portion of Zone 1 is within the zone of transformer differential protection (87), which operates with no inherent time delay. Although this protection exists on both the UAT and SAT[12], for HEAF end states, only the portion within the UAT differential protection zone are credited in this methodology. All of the four operating experience generator-fed faults in the Zone 1 supply cubicle were quickly sensed by the UAT differential protection (87). Differential protection (87) is inherently credited in ZOIs developed on the supply side of the supply breaker in Zone 1. Faults downstream of the Zone 1 switchgear supply breaker are outside the differential protection zone, which results in additional time at a stiff energy period before entering the generator decay period. See Section 6.4 for determining the backup FCT.

8.2 Inputs for Quantification of MV Switchgear HEAF Scenarios

The first step in quantifying MV switchgear HEAF scenarios is to properly assign the frequencies to individual switchgear. This step is necessary regardless of the level of detail analyzed for MV switchgear.

To use the screening ZOIs (see Section 8.4), the analyst must identify the power supplies feeding the switchgear and their respective FCTs. This process is explained in Section 6.4.

If more detail is needed, the analyst can use the event trees paired with the configuration-specific ZOIs (detailed in Section 8.5 [Zone 1] and Section 8.6 [Zone 2]). Similar to the screening approach, the analyst identifies the normal and alternate supplies for the switchgear and determines the FCTs. The switchgear bank frequency is then apportioned by switchgear location (normal supply, alternate supply, and loads). Scenarios are postulated with a HEAF that is fed from a power transformer and where the fault is interrupted by the supply breaker (i.e., SBL). The default SBL ZOI is derived from bounding bus supply breaker opening times. If more refinement is necessary, the analyst can also determine the switchgear-specific bus supply circuit breaker opening time and use the anticipated FCT for additional granularity in ZOI selection.

8.2.1 MV Switchgear Weighting Factor and Ignition Frequency

To determine the scenario frequency, the analyst should 1) count MV switchgear banks, 2) identify the zones, and 3) apply the zone weighting factor. The methodology for assigning the zone weighting factor is in Section 5.2.2.3.

The zones for MV switchgear are as follows:

- Zone 1: MV switchgear fed directly from the SAT, UAT, or equivalent
- Zone 2: MV switchgear fed from an intermediate bus (e.g., Zone 1 MV switchgear)

Once the counts are known, the analyst apportions 86% of the generic frequency to the Zone 1 sub-frequency, and apportion the remaining 14% of the generic frequency to the Zone 2 sub-frequency. Once the sub-frequencies are determined, the analyst can calculate scenario-specific switchgear frequencies by apportioning the sub-frequencies among the population of equipment within that particular zone.

[12] For faults on the SAT, differential protection (87) is assumed failed. If differential protection (87) is successful, the FCT is unlikely to result in HEAF-level consequences. To overcome this, the SAT differential protection (87) is postulated to fail. The analyst should use the transformer's backup (TOC) FCT to determine the ZOI selection.

A Zone 1 switchgear bank frequency is calculated as follows:

= (Bin 16.b frequency × Zone 1 weighting factor) × (Zone 1 MV switchgear bank / Σ of Zone 1 MV switchgear banks)

$$= [(\lambda_{16.b} \times 0.86)] \times \left(\frac{Zone\ 1\ switchgear\ bank}{\Sigma\ of\ Zone\ 1\ switchgear\ banks}\right)$$

A Zone 2 switchgear bank frequency is calculated as follows:

= (Bin 16.b frequency × Zone 2 weighting factor) × (Zone 2 MV switchgear bank / Σ of Zone 2 MV switchgear banks)

$$= [(\lambda_{16.b} \times 0.14)] \times \left(\frac{Zone\ 2\ switchgear\ bank}{\Sigma\ of\ Zone\ 2\ switchgear}\right)$$

8.2.2 Switchgear Power Supplies and Split Fractions

This section introduces the concepts of normal and alternate power supplies and explains assigning split fractions when using the configuration-specific ZOIs in Section 8.5 and 8.6.

The normal supply is defined as the cubicle (vertical section) that houses the bus supply breaker aligned during normal operating conditions. This can be fed from the UAT or SAT. Analysis of the normal supply includes the incoming bus bars, circuit breaker, and main bus bar parts contained within the supply vertical section.

The secondary supply is defined as the cubicle (vertical section) that houses the bus supply circuit breaker available to power the MV switchgear during off-normal conditions, such as during maintenance of the normal bus supply circuit breaker or associated transformer. For Zone 1 MV switchgear, the secondary supply is typically from an SAT and may be part of an automatic bus transfer scheme if the normal supply is from the UAT. For Zone 2, the secondary supply may either be a bus-tie from another MV switchgear or powered from another transformer. Analysis of the secondary supply includes the incoming bus bars, circuit breaker, and main bus bar parts contained within the supply vertical section.

The loads include the remaining vertical sections not defined as supply sections (including load circuit breakers, empty cubicles, EDG, and so on). Analysis of the load sections also includes the main bus bar[13] portion that runs along the length of the switchgear in the load sections. This portion of the scenario frequency will typically include multiple vertical sections. The analyst may elect to analyze the load vertical sections as a single scenario or partition the frequency into one or more sub-scenarios as necessary to achieving analysis goals. For example, the count of load vertical sections within the switchgear bank may be used as a denominator to apportion the scenario frequency among the load vertical sections.

Some switchgear may contain a vertical section associated with the EDG, as shown in Figure 3-1. The energy associated with the EDG is not sufficient to produce damage on a similar scale as a generator- or switchyard-supply-fed fault. Therefore, EDG supply vertical section(s) are analyzed with the load vertical sections.

[13] Like the SAT, bus differential protection (discussed in Section 3.6.3) is not credited (assumed failed). If differential protection (87) is successful, the FCT is unlikely to result in HEAF-level consequences. To overcome this, bus differential protection (87) is postulated to fail. The analyst should use the supply breaker limited FCT to determine the ZOI selection.

The basis for the Zone 1 and Zone 2 split fractions is documented in Appendix C. The results are summarized as follows:

<u>Zone 1 Split Fractions:</u>

If there are two supplies, the split fractions are as follows:

- Normal: 0.57
- Secondary: 0.28

Some configurations may have less than or more than two supplies. For these instances, the split fractions assigned to the supply sections should be preserved.

If there is a single supply, add the normal and secondary supply split fractions: 0.57 + 0.28 = 0.85.

If there are three supplies, the normal supply split fraction remains unchanged at 0.57). The split fraction for the secondary supply, 0.28, is divided between the second and third supplies. This is summarized as follows:

- Normal: 0.57
- Supply 2: 0.28/2 = 0.14
- Supply 3: 0.28/2 = 0.14

The remaining fraction is apportioned between the load vertical sections.

- Loads: 0.15

As noted above, 0.15 may be applied to the load vertical sections as a group or apportioned to individual sections for scenario development. Consider as an example, the switchgear in Figure 8-1 with 5 vertical sections – two supply sections (normal shown in red and secondary in blue), the remaining 3 sections are load sections. In this example a cable tray is located where only a fire in the end load section (E) is capable of damaging the tray. Therefore, an analyst may choose to develop the scenarios such that the E vertical section is separate from the C and D sections. The resulting load section split fractions are apportioned as:

- Load sections C and D: 0.15 × (2/3) = 0.1
- Load section E: 0.15 × (1/3) = 0.05

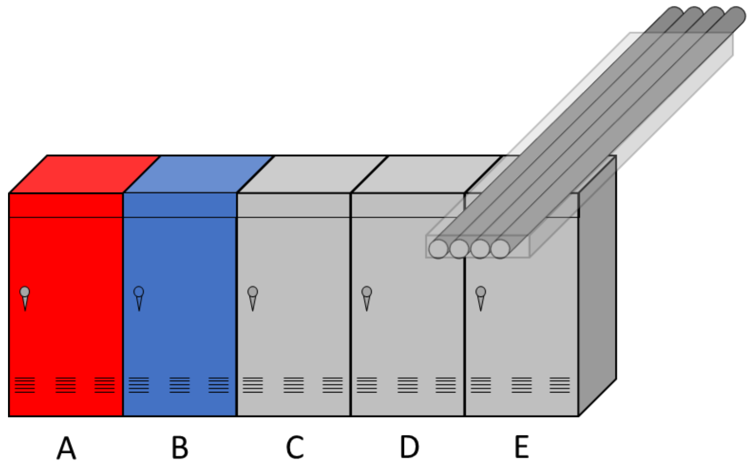


Figure 8-1
Example load vertical sections for split fraction apportioning

Zone 2 Split Fractions:

The process for assigning split fractions for Zone 2 is the same as for Zone 1, but the split fractions used are different. The results are summarized below.

If there are two supplies, the split fractions are as follows:

- Normal: 0.54
- Secondary: 0.32

If there is a single supply, add the normal and secondary supply split fractions: 0.54 + 0.32 = 0.86.

If there are three supplies, the normal supply split fraction remains unchanged (e.g., 0.54). The split fraction for the secondary supply, 0.32, is divided between the second and third supplies. This is summarized as follows:

- Normal: 0.54
- Supply 2: 0.32/2 = 0.16
- Supply 3: 0.32/2 = 0.16

The remaining fraction is apportioned between the load vertical sections.

- Loads: 0.14

The loads split fraction in Zone 2 may be apportioned between the various vertical sections similar to Zone 1.

8.2.3 Vertical-Lift Versus Horizontal-Draw-out Breakers (for Configuration-Specific ZOIs)

Differences in the geometry of the two main styles of MV switchgear can result in differences in ZOIs. The horizonal draw-out circuit breakers typically provides the bounds for the ZOIs. For plants with vertical-lift circuit breakers, refinements can be considered in the switchgear's side and back directions. The definitions and manufacturer/model of each style is explained as follows:

Vertical-lift-style circuit breaker: MV circuit breakers that rack in vertically. Based on the EPRI survey [43], the only known vertical-lift-style circuit breaker in use in U.S. NPPs is the GE Magne-Blast.

Horizontal-draw-out-style breaker: MV circuit breakers that rack in horizontally. Based on the EPRI survey [43], the most common styles in United States NPPs include ABB (ITE), GE AMH Magne-Blast, and Westinghouse DHP breakers. The FDS runs are based on the ABB (ITE) HK breakers, but the use of the horizontal-draw-out-style breaker ZOIs are applicable for all other manufacturers of horizontal-draw-out-style breakers.

8.3 Summary of FDS Cases and Insights for MV Switchgear

As described in Section 6 and the FDS ZOI report [16], the working group developed FDS input files for a range of MV switchgear types, fault locations, total energies, fault profile and durations, and bus bar compositions. Table 8-1 summarizes these parameters.

Table 8-1
FDS simulation parameter ranges for MV switchgear

Parameter	Range Considered or Configurations
Fault locations	• Main bus bar • Primary cable compartment bus or riser bus bar—load configuration • Primary cable compartment bus or riser bus bar—supply configuration • Circuit breaker connection stabs
Switchgear type	• Vertical-lift circuit breaker • Horizontal-draw-out circuit breaker
Fault profile and duration	• Constant-current fault (2–5 s) • Generator-fed fault (15 s of decaying current) • Constant-current (0–5 s) with a generator-fed fault (15 s of decaying current)
Total fault energy	68–300 MJ
Bus bar material composition	• Copper • Aluminum

The FDS inputs were evaluated using FDS Version 6.7.6 with application-specific updates, as described in the FDS ZOI report [16]. Not all permutations were evaluated; instead, evaluation was limited to combinations that represent realistic configurations and fault types. In addition, parameter combinations with similar arc locations, distances from the switchgear enclosure boundary, and number of enclosure boundaries between the fault and the exterior were consolidated to the extent possible.

Overall, 48 unique FDS input files and simulations were developed for the MV switchgear. The FDS results were used to develop ZOI for targets with 15 MJ/m² and 30 MJ/m² fragilities around the switchgear on the sides (left/right), front, back, and top (see Figure 8-2). Appendix D of this report provides the energetic ZOIs for the 48 simulations.

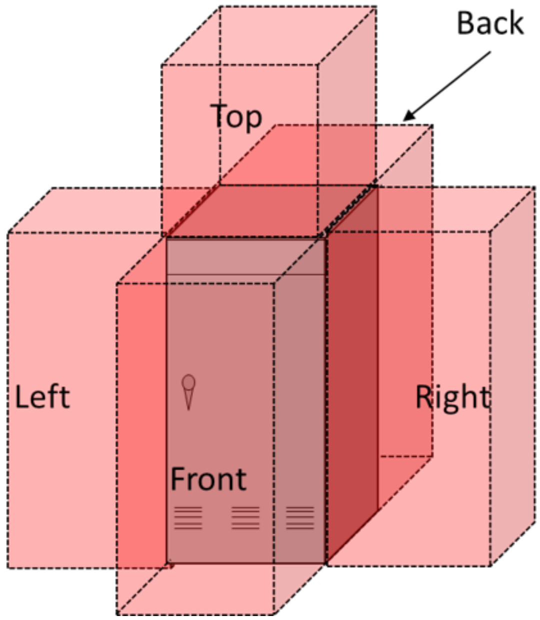


Figure 8-2
MV switchgear ZOI configuration for a single vertical section

The key findings identified in the FDS ZOI report simplify the number of ZOIs to characterize the hazard as follows [16]:

- The dominant parameter affecting the ZOIs in MV switchgear is the total arc energy.
  - A secondary parameter is the switchgear type (vertical-lift style or horizontal-draw-out style).
- The bus bar material composition does not have a significant effect on the ZOI. The ZOIs are within the results uncertainty range for copper and aluminum bus-bar simulations for a given fault location, fault type, and fault energy. In other words, the ZOI ranges for aluminum and copper bus-bar materials overlap. The working group concluded that ZOIs are independent of the bus bar material and that developing separate copper and aluminum ZOIs was not needed.
- The ZOI results are sensitive to the distance between the target and the arc location and to the number of enclosure boundaries (including internal barriers) between the arc and the target.

Based on these observations, the FDS simulation results are grouped and linked to screening and configuration-specific ZOIs described in Sections 8.4 through 8.6. Appendix D of this report describes the simulation grouping in detail. The simulation grouping is summarized as follows:

- The screening ZOIs for each panel face are determined through consideration of all FDS MV results at specific arc energies. The UAT and SAT FCTs correspond to FDS simulations with different durations.
- The configuration-specific ZOIs for Zone 1 and Zone 2 are determined by considering the fault location within the vertical sections (i.e., supply or load). For supply circuit breaker switchgear vertical sections, FDS simulations corresponding to the primary cable

compartment in the supply configuration, the main bus bar, and the breaker stabs are used. For load vertical sections, FDS simulations corresponding to the primary cable compartment in the load configuration, the main bus bar, and the breaker stabs are used. The UAT and SAT FCTs correspond to FDS simulations with different durations.

- The SBL ZOIs are determined through considering the FDS simulations corresponding to the primary cable compartment in the load configuration, the main bus bar, and the circuit breaker connection stabs with a constant-current duration of 4 s for Zone 1 supply circuit breaker section and 2 s for Zone 2.
- The ZOIs for the vertical-lift circuit breaker refinement are determined using the same process as the configuration-specific ZOIs, except that the horizontal-draw-out-style FDS results are removed.

Appendix D provides the overall grouping of FDS simulations associated with the screening ZOIs, Zone 1, and Zone 2 configuration-specific ZOIs.

The working group determined the screening and configuration-specific ZOIs using the FDS simulation results for the applicable group. The general process involved reviewing predicted ZOIs and selecting a representative value within this group in units of feet that was then rounded up in increments of 0.5 ft (15 cm). Appendix D provides a more detailed description of this process and provides several examples for illustration.

8.4 Screening ZOIs for MV Switchgear

When practical (where detailed analysis is not required), screening ZOIs can be applied. In the EPRI aluminum HEAF survey results [43], the FCTs of the auxiliary power transformer vary across the industry. The longer it takes to clear the fault, the more energetic the HEAF hazard. The PRA method accounts for this by binning the range of FCTs and developing different ZOIs dependent on the energy level. The analyst should determine the limiting FCT for each feed to the switchgear (the normal supply and the alternate supply). Analyzing the alternate supply is necessary to account for the HEAF potential during a power supply switch.

Table 8-2 shows the screening ZOIs for MV switchgear in English units. Table E-2 provides the screening ZOIs for MV switchgear in SI units. The screening ZOI is bounded on the lower end by the 4 s SBL fault (e.g., SAT FCTs less than 4 s are bound by the 4 s SBL fault).

The analyst should reference the FCT for the MV switchgear fed by the normal and secondary supplies. Once these FCTs are mapped to each MV switchgear, the analyst should use Table 8-2 and select the larger ZOI (bounding) between the normal and secondary supplies. In addition to the energetic screening ZOIs, postulate a post-HEAF ensuing fire (see Section 6.5).

Table 8-2
Energetic screening ZOIs for MV switchgear (Zone 1 and Zone 2)

SAT fault clearing time	SAT arc energy (MJ)	UAT fault clearing time into generator-fed fault	UAT arc energy (MJ)	15 MJ/m^2 target fragility (feet)	30 MJ/m^2 target fragility (feet)
SAT (0–4.00 s)	135	UAT (0–0.50 s)	132	3	2
SAT (4.01+ s)	169	UAT (0.51–2.00 s)	200	3.5	2.5
		UAT (2.01–3.00 s)	233	4	3
		UAT (3.01+ s)	300	4.5	3.5

For feeds on the UAT, the screening ZOI is bounded by a generator-fed fault outside the differential protection zone with an FCT of 3 s or greater. This equates to 4.5 ft for the 15 MJ/m^2 fragility and 3.5 ft for the 30 MJ/m^2 fragility.

To apply the screening value, the distances in Table 8-2 are taken from the edge of the switchgear bank (shown in Figure 8-3). The bounding ZOI is applied in both the horizontal and vertical directions of the switchgear bank (shown in Figure 8-3 and Figure 8-4). The screening-level ZOI does not require the use of an event tree or split fractions.

As an example, the Zone 1 switchgear is normally powered by the UAT (connected to the main generator), and the secondary supply is powered by the SAT (off-site power). For a hypothetical plant, assume that the UAT FCT is 2.2 s, and the SAT FCT is 3.4 s. For this Zone 1 switchgear, the analyst would select the maximum ZOI between row *UAT (2.01–3.00 s)* and row *SAT (0–4.00 s)* from Table 8-2. Assuming thermoset jacketed cables (30 MJ/m^2 target fragility), the ZOI for the UAT is 3 ft and the SAT is 2 ft, respectively. The bounding ZOI is the largest ZOI, in this case 3 ft, bounded by the UAT.

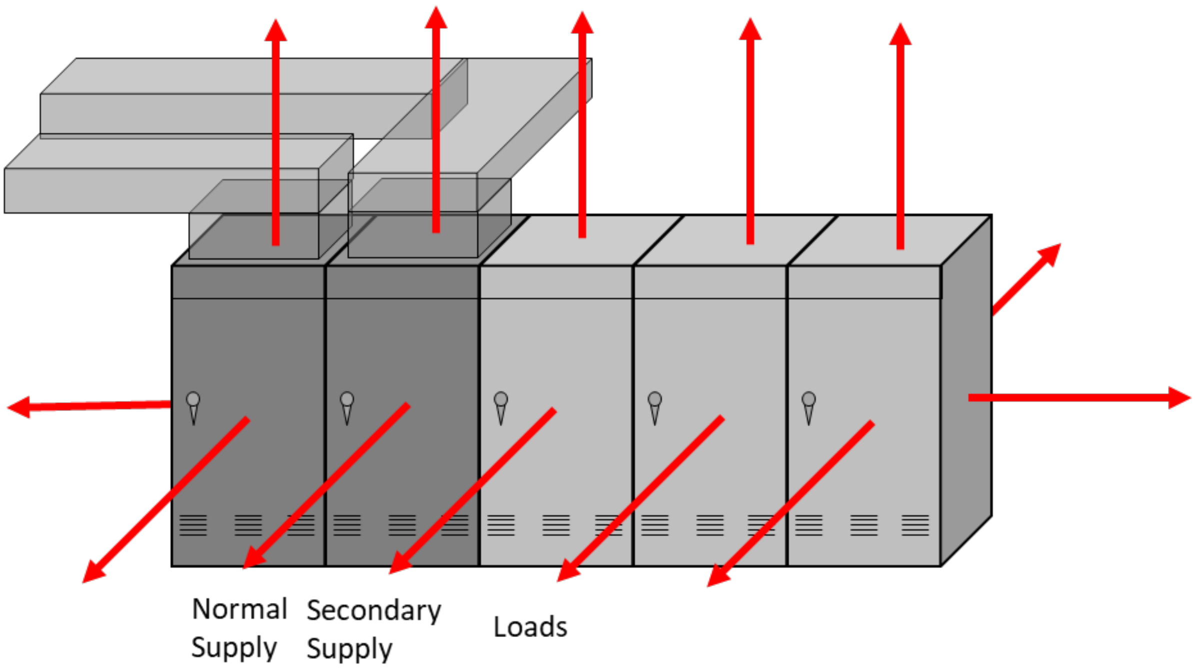


Figure 8-3
Application of MV switchgear screening ZOI

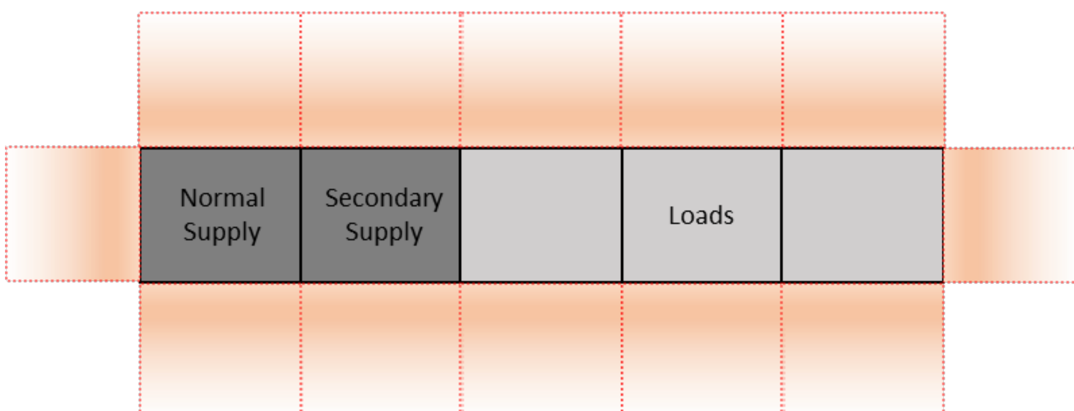


Figure 8-4
Overhead view of MV switchgear screening ZOI

8.5 Zone 1 Configuration-Specific ZOIs

The screening ZOIs are intended to be bounding as they are developed based on the maximum hazard dimensions and applied to the entire bank of switchgear. When more detail is necessary, the analyst can consider the fault location and likelihood to refine the results.

Zone 1 is the MV switchgear fed directly from either the generator (via the UAT) or off-site power (via the SAT). When fed by the UAT, if the supply circuit breaker fails to open (or is the fault initiation point), Zone 1 supply is susceptible to a generator-fed fault.

The configuration-specific ZOIs and split fractions are intended for use when the screening value does not provide the level of detail needed for realistic quantification. The configuration-specific ZOIs postulate HEAFs based on the likelihood within the switchgear (split fractions), power source, and FCT, and provide ZOI dimensions for left/right, front, back, and top (vertical). For Zone 1, the analyst should consider the following four scenarios in conjunction with Figure 8-5 and either Table 8-3 (15 MJ/m^2 target fragility) or Table 8-4 (30 MJ/m^2 target fragility):

- Normal supply: Identify the normal source of power feeding the switchgear (either the UAT or SAT). This vertical section has a split fraction of 0.57. The energetic ZOI is applied around the normal supply vertical section.
    - If the switchgear is fed from the UAT, the UAT generator fed ZOI (end state GF) should be used.
        - If a GCB is installed, a GCB can be credited to reduce the frequency in a generator-fed fault for this end state because it is within the differential protection zone. A 3.5E-05 modifier can be used (see Section 5.3.1 for more details). If the GCB operates as designed (1 - 3.5E-05), the GCB prevents the main generator coast-down energy from feeding a fault within the GCB zone of protection. The working group determined that plants with installed GCBs are expected to have a better than average performance as compared to plants without GCBs. Therefore, for an end state where the GCB is credited, the scenario frequency is not conserved, since the 1 – 3.5E-05 when applied to the branch end state does not result in HEAF-type consequences.
    - If the switchgear is fed from the SAT, the analyst should determine the SAT's backup FCT and select the ZOI based on the time regimes (0–2 s, 2.01–3 s, 3.01–4 s, or 4+ s).
- Secondary supply: Identify the secondary source of power feeding the switchgear (either the UAT or SAT). This vertical section has a split fraction of 0.28. The energetic ZOI is applied around the secondary supply vertical section.
    - If the switchgear is fed from the UAT, the UAT generator fed ZOI (end state GF) should be used.
        - If a GCB is installed, a GCB can be credited to reduce the frequency in a generator-fed fault for this end state because it is within the differential protection zone. A 3.5E-05 modifier can be used (see Section 5.3.1 for more details). If the GCB operates as designed (1 - 3.5E-05), the GCB prevents the main generator coast-down energy from feeding a fault within the GCB zone of protection. The working group determined that plants with installed GCBs are expected to have a better than average performance as compared to plants without GCBs. Therefore, for an end state where the GCB is credited, the scenario frequency is not conserved, since the 1 – 3.5E-05 when applied to the branch end state does not result in HEAF-type consequences.
    - If the switchgear is fed from the SAT, the analyst should determine the SAT's backup FCT and select the ZOI based on the time regimes (0–2 s, 2.01–3 s, 3.01–4 s, or 4+ s).

- Loads (include faults in the main bus bar and loads) fed by the normal supply. This switchgear location also includes load circuit breaker cubicles and empty cubicles. As discussed in Section 8.2.2 the load section includes the non-supply sections of the MV switchgear. The analyst may elect to analyze the load vertical sections together or model the HEAFs more discretely (e.g., on a vertical section). The loads are analyzed considering two different outcomes as follows:
    - Faults in the load breaker or main bus bar and fed via a stuck normal supply breaker. Because the fault is not cleared by the Zone 1 bus supply circuit breaker, the fault is fed by the normal auxiliary power transformer.
        - End state probability = (0.15) × (0.09) = 0.01.
        - For selecting an end state, the analyst should assume the normal supply is feeding the fault. Analyzing the secondary supply is not necessary for this branch.
            - If the fault is fed from the UAT, this fault point is outside the zone of the UAT differential protection (87). The next-level upstream protection, typically the UAT TOC relay protection (51 or 51G, 51N) is called on to detect the fault. The analyst should follow the steps in Section 6.4 to determine the TOC (51) relay protection for the UAT and select the ZOI based on the time regimes (0–0.5 s, 0.51–2 s, 2.01–3 s, 3+ s).
        - The energetic ZOI is applied around the load vertical sections (and not applied around the supply vertical sections).
    - Faults in the load breaker or main bus bar and interrupted by the Zone 1 bus supply circuit breaker. Based on an aggregate review of several NPPs, this time can extend up to 4 s. The analyst can use the end state ZOIs associated with SBL4 (see basis in Section 6.3.2).
        - End state probability = (0.15) × (0.91) = 0.14.
        - If more refinement is necessary, the analyst can determine the actual Zone 1 bus supply circuit breaker opening time based on the speed of the protection. This can be determined using the steps in Section 6.4.2. If the FCT is 3 s[14] or faster, the following end states can be used:
            - For a FCT between 2.01 and 3 s, use the SBL3 end state.
            - For FCTs of 2 s or faster, use the SBL2 end state.
        - The energetic ZOI is applied around the load vertical sections (and not applied around the supply vertical sections).

[14] The SBL4 end state uses the results from the 4 second FDS simulations. During the process to assign ZOIs this end state includes FCTs from 3.01-4 seconds, so no refinement is available for FCTs within this time regime.

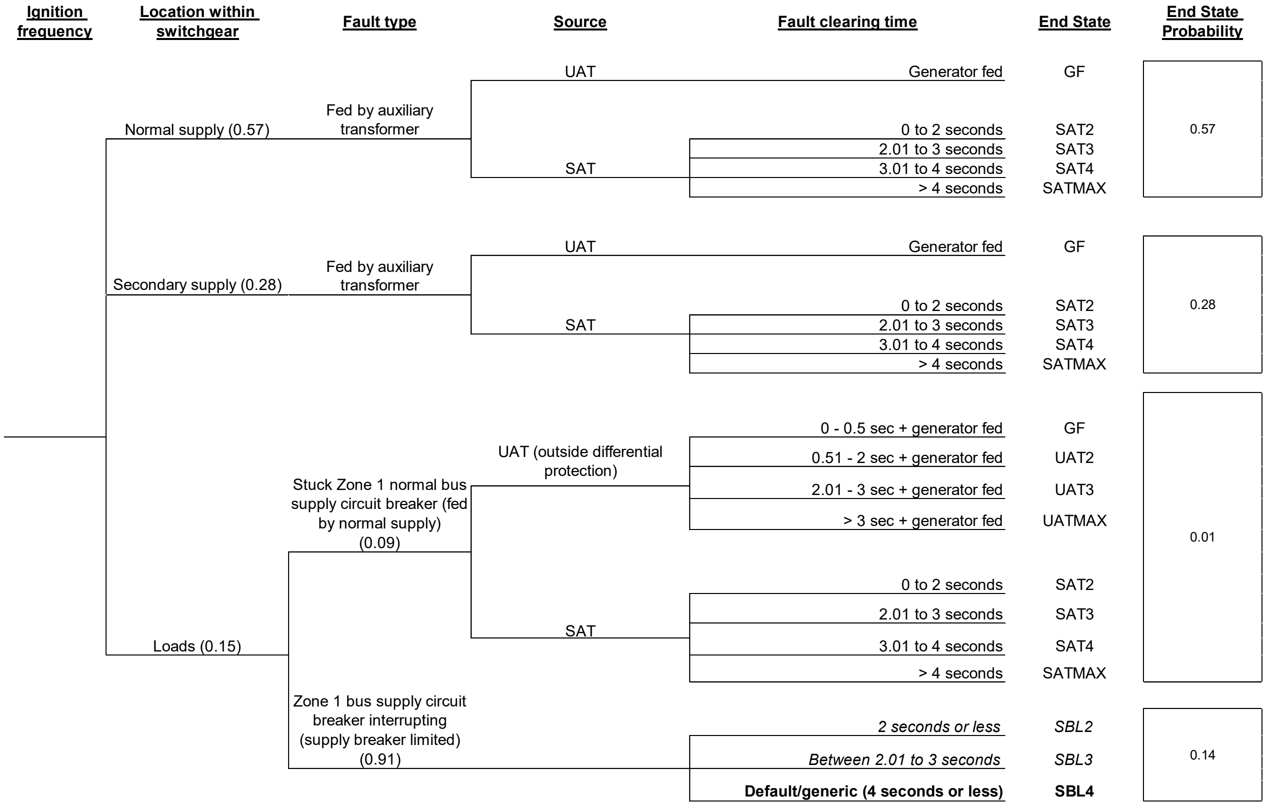


Figure 8-5
Zone 1 HEAF event tree

Table 8-3 and Table 8-4 present the ZOIs, taken from the edge of the switchgear vertical sections containing the fault location, in English units for the 15 MJ/m^2 and 30 MJ/m^2 threshold criteria, respectively. Table E-3 (15 MJ/m^2) and Table E-4 (30 MJ/m^2) provide the ZOIs in SI units. The first set of numbers—default ZOI dimensions—are applicable to both horizontal and vertical circuit breakers (the horizontal circuit breaker results bound the vertical breaker results). If the switchgear contains vertical-lift breakers, the right-hand set of numbers are applicable: “ZOI dimensions for vertical-lift-style circuit breakers.” The vertical-lift circuit breakers have smaller ZOIs in the side (left/right) and back directions.[15] For horizontal-draw-out circuit breakers (both supply and load) and vertical-lift circuit breakers, a split fraction can be applied. A 20% split fraction uses the back dimension specified in either Table 8-3 or Table 8-4. The remaining 80% split fraction should be analyzed as having no back ZOI.

[15] Horizontal-draw-out style circuit breakers have the circuit breaker stabs at the back of the circuit breaker truck. For faults occurring at these locations, the mass of the circuit breaker directs the HEAF energy to breach the side enclosures of the vertical section, whereas vertical-lift circuit breakers allow the HEAF energy to dissipate toward the front of the switchgear. The physical construction of vertical-lift-style switchgear uses PCCBBs that run in horizontally from the center of the switchgear to the rear. Faults occurring in this location in supply breaker vertical sections will be located toward the center of the vertical section, without breaching the rear of the switchgear enclosure.

Table 8-3
Configuration-specific ZOIs for Zone 1 – 15 MJ/m^2 target fragility

Zone 1 – 15 MJ/m^2 target fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	Power Source and Duration	Arc Energy (MJ)	End State	Left/ right (feet)	Front (feet)	Back (feet)	Top (feet)	Left/right (feet)	Front (feet)	Back (feet)	Top (feet)
Normal supply (0.57) and secondary supply (0.28)	UAT: Generator fed	132	GF-15	2.5	2	3*	1.5	2	2	None	1.5
	SAT: 0–2.00 s	68	SAT2-15	1.5	1	2*	1	0.5	1	None	1
	SAT: 2.01–3.00 s	101	SAT3-15	2	1.5	2.5*	1.5	1.5	1.5	None	1.5
	SAT: 3.01–4.00 s	135	SAT4-15	2.5	2	3*	1.5	2	2	None	1.5
	SAT: ≥ 4.01 s	169	SATMAX-15	3	2.5	3.5*	2	2.5	2.5	None	2
Loads: SBL (0.14)	SBL: Z1 generic (≥ 4 s)	135	SBL4-15	2.5	2	3*	1.5	2	2	None	1.5
	SBL: ≥ 2 s	68	SBL2-15	1.5	1	2*	1	0.5	1	None	1
	SBL: 2.01–3 s	101	SBL3-15	2	1.5	2.5*	1.5	1.5	1.5	None	1.5
Loads fed by normal supply (0.01)	UAT: 0–0.5 s + GF	132	GF-15	2.5	2	3*	1.5	2	2	3**	1.5
	UAT: 0.51–2 s + GF	200	UAT2-15	3	2.5	3.5*	2.5	2.5	2.5	3.5**	2.5
	UAT: 2.01–3 s + GF	233	UAT3-15	3.5	3	4*	3	3	3	4**	3
	UAT: ≥ 3 s + GF	300	UATMAX-15	4	3.5	4.5*	3.5	3.5	3.5	4.5**	3.5
	SAT: 0–2.00 s	68	SAT2-15	1.5	1	2*	1	0.5	1	2**	1
	SAT: 2.01–3.00 s	101	SAT3-15	2	1.5	2.5*	1.5	1.5	1.5	2.5**	1.5
	SAT: 3.01–4.00 s	135	SAT4-15	2.5	2	3*	1.5	2	2	3**	1.5
	SAT: ≥ 4.01 s	169	SATMAX-15	3	2.5	3.5*	2	2.5	2.5	3.5**	2

GF= generator fed

*For horizontal-draw-out-style supply circuit breaker cubicles and load circuit breaker cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to no back ZOI (left/right/front/top dimensions the same).

**For the vertical-lift circuit breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% no back ZOI (left/right/front/top dimensions the same).

Table 8-4
Configuration-specific ZOIs for Zone 1 – 30 MJ/m² target fragility

Zone 1 – 30 MJ/m² Target Fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	Power Source and Duration	Arc Energy (MJ)	End State	Left/right (feet)	Front (feet)	Back (feet)	Top (feet)	Left/Right (feet)	Front (feet)	Back (feet)	Top (feet)
Normal supply (0.57) and Secondary supply (0.28)	UAT: Generator fed	132	GF-30	1.5	1	2*	1	1	1	None	1
	SAT: 0–2.00 s	68	SAT2-30	0.5	None	1*	None	None	None	None	None
	SAT: 2.01–3.00 s	101	SAT3-30	1	0.5	1.5*	0.5	0.5	0.5	None	0.5
	SAT: 3.01–4.00 s	135	SAT4-30	1.5	1	2*	1	1	1	None	1
	SAT: ≥ 4.01 s	169	SATMAX-30	2	2	2.5*	1	1.5	2	None	1
Loads: SBL (0.14)	SBL: Z1 generic (≥ 4 s)	135	SBL4-30	1.5	1	2*	1	1	1	None	1
	SBL: ≥ 2 s	68	SBL2-30	0.5	None	1*	None	None	None	None	None
	SBL: 2.01–3 s	101	SBL3-30	1	0.5	1.5*	0.5	0.5	0.5	None	0.5
Loads fed by normal supply (0.01)	UAT: 0–0.5 s + GF	132	GF-30	1.5	1	2*	1	1	1	2**	1
	UAT: 0.51–2 s + GF	200	UAT2-30	2	1.5	2.5*	1.5	1.5	1.5	2.5**	1.5
	UAT: 2.01–3 s + GF	233	UAT3-30	2.5	2	3*	2	2	2	3**	2
	UAT: ≥ 3 s + GF	300	UATMAX-30	3	2.5	3.5*	2.5	2.5	2.5	3.5**	2.5
	SAT: 0–2.00 s	68	SAT2-30	0.5	None	1*	None	None	None	1**	None
	SAT: 2.01–3.00 s	101	SAT3-30	1	0.5	1.5*	0.5	0.5	0.5	1.5**	0.5
	SAT: 3.01–4.00 s	135	SAT4-30	1.5	1	2*	1	1	1	2**	1
	SAT: ≥ 4.01 s	169	SATMAX-30	2	2	2.5*	1	1.5	2	2.5**	1

GF= generator fed

*For horizontal-draw-out-style supply circuit breaker cubicles and load circuit breaker cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to no back ZOI (left/right/front/top dimensions the same).

**For the vertical-lift circuit breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% no back ZOI (left/right/front/top dimensions the same).

The distances in Table 8-3 and Table 8-4 are applied to their respective faces, as shown in Figure 8-6 and Figure 8-7. In the drawings, the supply sections are adjacent to each other. However, other configurations may exist, including ones where the primary/normal supply and secondary supply are on opposite ends, which should be modeled where they appear in the bank. These configuration-specific ZOIs should be applied in four sub-scenarios per the event tree in Figure 8-5.

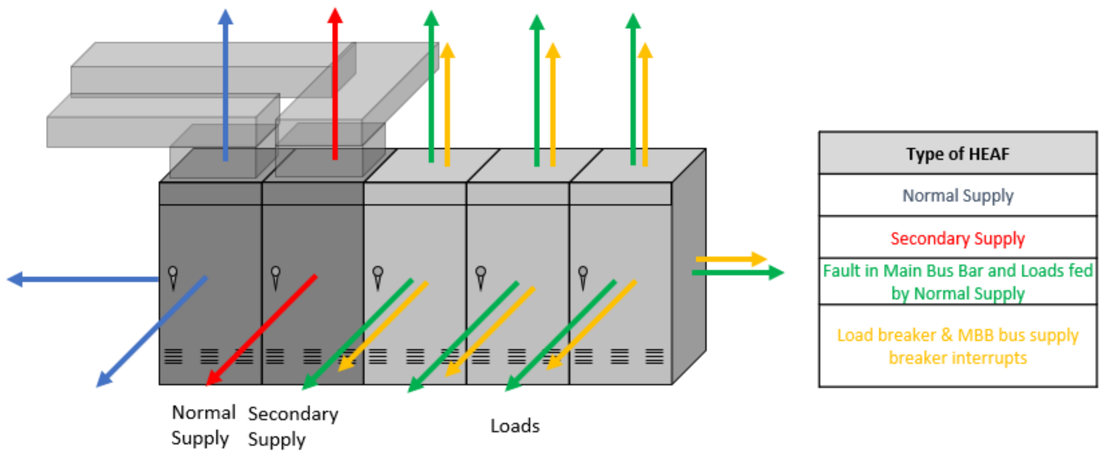


Figure 8-6
MV switchgear configuration-specific ZOIs

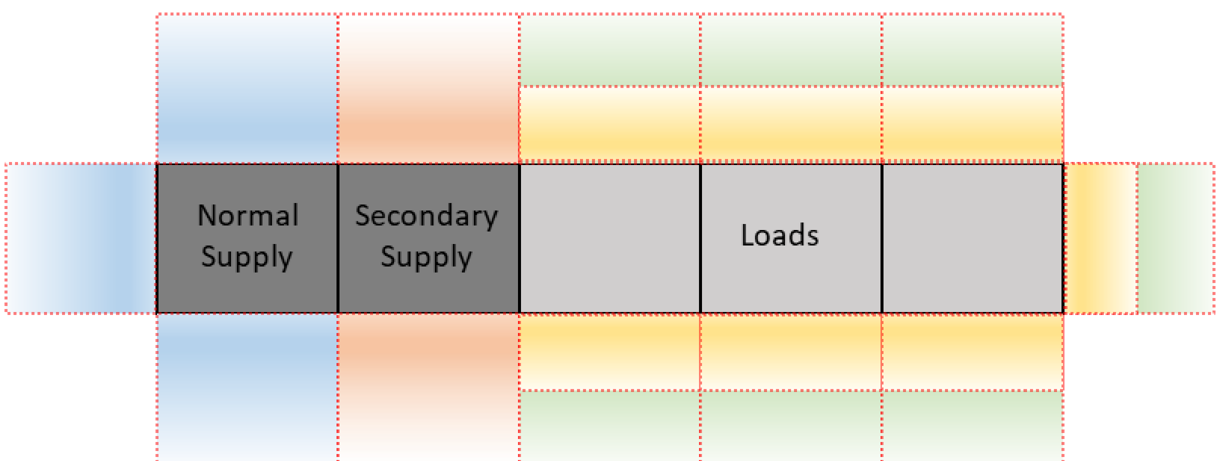


Figure 8-7
Overhead view of MV switchgear configuration-specific ZOIs

8.6 Zone 2 Configuration-Specific ZOIs

Faults in Zone 2 occur in the MV switchgear bus fed by an intermediary switchgear downstream of the UAT or SAT. The Zone 2 switchgear is less likely to experience a fault fed by a generator or off-site power because at least two circuit breakers (Zone 1 and Zone 2 supply circuit breakers) must fail or be involved in the fault's collateral damage (e.g., fault location is the breaker stabs).

The screenings ZOIs in Table 8-2 can be used to model the Zone 2 switchgear. If more refinement is necessary, the ZOIs in Table 8-5 and Table 8-6 should be used. To pair these ZOIs with scenarios, two levels of refinement are available for Zone 2 switchgear as follows:

- Refinement level 1. The ignition frequency is split into two scenarios. Similar to the screening ZOIs, the ZOI is applied around the entire bank of switchgear. In refinement level 1, a bounding fault fed by the auxiliary transformer (either UAT or SAT) and an SBL fault (typically of smaller ZOI dimensions) are postulated. The supply breaker fault represents 95% of the frequency and can help reduce conservatism from the screening ZOIs. The two scenarios include the following:
  - Fault in Zone 2 with the Zone 1 bus supply breaker interrupting (SBL fault)
  - Fault in the normal or secondary supply with an upstream breaker failure (fed by an auxiliary power transformer)
- Refinement level 2 provides the most detailed approach. The normal supply, secondary supply, and load vertical sections can be analyzed individually as detail allows. Refinement 2 is applied by analyzing each vertical section individually or as a group. This refinement level provides flexibility by allowing the analyst to group or individually analyze vertical sections based on the differences in targets between vertical sections.

8.6.1 Zone 2: Refinement Level 1

In refinement level 1, two scenarios are modeled in Zone 2 as shown in the event tree in Figure 8-8. The two scenarios include an SBL fault and a fault fed by the normal supply or secondary supply (the analyst should use the limiting supply configuration). For both scenarios, the ZOI is applied around the entire bank of switchgear (similar to the screening ZOIs).

- SBL fault. This 0.95 split fraction represents a fault in the Zone 2 bus supply circuit breaker that is interrupted by the Zone 1 supply circuit breaker (two potential SBL scenarios are in Zone 2 and this is the bounding end state). In Zone 2, an SBL fault is possible at all three switchgear locations (normal supply, secondary supply, and the load parts).

  As a default, use the 4 s SBL fault (end state SBL4) to bound the modeling. If more refinement is necessary, the analyst can calculate the Zone 1 bus supply breaker FCT, as Section 6.4.2 describes. If the FCT is 3 s.[16] or less, or the Zone 1 switchgear has a load circuit breaker with overcurrent protection, the following additional refinements can be applied:

[16] The SBL4 end state uses the results from the 4 second FDS simulations. During the process to assign ZOIs this end state includes FCTs from 3.01-4 seconds, so no refinement is available for FCTs within this time regime.

  - If the Zone 1 bus supply breaker FCT is 3 s or less, the analyst can use the ZOIs for SBL2 (0–2 s) or SBL3 (2.01–3 s), based on the actual Zone 1 FCT as appropriate. This ZOI is applied around the entire switchgear, as Figure 8-9 shows.
  - If the Zone 1 switchgear has a load circuit breaker with overcurrent protection (not used as a maintenance switch) to the Zone 2 bus and can interrupt in 3 s or less, use the ZOIs for SBL2 (0–2 s), or SBL3 (2.01–3 s). This ZOI is applied around the entire switchgear, as Figure 8-9 shows.
- Fault in bus supply circuit breaker cubicle with an upstream breaker failure: Identify the normal and secondary power sources (SAT and/or UAT) feeding the switchgear and their respective FCTs. Select the bounding ZOI based on the available power sources (e.g., the screening ZOI selected from Table 8-2). In refinement level 1, this bounding ZOI is drawn around the entire switchgear. The 0.05 split fraction is applied around the entire switchgear bank, which conservatively represents circuit breaker/protection failures resulting in a HEAF fed directly from an auxiliary power transformer.

Figure 8-8 shows the event tree for refinement level 1 for Zone 2. Table 8-5 and Table 8-6 show the corresponding ZOIs for Zone 2 for 15 MJ/m^2 and 30 MJ/m^2 fragilities, respectively. The first set of numbers are applicable to both horizontal-draw-out and vertical-lift circuit breakers (the horizontal-draw-out circuit breaker ZOI results bound the vertical-lift circuit breaker results). If the switchgear contains vertical-lift circuit breakers, the right-hand set of numbers are applicable. The vertical-lift circuit breakers have smaller ZOIs in the side (left/right) and back directions.[17] For horizontal-draw-out circuit breakers (both supply and load) and vertical-lift circuit breakers, a split fraction can be applied. A 20% split fraction uses the back dimension specified in either Table 8-5 or Table 8-6. The remaining 80% split fraction should be analyzed as having no back ZOI.

[17] In horizontal-draw-out-style circuit breakers, the circuit breaker connection stabs are at the back of the circuit breaker truck. For faults occurring in these locations, the mass of the circuit breaker directs the HEAF energy to breach the side enclosures of the vertical section, whereas vertical-lift breakers allow the HEAF energy to dissipate toward the front of the switchgear. The physical construction of vertical-lift style switchgear uses PCCBBs that run in horizontally from the center of the switchgear to the rear. Faults that occur in this location in supply circuit breaker vertical sections will occur more toward the center of the vertical section, thus not breaching the rear of the switchgear enclosure.

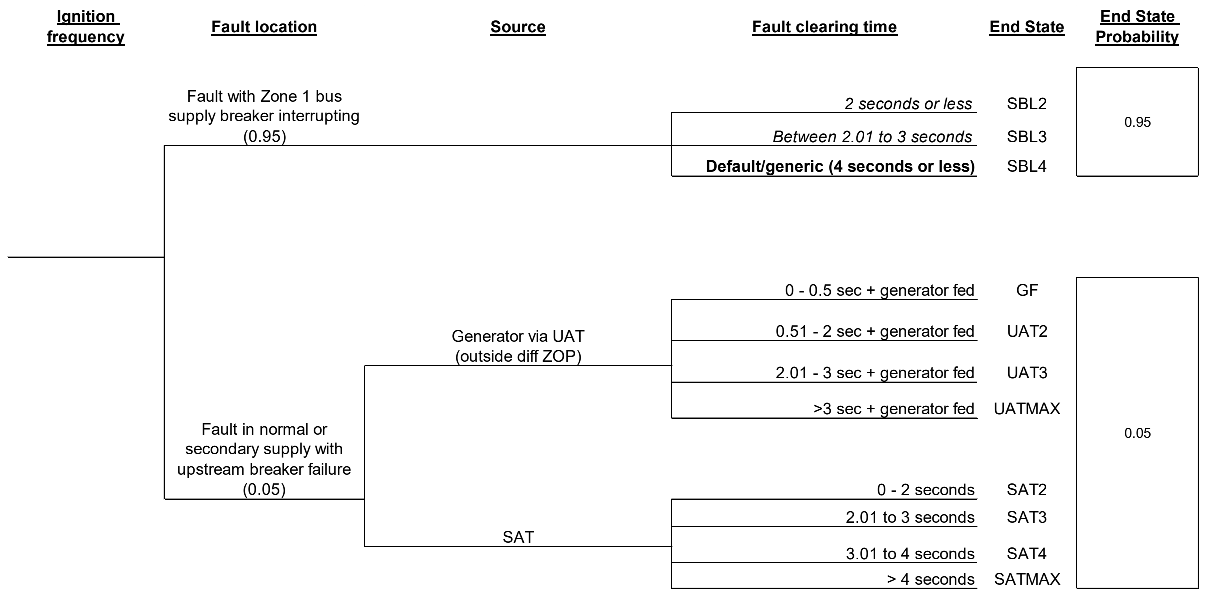


Figure 8-8
Zone 2: refinement level 1

The ZOIs for the two scenarios are applied to the entire bank of switchgear, as shown in Figure 8-9 and Figure 8-10.

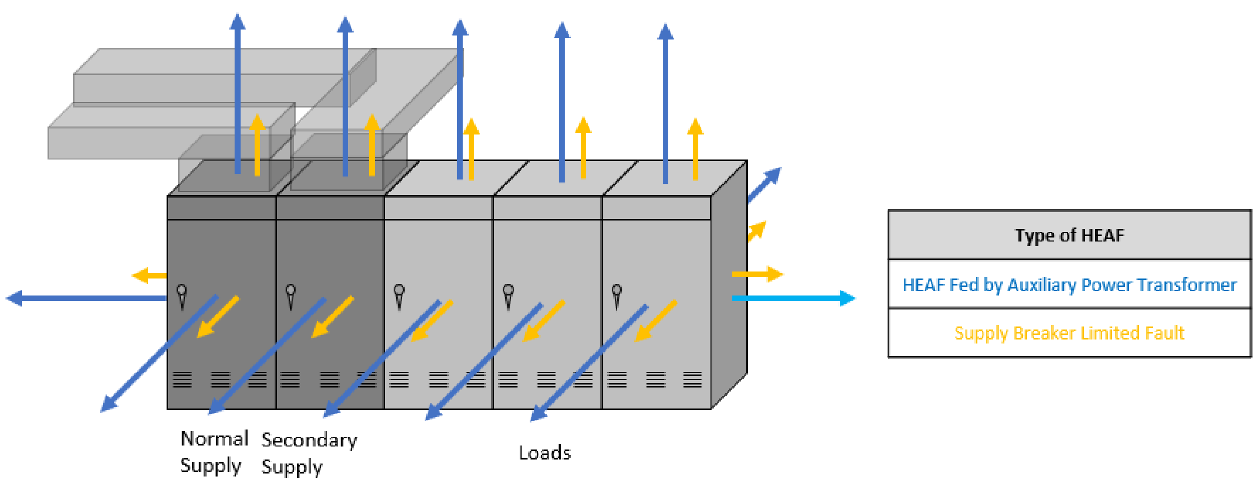


Figure 8-9
Zone 2 refinement level 1 ZOIs

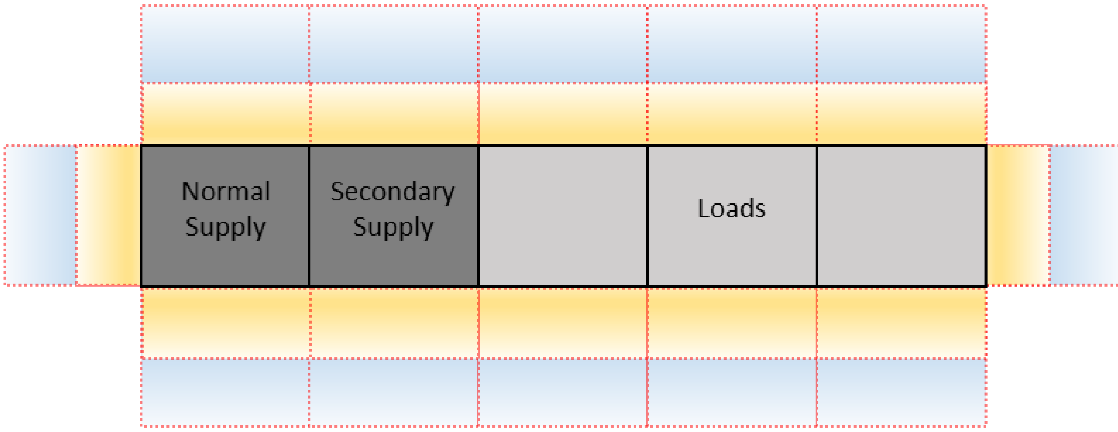


Figure 8-10
Overhead view of refinement level 1

8.6.2 Zone 2: Refinement Level 2

Refinement level 2 expands the treatment of faults by discretely modeling the normal supply, secondary supply, and load portions of the Zone 2 switchgear. Similar to refinement level 1, the event trees are intended to be paired with the configuration-specific ZOIs to postulate HEAFs based on the likelihood within the switchgear (split fractions), power source, and FCT. For Zone 2, the analyst should consider HEAFs at the following three fault locations (see the event tree in Figure 8-11):

- Normal supply: Identify the normal source of power feeding the Zone 2 switchgear. This vertical section has a total split fraction of 0.54 (the final end state probability is in the sub-bullets below). Two types of HEAFs are postulated: a HEAF fed by the generator or switchyard and an SBL fault. For both HEAF types, the ZOI is applied around the normal supply vertical section.
    - Generator/switchyard HEAF, end state probability 0.03. The ZOI is dependent on the power source as follows:
        - If power is fed from the UAT, this fault point is outside the zone of the UAT differential protection (87). The next level of upstream protection, typically the UAT TOC relay protection (51 or 51G, 51N) is called upon to detect the fault. The analyst should follow the steps in Section 6.4 to determine the UAT's TOC relay protection and select the ZOI based on the time regimes (0–0.5 s, 0.51–2 s, 2.01–3 s, 3+ s).
    - If power is fed from the SAT, the analyst should determine the SAT's FCT (per Section 6.4) and select the ZOI based on the time regimes (0–2 s, 2.01–3 s, 3.01–4 s, 4+ s).

SBL fault (Zone 1), end state probability 0.51. This represents a fault in the Zone 2 supply section that is interrupted by the Zone 1 supply circuit breaker. Based on an aggregate review of several NPPs, this time is around 4 s. As a default, use the 4 s SBL fault (end state SBL4) to bound the modeling. If more refinement is necessary, the analyst can calculate the Zone 1 bus supply breaker FCT, as Section 6.4.2 describes. If the FCT is 3 s[18] or less or the Zone 1 switchgear has a load circuit breaker with overcurrent protection, the following additional refinements can be applied:

- If the Zone 1 bus supply breaker FCT is 3 s or less, the analyst can use the ZOIs for SBL2 (0–2 s) or SBL3 (2.01–3 s) based on the actual Zone 1 FCT as appropriate. This ZOI is applied around the normal supply section of the switchgear, shown in dark blue arrows in Figure 8-12.
- If the Zone 1 switchgear has a load circuit breaker with overcurrent protection (that is not used as a maintenance switch) for the Zone 2 bus and can interrupt in 3 s or less, use the ZOI for SBL2 (0–2 s) or SBL3 (2.01–3 s). This ZOI is applied around the normal supply section of the switchgear, shown in dark blue arrows in Figure 8-12.

- Secondary supply: Identify the secondary source of power feeding the Zone 2 switchgear. This vertical section has a split fraction of 0.32 (the final end state probabilities are outlined in the sub-bullets below). Two types of HEAFs are postulated: a HEAF fed by the generator or switchyard and an SBL fault. For both HEAF types, the ZOI is applied around the secondary supply vertical section.
    - Generator/switchyard HEAF, end state probability 0.02. The ZOI is dependent on the power source as follows:
        - If power is fed from the UAT, this fault point is outside the zone of the UAT differential protection (87). The next level of upstream protection, typically the UAT TOC relay protection (51 or 51G, 51N), is called upon to detect the fault. The analyst should follow the steps in Section 6.4 to determine the UAT's TOC relay protection and select the ZOI based on the time regimes (0–0.5 s, 0.51–2 s, 2.01–3 s, 3+ s).
        - If power is fed from the SAT, the analyst should determine the SAT's FCT (per Section 6.4) and select the ZOI based on the time regimes (0–2 s, 2.01–3 s, 3.01–4 s, 4+ s).
    - SBL fault (Zone 1), end state probability 0.30. This represents a fault in the Zone 2 supply section that is interrupted by the Zone 1 supply breaker. Based on an aggregate review of several NPPs, this time is around 4 s. As a default, use the 4 s SBL fault (end state SBL4) to bound the modeling. If more refinement is necessary, the analyst can calculate the Zone 1 bus supply breaker FCT, as described in Section 6.4.2. If the FCT is 3 s[18] or less or the Zone 1 switchgear has a load circuit breaker with overcurrent protection, the following additional refinements can be applied:

[18] The SBL4 end state uses the results from the 4 second FDS simulations. During the process to assign ZOIs this end state includes FCTs from 3.01-4 seconds, so no refinement is available for FCTs within this time regime.

    - If the Zone 1 bus supply breaker FCT is 3 s or less, the analyst can use the ZOI for SBL2 (0–2 s) or SBL3 (2.01–3 s) based on the actual Zone 1 FCT as appropriate. This ZOI is applied around the supply section (shown in dark blue arrows) of the switchgear in Figure 8-12.
    - If the Zone 1 switchgear has a load circuit breaker with overcurrent protection (not used as a maintenance switch) to the Zone 2 bus and can interrupt in 3 s or less, use the ZOIs for SBL2 (0–2 s), or SBL3 (2.01–3 s). This ZOI is applied around the supply section of the switchgear, shown in dark blue arrows in Figure 8-12.

- Fault in the loads fed by the normal supply. The split fraction, 0.14, considers HEAFs in the load sections (e.g., load circuit breaker cubicles, main bus bar, and empty cubicles). As discussed in Section 8.2.2 the load section includes the non-supply sections of the MV switchgear. The analyst may elect to analyze the load vertical sections together or model the HEAFs more discretely (e.g., on a vertical section). The ZOI is applied around the load sections of the switchgear (however discrete the modeling choice).
  - SBL fault (Zone 1), end state probability 0.01. This represents a fault in the Zone 2 load vertical sections that is interrupted by the Zone 1 supply breaker. Based on an aggregate review of several NPPs, this time is around 4 s. As a default, use the 4 s SBL fault (end state SBL4) to bound the modeling. If more refinement is necessary, the analyst can calculate the Zone 1 bus supply breaker FCT, as described in Section 6.4.2. If the FCT is 3 s[18] or less or the Zone 1 switchgear has a load circuit breaker with overcurrent protection, the following additional refinements can be applied:
    - If the Zone 1 bus supply breaker FCT is 3 s or less, the analyst can use the ZOI for SBL2 (0–2 s) or SBL3 (2.01–3 s) based on the actual Zone 1 FCT as appropriate. This ZOI is applied around the supply section (shown in dark blue arrows) of the switchgear in Figure 8-12.
    - If the Zone 1 switchgear has a load circuit breaker with overcurrent protection (not used as a maintenance switch) to the Zone 2 bus and can interrupt in 3 s or less, use the ZOIs for SBL2 (0–2 s), or SBL3 (2.01–3 s). This ZOI is applied around the supply section of the switchgear, shown in dark blue arrows in Figure 8-12.
  - SBL fault (Zone 2). The end state probability (0.13) represents a fault in the load or main bus bars that is interrupted by the Zone 2 supply breaker. Based on an aggregate review of several NPPs, the time for Zone 2 is approximately 2 s. The analyst should use the ZOI associated with the SBL fault for 2 s (SBL2). The ZOI is around the load parts of the switchgear, as shown with yellow arrows in Figure 8-12.

Figure 8-11 shows the event tree for Zone 2 refinement level 2. Table 8-5 and Table 8-6 show the corresponding ZOIs, taken from the edge of the switchgear vertical sections containing the fault location, for Zone 2 in English units for 15 MJ/m^2 and 30 MJ/m^2 fragilities, respectively. Table E-5 (15 MJ/m^2) and Table E-6 (30 MJ/m^2) provide the ZOIs in SI units. The first set of numbers are applicable to both horizontal-draw-out and vertical-lift circuit breakers (the horizontal-draw-out circuit breaker ZOI results bound the vertical-lift circuit breaker results). If the switchgear contains vertical-lift circuit breakers, the right-hand set of numbers are also applicable. The vertical-lift circuit breakers have smaller ZOIs in the side (left/right) and back directions.[19] For horizontal-draw-out circuit breakers (both supply and load) and vertical-lift circuit breakers, a split fraction can be applied. A 20% split fraction uses the back dimension specified in either Table 8-5 or Table 8-6. The remaining 80% split fraction should be analyzed as having no back ZOI.

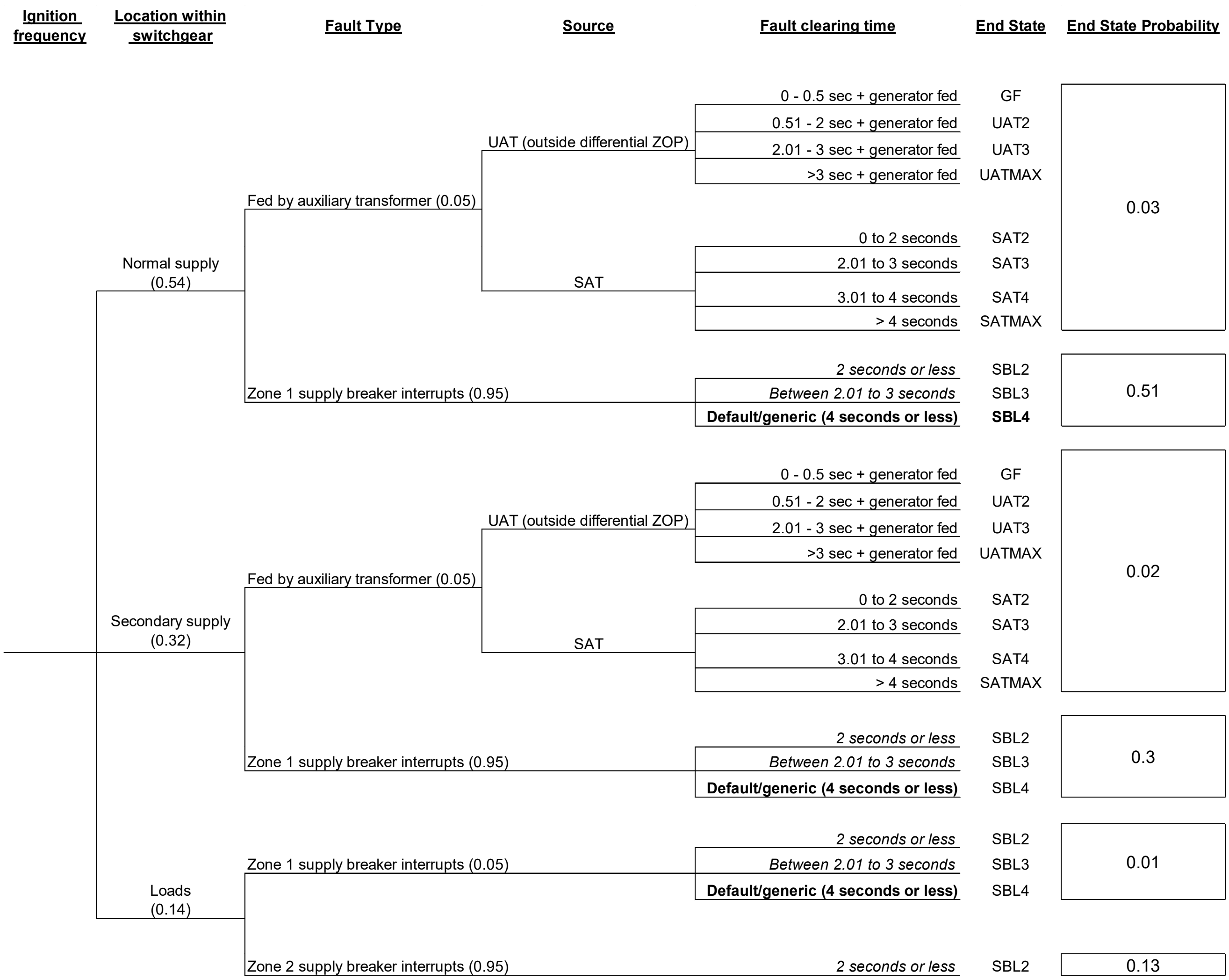


Figure 8-11
Zone 2: Refinement level 2

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19 Horizontal-draw-out style circuit breakers have the circuit breaker connection stabs at the back of the circuit breaker truck. For faults occurring at these locations, the mass of the circuit breaker directs the HEAF energy to breach the side enclosures of the vertical section, whereas vertical-lift breakers allow the HEAF energy to dissipate toward the front of the switchgear. The physical construction of vertical-lift style switchgear uses PCCBBs that run horizontally from the center of the switchgear to the rear. Faults occurring in this location in supply circuit breaker vertical sections will be located more toward the center of the vertical section and thus will not breach the rear of the cabinet.

Table 8-5
Configuration-specific ZOIs for Zone 2 – 15 MJ/m² target fragility

Zone 2 – 15 MJ/m² Target Fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	Power Source and Duration	Arc Energy (MJ)	End State	Left/Right (feet)	Front (feet)	Back (feet)	Top (feet)	Left/Right (feet)	Front (feet)	Back (feet)	Top (feet)
Refinement Level 1: Primary, secondary, and loads: 0.05 **Refinement Level 2:** Normal supply: 0.03 Secondary supply: 0.02	UAT: 0–0.5 s + GF	132	GF-15	2.5	2	3*	1.5	2	2	3**	1.5
	UAT: 0.51–2 s + GF	200	UAT2-15	3	2.5	3.5*	2.5	2.5	2.5	3.5**	2.5
	UAT: 2.01–3 s + GF	233	UAT3-15	3.5	3	4*	3	3	3	4**	3
	UAT: ≥3 s + GF	300	UATMAX-15	4	3.5	4.5*	3.5	3.5	3.5	4.5**	3.5
	SAT: 0–2.00 s	68	SAT2-15	1.5	1	2*	1	0.5	1	None	1
	SAT: 2.01–3.00 s	101	SAT3-15	2	1.5	2.5*	1.5	1.5	1.5	None	1.5
	SAT: 3.01–4.00 s	135	SAT4-15	2.5	2	3*	1.5	2	2	None	1.5
	SAT: ≥4.01 s	169	SATMAX-15	3	2.5	3.5*	2	2.5	2.5	None	2
Refinement Level 1: Zone 1 SBL: 0.95 **Refinement Level 2:** Zone 1 SBL Normal supply: 0.51 Secondary supply: 0.30 Loads: 0.01	SBL: Z1 generic (≥ 4s)	135	SBL4-15	2.5	2	3*	1.5	2	2	None	1.5
	SBL: ≥2 s	68	SBL2-15	1.5	1	2*	1	0.5	1	None	1
	SBL: 2.01–3 s	101	SBL3-15	2	1.5	2.5*	1.5	1.5	1.5	None	1.5
Refinement Level 2: Zone 2 SBL (loads): 0.13	SBL: Z2 generic (≥2 s)	68	SLB2-15	1.5	1	2*	1	0.5	1	None	1

GF= generator fed
*For horizontal-draw-out-style supply cubicles and load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to a no-back ZOI (left/right/front/top dimensions the same).
**For the vertical-lift breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI in the table, 80% to the no-back ZOI (left/right/front/top dimensions the same).

Table 8-6
Configuration-specific ZOIs for Zone 2 – 30 MJ/m² target fragility

Zone 2 – 30 MJ/m² Target Fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	Power Source and Duration	Arc Energy (MJ)	End State	Left/Right (feet)	Front (feet)	Back (feet)	Top (feet)	Left/Right (feet)	Front (feet)	Back (feet)	Top (feet)
Refinement Level 1: Primary, secondary, and loads: 0.05 **Refinement Level 2:** Normal supply: 0.03 Secondary supply: 0.02	UAT: 0–0.5 s + GF	132	GF-30	1.5	1	2*	1	1	1	2**	1
	UAT: 0.51–2 s + GF	200	UAT2-30	2	1.5	2.5*	1.5	1.5	1.5	2.5*	1.5
	UAT: 2.01–3 s + GF	233	UAT3-30	2.5	2	3*	2	2	2	3**	2
	UAT: ≥3 s + GF	300	UATMAX-30	3	2.5	3.5*	2.5	2.5	2.5	3.5**	2.5
	SAT: 0–2.00 s	68	SAT2-30	0.5	None	1*	None	None	None	None	None
	SAT: 2.01–3.00 s	101	SAT3-30	1	0.5	1.5*	0.5	0.5	0.5	None	0.5
	SAT: 3.01–4.00 s	135	SAT4-30	1.5	1	2*	1	1	1	None	1
	SAT: ≥4.01 s	169	SATMAX-30	2	2	2.5*	1	1.5	2	None	1
Refinement Level 1: Zone 1 SBL: 0.95 **Refinement Level 2:** Zone 1 SBL Normal supply: 0.51 Secondary supply: 0.30 Loads: 0.01	SBL: Z1 generic (≥ 4s)	135	SBL4-30	1.5	1	2*	1	1	1	None	1
	SBL: ≥2 s	68	SBL2-30	0.5	None	1*	None	None	None	None	None
	SBL: 2.01–3 s	101	SBL3-30	1	0.5	1.5*	0.5	0.5	0.5	None	0.5
Refinement Level 2: Zone 2 SBL (loads): 0.13	SBL: Z2 generic (≥2 s)	68	SBL2-30	0.5	None	1*	None	None	None	None	None

GF= generator fed
*For horizontal-draw-out-style supply circuit breaker cubicles and load circuit breaker cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to the no-back ZOI (left/right/front/top dimensions the same).
**For the vertical-lift circuit breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI in the table, 80% to the no-back ZOI (left/right/front/top dimensions the same).

The distances in Table 8-5 and Table 8-6 are applied to their respective faces depending on the refinement, as shown in Figure 8-12 and Figure 8-13. These figures show the supply sections adjacent to each other, but other configurations may exist, such as supply sections located on opposite ends of the switchgear bank. The analyst should confirm the location of the supply cabinets and model the supply sections where they are located in the switchgear bank.

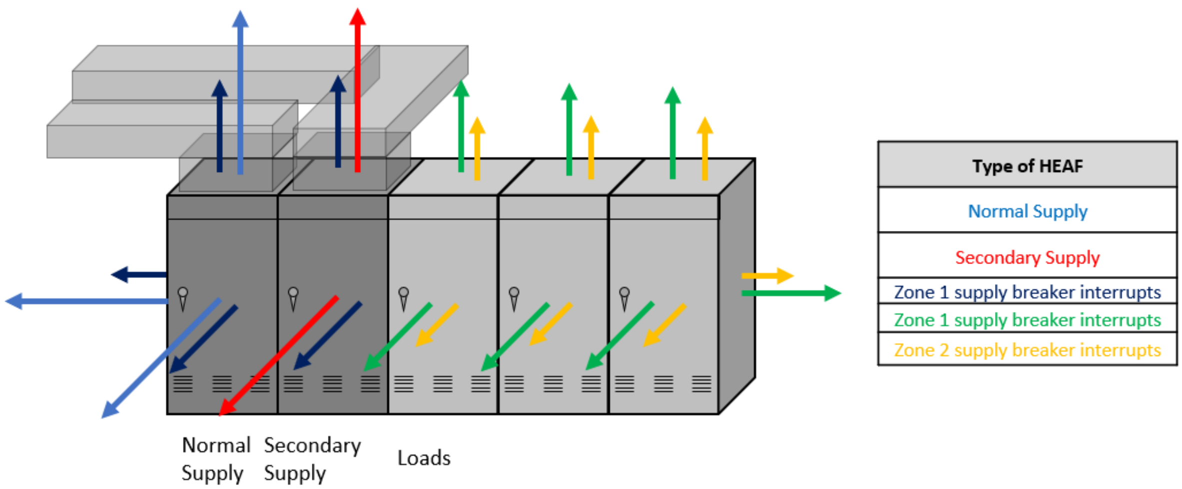


Figure 8-12
MV switchgear configuration-specific ZOIs: Refinement level 2

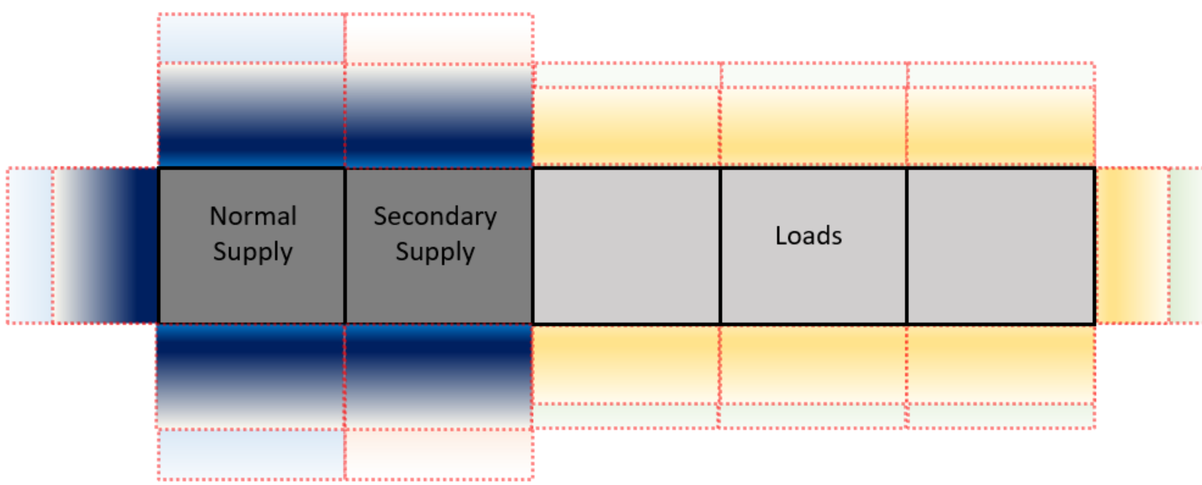


Figure 8-13
Overhead view of MV switchgear configuration-specific ZOIs: refinement level 2

9

HIGH ENERGY ARCING FAULTS IN BUS DUCTS

Faults in NSBDs are divided into two ignition source bins based on the higher likelihood of faults in the ductwork between the power transformer and the first switchgear. The analyst uses the frequency for Bin 16.1-1 and apportions the frequency between BDUAT and BDSAT. The remaining bus ducts (BD1, BD2, and BDLV) use the frequency for Bin 16.1-2. Iso-phase bus ducts are analyzed in Bin 16.2.

The ZOIs for bus ducts are dependent on the fault location, bus duct housing material (aluminum or steel), power source, and FCT. Bus duct zones BDUAT, BDSAT, and BDLV have one end state and corresponding ZOI. Bus duct zones BD1 and BD2 can experience a fault fed by the auxiliary power transformer or SBL fault. If detailed modeling is required, the analyst can split the scenario frequency using the split fractions provided and model the scenarios for the fault fed by the auxiliary power transformer and an SBL fault. For BD1 and BD2 the analyst can also use the limiting/bounding configuration (either directly fed by an auxiliary power transformer or SBL fault) as a screening.

9.1 Summary of FDS Cases and Insights for Bus Ducts

The working group developed FDS input files for a range of potential NSBD fault energies, power sources, fault durations, bus-bar compositions, bus duct housing compositions, and bus duct geometry [16]. Table 9-1 summarizes these parameters.

Table 9-1
FDS simulation parameter ranges for NSBDs

Parameter	Range Considered or Configuration
Bus duct geometry	• Straight segment • Vertical tee • Vertical elbow
Fault type and duration	• Constant-current fault (1–5 s) • Generator-fed fault (15 s of decaying current) • Constant-current (0–5 s) with a generator-fed fault (15 s of decaying current)
Total fault energy	34–300 MJs
Bus bar material composition	• Copper • Aluminum
Bus duct housing material composition	• Steel • Aluminum

The FDS inputs were evaluated using FDS, Version 6.7.6, with application-specific updates as described in the FDS ZOI report [16]. Overall, a total of 58 unique FDS input files and simulations were developed for the NSBDs. The FDS simulation results were used to develop ZOIs for targets with 15 MJ/m² and 30 MJ/m² fragilities around the duct enclosure. Appendix D of this report provides the ZOIs for 57 of these simulations (one failed with a numerical instability).

The key findings of the FDS ZOI report simplify the number of ZOIs to characterize the HEAF hazard as follows [16]:

- The dominant parameter affecting the ZOIs in NSBDs was the total arc energy.
    - A secondary parameter was the duct housing material (aluminum or steel).
- The bus bar material composition does not have a significant effect on the ZOI. The ZOIs are within the uncertainty range for copper and aluminum bus bar simulations for a given fault type and energy.
- The duct geometry (straight, elbow, or tee) does not have a significant effect on the ZOI.

Based on these observations, the FDS simulation results were grouped and linked to specific energetic ZOI end states in Section 9.2. Appendix D of this report describes the simulation grouping in detail.

The working group determined the energetic ZOIs using the FDS simulation results for the applicable grouping. The general process included reviewing predicted ZOIs and selecting a representative value within this group in units of feet. This value was then rounded up in increments of 0.5 ft (15 cm). Appendix D provides a more detailed description of this process and provides several examples for illustration.

9.2 Energetic ZOIs for Bus Ducts

The five different zones defined for NSBDs are summarized as follows:

- BDUAT: One scenario based on BDGenFed
- BDSAT: One scenario, in which the analyst selects the ZOI based on the anticipated FCT of the SAT (either BSAT0.5, BDSAT1, BDSAT1.5, BDSAT2, BDSAT3, BDSAT4, BDSATMAX).
- BD1: Two scenarios, one based on the normal power supply, and one based on the 4 s SBL. The analyst selects either of the following:
    - Power Transformer
        - If normally powered by the UAT
            - FCT 0–0.5 s: BDGenFed
            - FCT 0.51–2 s: BDGF2
            - FCT 2.01–3 s: BDGF3
            - FCT ≥ 3 s: BDGFMAX
        - If normally powered by the SAT
            - FCT 0–0.50 s: BDSAT0.5
            - FCT 0.51–1.0 s: BDSAT1
            - FCT 1.01–1.50 s: BDSAT1.5
            - FCT 1.51–2 s: BDSAT2
            - FCT 2.01–3 s: BDSAT3
            - FCT 3.01–4 s: BDSAT4
            - FCT ≥ 4 s: BDSATMAX
    - SBL 4 s: BDSBL4 is the generic/default ZOI for the time for the Zone 1 bus supply circuit breaker to open. This value is based on the aggregate review of several NPPs to choose a bounding upper limit.

    - If more refinement is needed, the analyst can determine the actual Zone 1 bus supply circuit breaker opening time based on the speed of protection. This can be determined using the steps in Section 6.4.2. Based on the time, use one of the following end states:
        - Zone 1 bus supply circuit breaker FCT 0–0.50 s: BDSBL0.5
        - Zone 1 bus supply circuit breaker FCT 0.51–1.0 s: BDSBL1
        - Zone 1 bus supply circuit breaker FCT 1.01–1.50 s: BDSBL1.5
        - Zone 1 bus supply circuit breaker FCT 1.51–2 s: BDSBL2 (Z2 bus supply breaker interrupting [generic/default])
        - Zone 1 bus supply circuit breaker FCT 2.01–3 s: BDSBL3
        - Zone 1 bus supply circuit breaker FCT 3.01–4 s: BDSBL4 (Z1 bus supply breaker interrupting [generic/default])

- BD2: Two scenarios: one based on the normal power supply, and one based on the 2 s SBL.
    - Power transformer: Same as BD1.
    - SBL2: BDSBL2 is the generic/default ZOI for the time for the Zone 2 bus supply circuit breaker to open. This value is based on the aggregate review of several NPPs to choose a bounding upper limit.
        - If more refinement is needed, the analyst can determine the actual Zone 2 bus supply circuit breaker opening time based on the speed of protection. This can be determined using the steps in Section 6.4.2. Based on the time, use one of the following end states:
            - Zone 2 bus supply circuit breaker FCT 0–0.50 s: BDSBL0.5
            - Zone 2 bus supply circuit breaker FCT 0.51–1.0 s: BDSBL1
            - Zone 2 bus supply circuit breaker FCT 1.01–1.50 s: BDSBL1.5
            - Zone 2 bus supply circuit breaker FCT 1.51–2 s: BDSBL2 (default)
- BDLV: One scenario based on ZOI BDLV.

The analyst should determine the enclosure material of the initiating bus duct (either steel or aluminum) and then determine the fragility of nearby targets (either 15 MJ/m^2 or 30 MJ/m^2). Table 9-2 shows the ZOIs in English units. For metric units, see Table E-7.

Table 9-2
NSBD ZOIs

End state	Power transformer and fault clearing time	Bus duct enclosure material and target fragility			
		Steel enclosure with target fragility of 15 MJ/m^2 (feet)	Steel enclosure with target fragility of 30 MJ/m^2 (feet)	Aluminum enclosure with target fragility of 15 MJ/m^2 (feet)	Aluminum enclosure with target fragility of 30 MJ/m^2 (feet)
BDSAT0.5 BDSBL0.5	SAT: 0–0.50 s SBL: 0–0.50 s	0	0	0	0
BDSAT1 BDSBL1	SAT: 0.51–1.00 s SBL: 0.51–1.00 s	0	0	0.5	0.5
BDSAT1.5 BDSBL1.5	SAT: 1.01–1.50 s SBL: 1.01–1.50 s	0.5	0.5	1	1
BDSAT2 BDSBL2 BDLV	SAT:1.51–2.00 s SBL: Z2 generic* (≥ 2 s) and 1.51-2.00s Low voltage	1	0.5	1.5	1
BDSAT3 BDSBL3	SAT: 2.01–3.00 s SBL: 2.01–3.00 s	2	1	2.5	1.5
BDSAT4 BDSBL4	SAT: 3.01–4.00 s SBL: Z1 generic* (≥ 4 s)	2.5	1.5	3	2
BDSATMAX	SAT: ≥ 4.01 s	3	2	3.5	2
BDGenFed	UAT: 0–0.5 s + GF	2.5	1.5	3	2
BDGF2	UAT: 0.51–2 s + GF	3.5	2	4	2.5
BDGF3	UAT: 2.01–3 s + GF	4	2.5	4	2.5
BDGFMAX	UAT: ≥3 s + GF	4.5	3	5	3

GF= generator fed
*For the SBL end state, an optional refinement can be made by calculating the FCT of the primary supply breaker for the MV switchgear feeding the NSBD following the steps in Section 6.4. The appropriate end state (BDSBL0.5, BDSBL1, BDSBL1.5, BDSBL2, or BDSBL3) should be selected based on the FCT.

The distances provided in Table 9-2 should be measured from each outer surface in each direction around the bus duct, shown in the upper left corners of Figure 9-1 and Figure 9-2 as distance *X*. In addition to the ZOI immediately around the bus duct, targets within an area below the postulated point of the bus duct fault are postulated damaged because of molten metal slag. The molten slag can damage and ignite cables in the first open cable tray underneath the bus duct. This “waterfall” is shown in the upper right of Figure 9-1 and on the right-hand side of Figure 9-2. The waterfall has a distance of 1.5 ft from the edge of the duct. The distance of the ZOI is selected from Table 9-2 and runs along the duct in both directions, centered at the postulated fault location (shown as distance *X* in the diagram). For cases in which the distance *X* is 0 feet (End states, BDSAT0.5, BDSBL0.5, BDSAT1, and BDSBL1) there is no ZOI external to the bus duct for both the “along bus duct” and “waterfall”, only the bus duct (itself) is considered damaged.

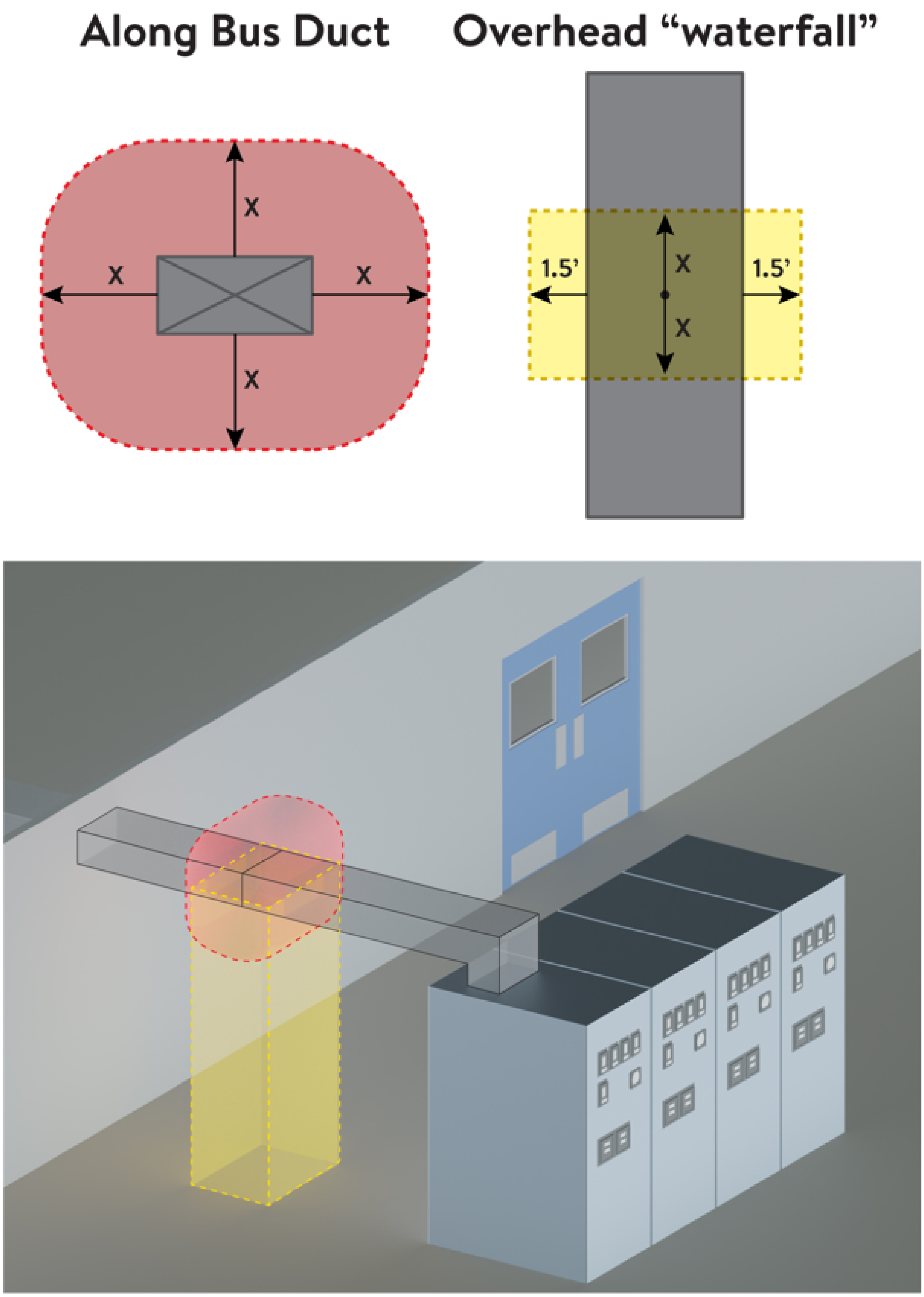


Figure 9-1
Depiction of bus duct ZOI

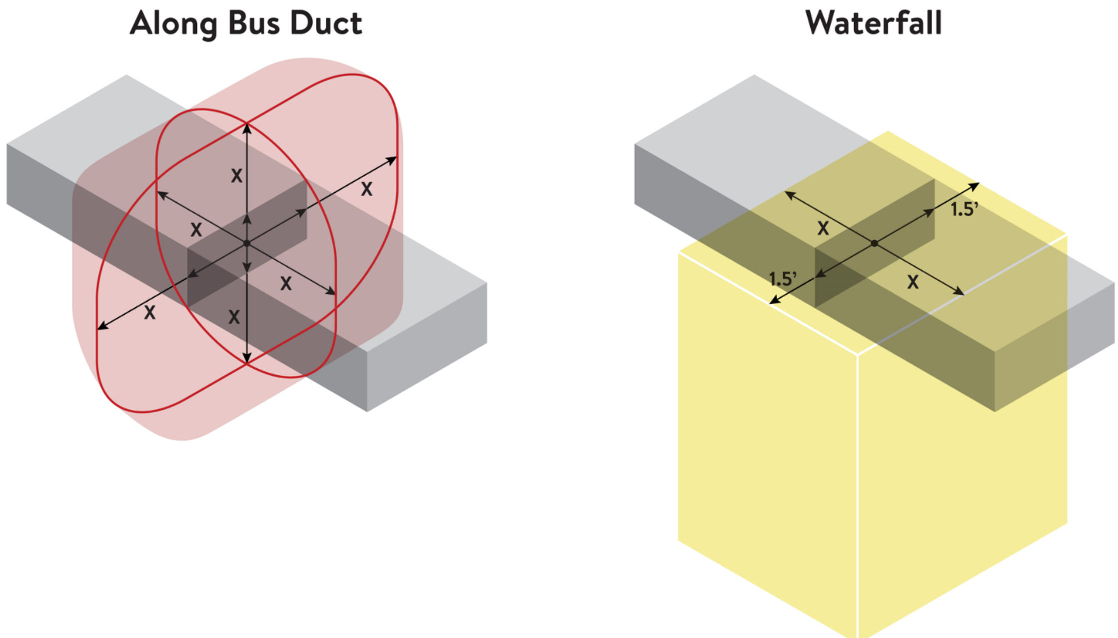


Figure 9-2
Alternate view of the bus duct ZOI

9.2.1 HEAFs in Zone IPBD

There is no change in the ZOI associated with an IPBD HEAF. The analyst should continue to use the guidance in NUREG/CR-6850, Supplement 1 [2], which is repeated below:

> The zone of influence should assume damage to any component or cable that would normally be considered vulnerable to fire damage (i.e., excluding items such as water-filled piping that would not normally be considered vulnerable to fire damage) located within a sphere centered on the fault point and measuring 5 feet in radius. Any flammable or combustible material within this same zone of influence should be assumed to ignite. The recommended zone of influence is intended to cover both the initial fault effect and the potential burning of hydrogen gas that may be released at low pressure from the bus casing upon rupture. An enduring fire (i.e., lasting beyond the initial fault) should be assumed consistent with the nature of any flammable or combustible materials present within the zone of influence and potential fire spread beyond the zone of influence.
>
> For the case of fire occurring at the main transformer termination points, the potential for involvement of the main transformer (and its oil) should be considered. In particular, the electrical lines will each penetrate the casing of the transformer, and this could allow the fire to spread to the transformer itself. Failure of the electrical penetration seals (e.g., melting of a rubber boot) could also create a path for oil leakage outside of the transformer as was observed in FEDB 127.
>
> The analysis should also consider the potential for involvement of additional hydrogen gas beyond that which will leak from the casing as a result of the initial fault. That is, the configuration of, and potential failure in, the hydrogen purge/fill system should be

evaluated to determine if additional leakage of hydrogen gas is plausible. This assessment will require consideration of case-specific storage, piping, and valve arrangements.

For NPPs with installed GCBs, a factor of 3.5E-05 can be applied to the scenario frequency to reduce the frequency of generator-fed faults. See Section 5.3.1 for more detail. If the GCB operates as designed (1 - 3.5E-05), the GCB prevents the main generator coast-down energy from feeding a fault within the GCB zone of protection. The working group determined that plants with installed GCBs are expected to have a better than average performance as compared to plants without GCBs. Therefore, for an end state where the GCB is credited, the scenario frequency is not conserved, since the 1 – 3.5E-05 when applied to the branch end state does not result in HEAF-type consequences.

9.2.2 HEAFs in Zone BDUAT

A fault in Zone BDUAT results in an UAT protective trip lockout (86) and a subsequent turbine–generator trip (see Section 3.4). This is modeled as a generator-fed fault, within the differential protection zone (87) of the UAT. For Zone BDUAT, use end state BDGenFed from Table 9-2. The analyst should determine the enclosure material of the initiating bus duct (either steel or aluminum) and then determine the fragility of nearby targets (either 15 MJ/m^2 or 30 MJ/m^2).

For NPPs with GCBs, the GCB modifier can be used on bus duct scenarios in Zone BDUAT. This factor of 3.5E-05 can be applied to the frequency to reduce the frequency of generator-fed faults (and should only be applied to fault locations where the GCB can interrupt the fault). If the GCB operates as designed (1 - 3.5E-05), the GCB prevents the main generator coast-down energy from feeding a fault within the GCB zone of protection. The working group determined that plants with installed GCBs are expected to have a better than average performance as compared to plants without GCBs. Therefore, for an end state where the GCB is credited, the scenario frequency is not conserved, since the 1 – 3.5E-05 when applied to the branch end state does not result in HEAF-type consequences.

9.2.3 HEAFs in Zone BDSAT

A fault in Zone BDSAT is expected to result in a SAT protective trip lockout (86). The difference in duration is that subsequent SAT backup protection schemes limit the duration of an off-site power fed fault. The analyst should determine the backup FCT and select one of the following from Table 9-2: BDSAT 0.5, BDSAT1, BDSAT1.5, BDSAT2, BDSAT3, BDSAT4, or BDSATMAX. The analyst should determine the enclosure material of the initiating bus duct (either steel or aluminum) and then determine the fragility of nearby targets (either 15 MJ/m^2 or 30 MJ/m^2).

9.2.4 HEAFs in Zone BD1

Zone BD1 covers a fault occurring in the NSBD region between the first MV switchgear and either the high side of the second downstream MV switchgear bus supply breaker or the MV part of the NSBD that feeds a load center (see Figure 3-1).

HEAFs in Zone BD1 can have two potential outcomes: a HEAF fed directly from the auxiliary power transformer or an SBL fault. A fault directly fed by the auxiliary power transformer in BD1 represents a fault in the NSBD with an independent failure of the Zone 1 bus supply circuit breaker. The SBL fault is a fault on the NSBD that is interrupted by the Zone 1 supply circuit breaker.

The split fraction for the ZOI was developed through the expert panel exercise documented in Appendix C. The split fraction for BD1 of 5/95 is the same as Zone 2 refinement level 1 (Figure 8-8), which reflects the fraction where the bus supply breaker is expected to interrupt the fault (0.95) versus being fed by the auxiliary power transformer (0.05).

For Zone BD1, the analyst can pick the limiting scenario (bounding ZOI) without using the split fraction in Figure 9-3. If using the split fraction is desired to achieve the risk objective, the analyst can use the split fractions of 5% fed by the auxiliary power transformer and 95% SBL. For the part of the split fraction fed by the auxiliary power transformer, the analyst will select either the UAT branch or the SAT branch (based on the normal lineup of the NPP at power) and use the same TOC (51) relay FCT identified for the Zone 1 MV switchgear that normally powers the NSBD.

The SBL portion can be refined by determining the Zone 1 MV switchgear bus supply circuit breaker FCT. See Section 6.4.2 for more information on determining this FCT. If the FCT is 3 s or less, then a smaller ZOI can be used—either BDSBL0.5, BDSBL1, BDSBL1.5, BDSBL2, or BDSBL3—based on the determined FCT. If the Zone 1 switchgear has a load circuit breaker with overcurrent protection (not used as a maintenance switch) for the Zone 2 bus/Zone 3 load center that can interrupt in 3 s or less, then the corresponding FCT can be used to refine the ZOI (e.g., BDSBL0.5, BDSBL1, BDSBL1.5, BDSBL2, or BDSBL3 based on the determined FCT).

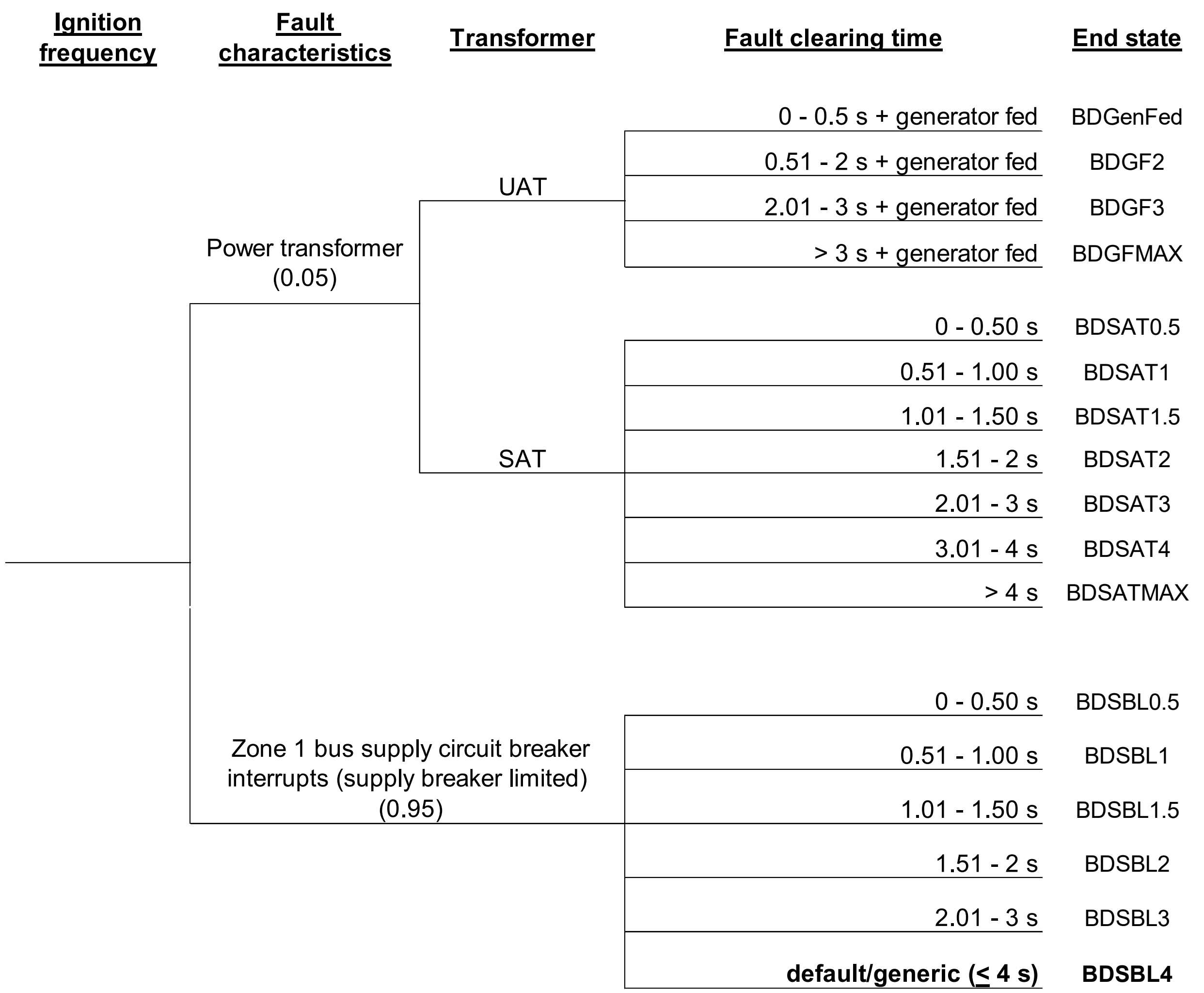


Figure 9-3
Zone BD1 ZOI event tree

9.2.5 HEAFs in Zone BD2

A fault in the bus duct below the second MV switchgear occurs in Zone BD2. HEAFs in Zone BD2 can have two potential outcomes: a HEAF fed directly from the auxiliary power transformer or an SBL fault. A fault fed by the auxiliary power transformer in BD2 represents a fault in the NSBD with independent failures of the Zone 2 bus supply circuit breaker and, if selectively coordinated, the Zone 1 bus supply circuit breaker. The SBL scenario is a fault in the NSBD that is interrupted by the Zone 2 supply circuit breaker.

The split fraction for the ZOI is developed through the expert panel exercise documented in Appendix C. The split fraction for BD2 of 5/95 is the same as Zone 2 refinement level 1 (Figure 8-8), which reflects the fraction where the bus supply breaker is expected to interrupt the fault versus being fed by the auxiliary power transformer.

For Zone BD2, the analyst can pick the limiting scenario—in this case, fed by the normal auxiliary power transformer—without using the split fraction in Figure 9-4. If the use of the split fraction is necessary, the analyst can use the split fractions of 5% fed by the auxiliary power transformer and 95% SBL. For the part of the split fraction directly fed by the auxiliary power transformer, the analyst will select either the UAT branch or the SAT branch of the normal supply and use the same FCT identified for the Zone 1 and Zone 2 MV switchgear that normally powers this NSBD.

As a starting point, the analyst should use the 2 s SBL ZOI (BDSBL2). The SBL portion can be further refined by determining the Zone 2 MV switchgear bus supply circuit breaker FCT. See Section 6.4.2 for more information on determining this FCT. If the FCT is 1.5 s or less, then a smaller ZOI can be used—either BDSBL0.5, BDSBL1, or BDSBL1.5, based on the determined FCT.

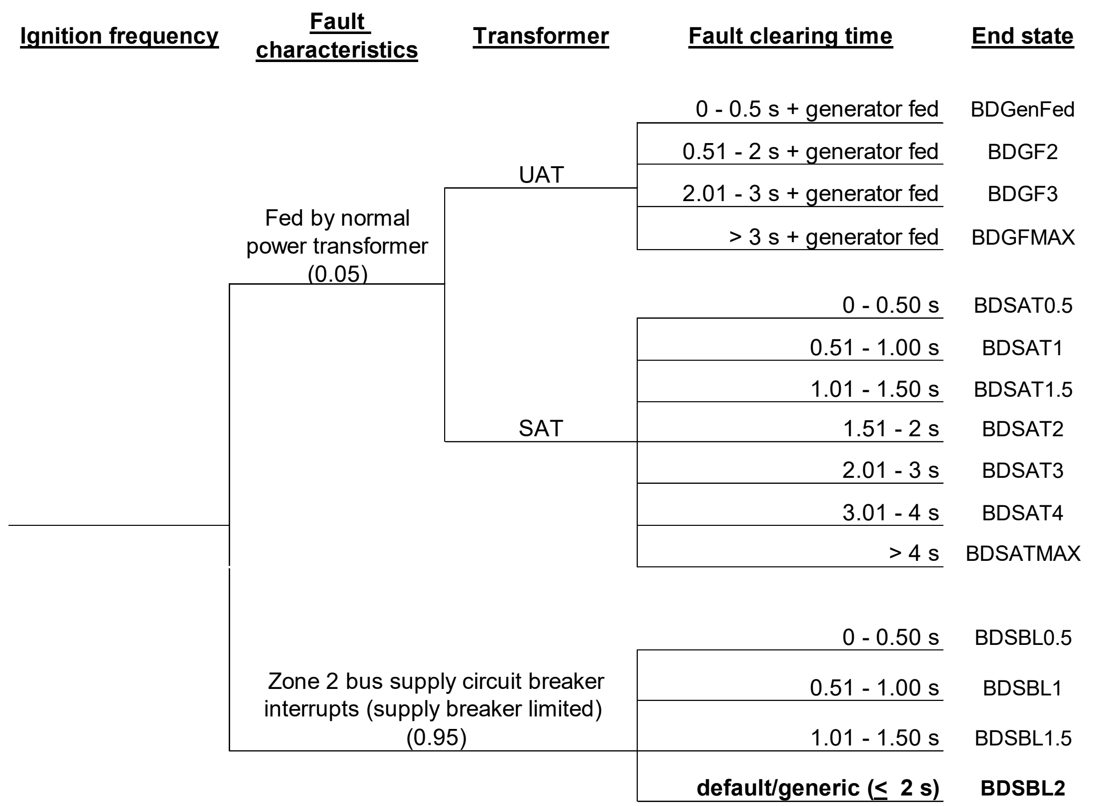


Figure 9-4
Zone BD2 ZOI event tree

9.2.6 HEAFs in BDLV

Some NPPs may have LV NSBDs. The analyst should use the ZOI associated with end state BDLV in Table 9-2. For the exclusion of HEAFs in LV DC bus ducts, refer to Section 5.2.3.5.

10 SUMMARY

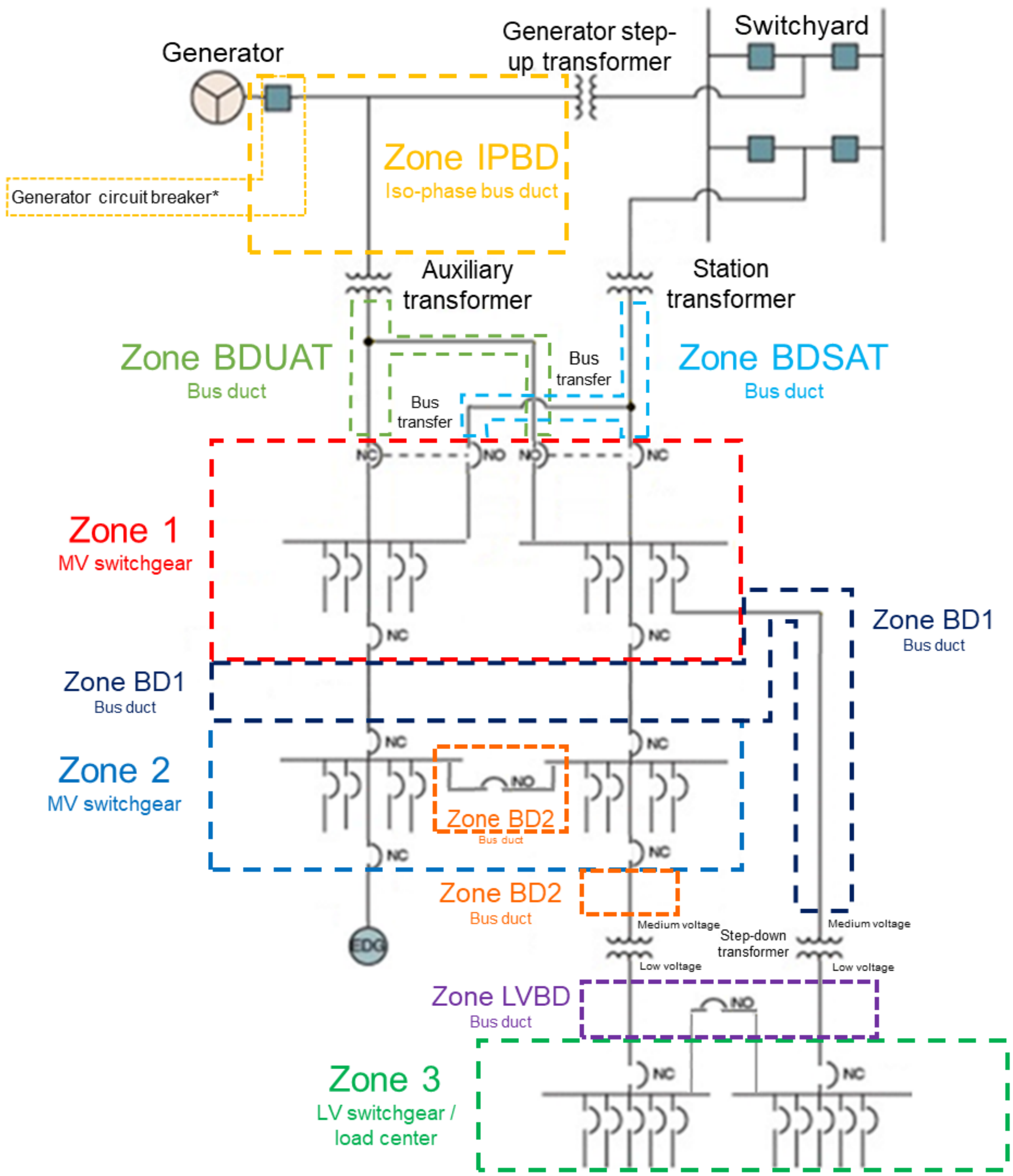
This report provides an updated methodology for modeling HEAFs in fire PRA. The following sections summarize the methodology in this report.

10.1 High Energy Arcing Fault Generic Fault Zones

Fault zones are developed for parts of the EDS with similar potential fault durations. Figure 10-1 presents graphically the fault zones of a common NPP EDS. Table 10-1 provides a short description of the fault zones.

Table 10-1
HEAF zones

Fault Zone	Portion of EDS	Ignition source bin	Equipment
IPBD	Iso-phase bus duct	16.2	Iso-phase bus duct connecting the station generator to the UAT and GSU transformer.
BDUAT	Bus duct between UAT and Zone 1	16.1-1	NSBD that connects the UAT secondary (tertiary) windings to the first downstream switchgear.
BDSAT	Bus duct between SAT and Zone 1	16.1-1	NSBD that connects the SAT secondary (tertiary) windings to the first downstream switchgear. BDSAT may also be used to represent any off-site power circuit that supports power production from dedicated-system service transformers not shown in the simplified NPP EDS in Figure 3-1. An example is a dedicated off-site power for cooling tower operation.
1	MV switchgear	16.b	First switchgear downstream of the UAT or SAT. This may also be referred to as an “intermediate bus” if it feeds another downstream MV bus.
2	MV switchgear	16.b	Second switchgear downstream of the UAT or SAT (via an intermediate bus)
3	Load center	16.a	Load centers or LV switchgear (480–1000 VAC)
BD1	MV bus duct between Zone 1 and Zone 2 and Zone 1 and Zone 3	16.1-2	Region of the MV NSBD between the first MV switchgear and either of the following: • The high side of the second MV switchgear bus supply breaker (bus duct from Zone 1 to Zone 2) • The high side of the load center transformer (bus duct from Zone 1 to Zone 3)
BD2	MV bus duct between Zone 2 and Zone 3 and Zone 2 to Zone 2	16.1-2	Region of the MV NSBD between the second MV switchgear and either of the following: • The high side of the load center transformer • Another Zone 2 switchgear (bus-tie)
LVBD	LV bus duct between Zone 1, Zone 2, and Zone 3 to Zone 3	16.1-2	Region of the LV NSBD between the Zone 1 step-down transformer and the load center (Zone 1 or Zone 2 to Zone 3) or between load centers (Zone 3 to Zone 3).



*Generator circuit breaker defined in Section 2 and discussed in Section 5.3.1.

Figure 10-1
HEAF zones for a generic NPP EDS

10.2 Summary of HEAF Methodology by Equipment Type

The HEAF methodology outlined in the preceding sections is summarized by general equipment type and location. The HEAF fault zone, counting guidance, ignition frequency, ZOIs, and ensuing fire location are summarized for each equipment type. For the HEAF manual suppression probability, the mean rate of 0.026 (from Table 5-10) can be applied for the post-HEAF ensuing fire for switchgear and load centers (including secondary combustibles) and ignition of combustibles in the waterfall region for NSBD HEAFs.

10.2.1 HEAFs in Load Centers

HEAFs in load centers are in HEAF zone 3. The counting guidance for Bin 16.a is as follows:

Bin 16.a: HEAFs for LV Electrical Cabinets (480–1000 VAC): Load center HEAFs are only postulated at the supply circuit breakers. Only count load center supply circuit breakers. Note: load centers are no longer counted by vertical section.

The plant-wide fire ignition frequency for load centers (Bin 16.a) is shown in Table 10-2.

Table 10-2
Fire ignition frequency for bin 16.a

Bin	Ignition Source	Power Modes	Period	Mean	Median	5th Percentile	95th Percentile
16.a	HEAF for LV electrical cabinets (480–1000V)	AA	2000–2021	5.32E-04	1.26E-04	4.67E-07	1.69E03

The energetic HEAF ZOI depends on the physical location of the supply circuit breaker within the load center. Table 10-3 reproduces the full set of ZOIs applied from the respective load center faces.

Table 10-3
Load center energetic ZOIs

Load center supply circuit breaker location and target fragility	Arc Energy (MJ)	Back/ Front	Side (feet)	Top (feet)
End location, upper elevation: 15 MJ/m^2	90	None	2.5	2
End location, upper elevation: 30 MJ/m^2	90	None	1.5	1
End location, lower elevation: 15 MJ/m^2	90	None	2.5	None
End location, lower elevation: 30 MJ/m^2	90	None	1.5	None
Interior, upper elevation: 15 MJ/m^2	90	None	None	2
Interior, upper elevation: 30 MJ/m^2	90	None	None	1
Interior, lower elevation: 15 MJ/m^2	90	None	None	None
Interior, lower elevation: 30 MJ/m^2	90	None	None	None

Immediately following the energetic blast, the ensuing fire has a HRR equal to the 98th percentile for switchgear and load centers. From NUREG-2178, Volume 1 [44], the 98th percentile HRR is 170 kW. The ensuing fire timing is modeled as follows:

- Growth period: 0 min (none)
- Steady-burning period: 8 min
- Decay period: 19 min

Fire propagation does not occur in adjacent vertical sections.

10.2.2 HEAFs in Zone 1 (First Downstream MV Switchgear from the Auxiliary Power Transformer)

HEAFs in the first downstream MV switchgear are in Zone 1. The counting guidance for Bin 16.b is as follows:

Bin 16.b: HEAFs for MV Electrical Cabinets (>1000 VAC): Counting MV switchgear is based on the count of switchgear (each bank of switchgear is counted as one). Note: MV switchgear are no longer counted by vertical section.

HEAFs in Zone 1 are within fire ignition frequency Bin 16.b. The ignition frequency for Bin 16.b is in Table 10-4.

Table 10-4
Fire ignition frequency for bin 16.b

Bin	Ignition Source	Power Modes	Period	Mean	Median	5th Percentile	95th Percentile
16.b	HEAF for MV cabinets (>1000V)	AA	2000–2021	1.98E-03	2.20E-04	3.59E-07	6.90E-03

As directed in Section 5.2.2.3, once all switchgears are counted and assigned to either Zone 1 or Zone 2, the ignition frequency for Zone 1 is weighted using 86% of the generic fire ignition frequency. Eighty-six percent of the generic fire ignition frequency is distributed between the Zone 1 switchgear.

Table 10-5 contains MV switchgear screening ZOIs taken from the edge of the switchgear bank.

Table 10-5
Screening ZOIs for MV switchgear

SAT fault clearing time	SAT arc energy (MJ)	UAT fault clearing time into generator-fed fault	UAT arc energy (MJ)	15 MJ/m^2 target fragility (feet)	30 MJ/m^2 target fragility (feet)
SAT (0–4.00 s)	135	UAT (0–0.50 s)	132	3	2
SAT (4.01+ s)	169	UAT (0.51–2.00 s)	200	3.5	2.5
		UAT (2.01–3.00 s)	233	4	3
		UAT (3.01+ s)	300	4.5	3.5

Table 8-3 (15 MJ/m^2 fragility) or Table 8-4 (30 MJ/m^2 fragility) provide the configuration-specific ZOIs for Zone 1.

Immediately following the energetic blast, the ensuing fire has a HRR equal to the 98th percentile associated with switchgear and load centers. From NUREG-2178, Volume 1 [44], the 98th percentile HRR is 170 kW. The ensuing fire timing is modeled as follows:

- Growth period: 0 min (none)
- Steady-burning period: 8 min
- Decay period: 19 min

Fire propagation to the adjacent vertical sections occurs only for arc energies greater than 101 MJ for single walled construction and 202 MJ for double walled construction. Do not postulate fire propagation for arc energies of 101 MJ and below for single walled construction. Do not postulate fire propagation for arc energies of 202 MJ and below for double walled construction. When fire spread is modeled, spread should occur in each vertical section that has an adjacent vertical section. The maximum number of vertical sections that can be modeled is limited to three. See Section 6.5.1 for more details and how to apply the fire spread event tree.

10.2.3 HEAFs in Zone 2 (MV Switchgear Downstream from Zone 1 Switchgear)

HEAFs in MV switchgear fed from an upstream MV switchgear are in Zone 2. The counting guidance for Bin 16.b is as follows:

Bin 16.b: HEAFs for MV Electrical Cabinets (>1000 VAC): The counting of MV switchgear is based on the count of switchgear (each bank of switchgear is counted as one). Note: MV switchgear are no longer counted by vertical section.

HEAFs in Zone 2 are within fire ignition frequency Bin 16.b. The ignition frequency for 16.b is in Table 10-6.

Table 10-6
Fire ignition frequency for bin 16.b

Bin	Ignition Source	Power Modes	Period	Mean	Median	5th Percentile	95th Percentile
16.b	HEAF for MV cabinets (>1000V)	AA	2000–2021	1.98E-03	2.20E-04	3.59E-07	6.90E-03

As directed in Section 5.2.2.3, once all switchgear are counted and assigned to either Zone 1 or Zone 2, the ignition frequency for Zone 2 is weighted using 14% of the generic fire ignition frequency. Fourteen percent of the generic fire ignition frequency is distributed between the Zone 2 switchgear.

Table 10-7 reproduces MV switchgear screening ZOIs taken from the edge of the switchgear bank.

Table 10-7
Screening ZOIs for MV switchgear

SAT fault clearing time	SAT arc energy (MJ)	UAT fault clearing time into generator-fed fault	UAT arc energy (MJ)	15 MJ/m² target fragility (feet)	30 MJ/m² target fragility (feet)
SAT (0–4.00 s)	135	UAT (0–0.50 s)	132	3	2
SAT (4.01+ s)	169	UAT (0.51–2.00 s)	200	3.5	2.5
		UAT (2.01–3.00 s)	233	4	3
		UAT (3.01+ s)	300	4.5	3.5

Configuration-specific ZOIs are provided in Table 8-5 (15 MJ/m^2 fragility) and Table 8-6 (30 MJ/m^2 fragility). The tables provide two levels of refinement.

Immediately following the energetic blast, the ensuing fire has an HRR equal to the 98th percentile associated with switchgear and load centers. From NUREG-2178, Volume 1 [44], the 98th percentile HRR is 170 kW. The ensuing fire timing is modeled as follows:

- Growth period: 0 min (none)
- Steady-burning period: 8 min
- Decay period: 19 min

Fire propagation to the adjacent vertical sections occurs only for arc energies greater than 101 MJ for single walled construction and 202 MJ for double walled construction. Do not postulate fire propagation for arc energies of 101 MJ and below for single walled construction. Do not postulate fire propagation for arc energies of 202 MJ and below for double walled construction. When fire spread is modeled, spread should occur in each vertical section that has an adjacent vertical section. The maximum number of vertical sections that can be modeled is limited to three. See Section 6.5.1 for more details and how to apply the fire spread event tree.

10.2.4 HEAFs in NSBD in Zones BDUAT and BDSAT

HEAFs in NSBDs connected to the auxiliary power transformers are in HEAF zones BDUAT (bus duct off the UAT) and BDSAT (bus duct off the SAT). The counting guidance for NSBDs is consistent with NUREG/CR-6850, Supplement 1 [2], with one addition identified in *italics*:

Bin 16.1-1 and 16.1-2: HEAFs for Non-segregated Bus Ducts

- For known transition points, the counting of NSBD is based on the total number of transition points. *Analysts should also look for fire PRA targets in locations with the potential for a HEAF to occur—including ventilation openings on outdoor NSBD, mechanical hatches on outdoor NSBD, and external wall penetrations (e.g., yard-to-turbine-building penetration)—and ensure they are captured with scenarios developed around the counted transition points or are treated as transition points with scenarios developed at these locations.*

- For unknown transition points, the counting of NSBD is based on the total length of the bus duct.

- HEAFs are not postulated along the length of continuous bus ducts or cable ducts, consistent with NUREG/CR-6850, Supplement 1 [2].

HEAFs in BDUAT and BDSAT are within fire ignition frequency Bin 16.1-1 as shown in Table 10-8.

Table 10-8
Fire ignition frequency for bin 16.1-1

Bin	Ignition Source	Power Modes	Period	Mean	Median	5th Percentile	95th Percentile
16.1-1	HEAF for segmented bus ducts (Zone BDUAT and Zone BDSAT)	AA	2010–2021	2.61E-03	1.06E-03	6.31E-06	8.28E-03

For both BDUAT and BDSAT, the analyst should determine the enclosure material of the initiating bus duct (either steel or aluminum) and then determine the fragility of nearby targets (either 15 MJ/m^2 or 30 MJ/m^2). If the material is unknown, use the ZOIs for an aluminum enclosure.

For BDUAT, the ZOI, originating from the edge of the bus duct enclosure, is modeled with end state BDGenFed (within the differential protection zone [87]) in Table 10-9.

Table 10-9
Energetic ZOIs for BDUAT

End state	Power transformer and fault clearing time	Bus duct enclosure material and target fragility			
		Steel enclosure with target fragility of 15 MJ/m^2 (feet)	Steel enclosure with target fragility of 30 MJ/m^2 (feet)	Aluminum enclosure with target fragility of 15 MJ/m^2 (feet)	Steel enclosure with target fragility of 15 MJ/m^2 (feet)
BDGenFed	UAT: 0–0.5 s + GF	2.5	1.5	3	2

For BDSAT, the ZOI depends on the FCT. Table 10-10 shows the ZOIs originating from the edge of the bus duct enclosure. The analyst selects the ZOI based on the anticipated FCT of the TOC relay, and then selects a ZOI end state that fits within the FCTs (either BDSAT 0.5, BDSAT1, BDSAT1.5, BDSAT2, BDSAT3, BDSAT4, or BDSATMAX).

Table 10-10
Energetic ZOIs for BDSAT (selected based on FCT)

End state	Power transformer and fault clearing time	Bus duct enclosure material and target fragility			
		Steel enclosure with target fragility of 15 MJ/m^2 (feet)	Steel enclosure with target fragility of 30 MJ/m^2 (feet)	Aluminum enclosure with target fragility of 15 MJ/m^2 (feet)	Steel enclosure with target fragility of 15 MJ/m^2 (feet)
BDSAT0.5	SAT: 0–0.50 s	0	0	0	0
BDSAT1	SAT: 0.51–1.00 s	0	0	0.5	0.5
BDSAT1.5	SAT: 1.01–1.50 s	0.5	0.5	1	1
BDSAT2	SAT: 1.51–2.00 s	1	0.5	1.5	1
BDSAT3	SAT: 2.01–3.00 s	2	1	2.5	1.5
BDSAT4	SAT: 3.01–4.00 s	2.5	1.5	3	2
BDSATMAX	SAT: ≥ 4.01 s	3	2	3.5	2

10.2.5 HEAFs in NSBD in Zones BD1, BD2, and LV

HEAFs in NSBD connected downstream of the MV switchgear are in one of the following locations:

- Zone BD1: MV bus duct between Zone 1 and Zone 2, and also Zone 1 and Zone 3
- Zone BD2: MV bus duct between Zone 2 and Zone 3, and also Zone 2 and Zone 2 [bus tie])
- LV bus ducts

The counting guidance for NSBDs is consistent with NUREG/CR-6850, Supplement 1 [2], with one addition identified in *italics*:

Bin 16.1-1 and 16.1-2: HEAFs for NSBD

- For known transition points, the counting of NSBD is based on the total number of transition points. *Analysts should also look for fire PRA targets in locations with the potential for a HEAF to occur—including ventilation openings on outdoor NSBD, mechanical hatches on outdoor NSBD, and external wall penetrations (e.g., yard-to-turbine-building penetration)—and ensure they are captured with scenarios developed around the counted transition points or are treated as transition points with scenarios developed at these locations*
- For unknown transition points, the counting of NSBD is based on the total length of the bus duct.
- HEAFs are not postulated along the length of continuous bus ducts or cable ducts, consistent with NUREG/CR-6850, Supplement 1 [2].

HEAFs in BD1, BD2, and BDLV are within fire ignition frequency Bin 16.1-2. The ignition frequency for 16.1-2 is in Table 10-11.

Table 10-11
Fire ignition frequency for bin 16.1-2

Bin	Ignition Source	Power Modes	Period	Mean	Median	5th Percentile	95th Percentile
16.1-2	HEAF for segmented bus ducts (BD1, BD2, BDLV)	AA	2000–2021	8.98E-04	1.73E-04	2.11E-07	2.95E-03

The analyst should determine the enclosure material of the initiating bus duct (either steel or aluminum) and then determine the fragility of nearby targets (either 15 MJ/m^2 or 30 MJ/m^2). If the material is unknown, use the ZOIs for an aluminum enclosure.

For BD1, up to two scenarios can be modeled (the analyst can also use the most bounding energetic ZOI):

- 5%: FCT based on normal supply from the auxiliary power transformer
- 95%: 4 s SBL fault (with refinement ZOI options for faster Zone 1 bus supply circuit breaker clearing times)

For BD2, up to two scenarios can be modeled (the analyst can also use the most bounding energetic ZOI):

- 5%: FCT based on normal supply from the auxiliary power transformer
- 95%: 2 s SBL fault (with refinement ZOI options for faster Zone 2 bus supply circuit breaker clearing times)

Table 10-12 shows the ZOIs for BD1, BD2, and LV ZOIs (entry for end state BDLV). The ZOI is assumed to originate from the edge of the bus duct enclosure.

Table 10-12
Energetic ZOIs for Zones BD1, BD2, and LV

End state	Power transformer and fault clearing time	Bus duct enclosure material and target fragility			
		Steel enclosure with target fragility of 15 MJ/m^2 (feet)	Steel enclosure with target fragility of 30 MJ/m^2 (feet)	Aluminum enclosure with target fragility of 15 MJ/m^2 (feet)	Steel enclosure with target fragility of 15 MJ/m^2 (feet)
BDSAT0.5 BDSBL0.5	SAT: 0–0.50 s SBL: 0–0.50 s	0	0	0	0
BDSAT1 BDSBL1	SAT: 0.51–1.00 s SBL: 0.51–1.00 s	0	0	0.5	0.5
BDSAT1.5 BDSBL1.5	SAT: 1.01–1.50 s SBL: 1.01–1.50 s	0.5	0.5	1	1
BDSAT2 BDSBL2 BDLV	SAT:1.51–2.00 s SBL: Z2 generic (≥ 2 s) and 1.51-2.00s Low voltage	1	0.5	1.5	1
BDSAT3 BDSBL3	SAT: 2.01–3.00 s SBL: 2.01–3.00 s	2	1	2.5	1.5
BDSAT4 BDSBL4	SAT: 3.01–4.00 s SBL: Z1 generic (≥ 4 s)	2.5	1.5	3	2
BDSATMAX	SAT: ≥ 4.01 s	3	2	3.5	2
BDGenFed	UAT: 0–0.5 s + GF	2.5	1.5	3	2
BDGF2	UAT: 0.51–2 s + GF	3.5	2	4	2.5
BDGF3	UAT: 2.01–3 s + GF	4	2.5	4	2.5
BDGFMAX	UAT: ≥3 s + GF	4.5	3	5	3

10.2.6 HEAFs in Iso-Phase Bus Ducts

HEAFs in the iso-phase bus duct are in HEAF zone IPBD. The counting guidance for Bin 16.2 is as follows:

Bin 16.2: HEAFs for Iso-phase Bus Ducts: There should generally be one iso-phase bus per unit (an iso-phase bus includes all three phases). If there is more than one iso-phase bus, simply count the total number of iso-phase buses per unit.

HEAFs in the IPBD are within fire ignition frequency Bin 16.1-2. The ignition frequency for 16.1-2 is in Table 10-13.

Table 10-13
Fire ignition frequency for bin 16.2

Bin	Ignition Source	Power Modes	Period	Mean	Median	5th percentile	95th percentile
16.2	HEAF for iso-phase bus ducts	AA	2000-2021	1.01E-03	2.81E-04	7.59E-07	3.28E-03

There is no change in the ZOI associated with an IPBD HEAF. The analyst should continue to use the guidance in NUREG/CR-6850, Supplement 1 [2], with the ZOI as a sphere centered on a fault point and measuring 5 ft in radius.

10.3 Conclusions

This report provides comprehensive guidance on how to treat the HEAF hazard in NPPs. The FCT and more generally the arc energy are key parameters for defining the energetic ZOI. For load centers, switchgear, and bus ducts, the conductor material (either aluminum or copper) does not affect the ZOI dimensions.

For load centers, the energetic ZOIs are smaller than the energetic ZOIs in NUREG/CR-6850 [1]. A post-HEAF ensuing fire is postulated following the energetic blast. The post-HEAF ensuing fire may be larger than the energetic ZOI, depending on the configuration. Regardless of the supply circuit breaker location (elevation and interior/exterior), load centers do not have a back or front energetic ZOI. For the smallest energetic ZOI, an interior supply circuit breaker on the lower half of the load center does not have an energetic ZOI (but a post-HEAF ensuing fire is still postulated). The largest energetic ZOI for a load center is a supply circuit breaker on the upper elevation at the end of the load center. This energetic ZOI has dimensions of 2.5 ft on the sides (no ZOI on back or front) and 2 ft vertically.

For MV switchgear, numerous ZOIs are developed to support screening and detailed analysis. Again, a post-HEAF ensuing fire is postulated immediately following the energetic phase of the HEAF. The energetic ZOI dimensions are sensitive to the backup TOC relay (51) setting of the auxiliary power transformer. Faster clearing times are not expected to challenge the energetic ZOI in NUREG/CR-6850, Appendix M [1]. The energetic ZOIs reported in NUREG/CR-6850, Appendix M, are challenged for the following:

- The 15 MJ/m^2 fragility (TP targets and aluminum-enclosed bus ducts) for fault points outside the auxiliary transformer zone of differential protection (87) (Zone 1 Loads and Zone 2)
    - UAT FCTs greater than 0.50 s
    - SAT FCTs greater than 4 s
- The 30 MJ/m^2 fragility (TS targets and steel-enclosed bus ducts) for fault points outside the transformer zone of differential protection (87) (Zone 1 Loads and Zone 2)
    - UAT FCTs greater than 3 s

For NSBD, the enclosure material (either aluminum or steel) has an impact on the ZOI dimensions. The steel enclosure requires more energy to breach the enclosure material, which results in less exposure to nearby targets. An aluminum enclosure breaches faster than steel and exposes more of the faulted conditions to nearby targets. On average, the aluminum enclosure ZOI is 0.5 ft larger than steel. Generally, the NSBD ZOIs are larger than those described in NUREG/CR-6850, Supplement 1 [2].

11
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A
SUMMARY OF U.S. HEAF EXPERIENCE

A.1 Summary of HEAF Events in the U.S. Nuclear Power Industry from 1979–2021

A summary of HEAF events in the U.S. nuclear power industry between 1979 and 2021 are presented in Table A-1. These summaries include the following:

- Event information, including the arcing fault duration, the means of extinguishment, and the suppression time
- Initiating electrical component information, including the equipment voltage, the arcing fault location, the safety class, the arc material, the EDS configuration from EPRI 3002015992 [12], the HEAF fault zone (Section 3), and the ignition source bin (Section 5)
- A summary of the event
- Summary observations on the ZOI and the HEAF subdivision (arc flash, arc blast, or HEAF)

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 195 Date: 04/15/1980 Location: Reactor Building Duration of Arc Fault: <2 s Means of Extinguishment: Unknown Suppression Time: N/A	Equipment: 480V segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum (6.9 kV) EDS Configuration: 7 Fault Zone: LVBD Bin N/A	Operating normally at 96% power, an arcing fault occurred on the feeder bus from a 480V segmented bus duct during a 4 kV shutdown bus transfer. The fault was caused by a loose busway bolt.	The board supplied by the bus was reenergized by an alternate source and was not damaged by the fault. Subdivision: Arc Flash
Incident Number: 434 Date: 08/02/1984 Location: Turbine Building Duration of Arc Fault: Unknown Means of Extinguishment: Automatic Halon System Suppression Time: N/A	Equipment: 480V Switchgear Arc Fault Location: Breaker Safety Class: Non-1E Arc Electrode Material: Unknown EDS Configuration: Unknown Fault Zone: 3 Bin 16.a	During normal operation in mode 1, a fault occurred in the 480V supply bus ACB. The cause of the fault was attributed to high resistance in the main disconnecting contacts of the center phase of the ACB, which caused an arc to propagate to the outside phases. The halon suppression system actuated. The fire brigade responded as required to verify that the fire was out.	The falling debris from the arcing fault damaged the metal enclosure of the breaker and the bus tie breaker below. The ensuing fire burned wire insulation in three cubicles of the switchgear vertical section, meter and relay covers outside the switchgear, and a few control cables in cable trays above the switchgear. Subdivision: HEAF
Incident Number: 575 Date: 03/19/1987 Location: Yard Duration of Arc Fault: 4–15 s Means of Extinguishment: Deluge Suppression System Suppression Time: 23 min	Equipment: 4.16 kV and 6.9 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 8 Fault Zone: BDUAT Bin 16.1-1	During operation at 54% power in operation condition 1, an arcing fault occurred in a NSBD, feeding the 4.1 kV and 6.9 kV loads from the UAT. The arcing event was likely caused by moisture intrusion into the bus duct. During the event, the UAT deluge system actuated.	The destructive nature of the fault hampered the investigation process, and it is not known on which bus duct (4.1 kV or 6.9 KV) the initiating fault occurred. Subdivision: HEAF
Incident Number: 922 Date: 07/10/1987 Location: Turbine Building Duration of Arc Fault: 4–15 s Means of Extinguishment: Deenergized Suppression Time: 3 min	Equipment: 4.16 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 8 Fault Zone: BDUAT Bin 16.1-1	During normal operation, an insulation failure and the resulting ground fault caused an arcing event in a 4.16-kV segmented bus duct. The bus fire terminated once the transformer was deenergized.	No other equipment was damaged. A small fire developed as a result of falling aluminum slag igniting rags and rubber goods on a maintenance cart below the duct. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 678 Date: 03/02/1988 Location: Turbine Building Duration of Arc Fault: 4–15 s Means of Extinguishment: Deenergized Suppression Time: 1 min	Equipment: 4.16 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 8 Fault Zone: BDUAT Bin 16.1-1	At 93% power for the end-of-life coast-down prior to annual refueling outage, an arcing fault occurred on a 4.16 kV bus. An insulation failure caused the fault. The differential current protection functioned as designed and opened all breakers on the affected protection zone. This deenergized the affected bus and terminated the fire.	A 10 ft section of the bus bar running from the main AT to the bus switchgear was damaged. Several non-safety-related cables in a tray adjacent to the bus bar were damaged. Subdivision: HEAF
Incident Number: 732 Date: 07/06/1988 Location: Turbine Building Duration of Arc Fault: 1.15 s Means of Extinguishment: Unknown Suppression Time: 19 min	Equipment: 13.8 kV Switchgear Arc Fault Location: Bus Bar Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 8 Fault Zone: 1 Bin: 16.b	During operation in mode 1 at 100% power, a ground fault occurred on a 13.8 kV switchgear. A breaker on the bus successfully opened in 0.34 s (no HEAF). Operations attempted to reenergize the bus 55 min later from the alternate offsite power source. The initial fault still existed, and a HEAF lasting 1.15 s occurred before the upstream breaker could open and clear the fault as designed.	Damage from the arcing fault breached the top of the switchgear cubicle and damaged nearby cubicles. The arcing fault did not damage any other equipment. Subdivision: HEAF
Incident Number: 947 Date: 01/03/1989 Location: Turbine Building Duration of Arc Fault: 4–15 s Means of Extinguishment: Manual Water Fog Suppression Time: 46 min	Equipment: 6.9 kV Switchgear Arc Fault Location: Unknown Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 1 Fault Zone: 1 Bin 16.b	During a power escalation following an earlier trip, at 26% power, an unknown equipment failure caused an arcing fault on a 6.9 kV switchgear. CO_2 fire extinguishers were used for the first time about 15 min after the fire brigade was dispatched. The fire was not suppressed. Dry chemical extinguishers were used 8 min after the CO_2 extinguishers. The fire was not suppressed. Eighteen minutes after the dry chemical extinguishers were used, the fire brigade decided to use water fog on the fire. The fire was reported out 15 min later.	Internal components in the switchgear caught fire. Cables near the switchgear fire caught fire. The rear cubicle door was blown off by the arcing event. Evidence suggests that the event could have damaged any target located within 3 ft. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 929 Date: 10/09/1989 Location: Turbine Building Duration of Arc Fault: 4–15 s Means of Extinguishment: Deluge Suppression System Suppression Time: 68 min	Equipment: 22 kV iso-phase bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 6 Fault Zone: IPBD Bin 16.2	During operation at 100% power, an electrical fault occurred on a 22 kV iso-phase bus duct. The fault resulted from aluminum debris in the bus duct from previous failures of the duct-cooling system dampers. Three fires occurred an oil fire at the main power transformer, a hydrogen fire, and a small oil fire in the generator housing. Actuating a deluge suppression system (main power transformer) and using dry chemical extinguishers suppressed the ensuing fires.	The initial fault caused three ensuing fires: 1) a transformer oil fire, 2) a hydrogen fire under the main generator, and 3) a small oil fire in the generator housing. Subdivision: HEAF
Incident Number: 18 Date: 07/13/1990 Location: Auxiliary Building Duration of Arc Fault: Unknown Means of Extinguishment: N/A Suppression Time: N/A	Equipment: 4 kV Switchgear Arc Fault Location: Breaker Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 8 Fault Zone: 1 Bin N/A	At mode 5 for a scheduled refueling outage, an arcing fault occurred when a contract electrician made contact with incoming feed cables in the back of a 4 kV breaker cubicle. The workers involved may not have known the feed lines were still energized, despite the fact that the bus feed breakers remained energized when the load side was deenergized and the breaker was racked out. The fire brigade responded to the event and found no fire.	The electrician who made contact with the feed cables was killed. The fault injured three other people in the area. Subdivision: Arc Flash

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 74 Date: 06/10/1995 Location: Turbine Building Duration of Arc Fault: 4–15 s Means of Extinguishment: Fire Brigade, Fire Extinguishers Suppression Time: 80 min	Equipment: 4.16 kV Switchgear Arc Fault Location: Breaker Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 6 Fault Zone: 1 Bin 16.b	During operation in mode 1 at 100% power, an arcing fault occurred in a 4.16 kV switchgear because of an improper automatic bus transfer from the UAT to the SUT. Twenty-nine minutes after an operator noticed smoke in the turbine-generator building, a fire was reported above the switchgear. The fire brigade attempted to extinguish the fire using halon, CO_2, and dry chemical extinguishers. Forty-three minutes after the initial attempt to extinguish the fire with fire extinguishers, the off-site fire department applied water to the insulation above the bus.	Damage to the breaker and surrounding equipment indicated an extremely high fault energy. The arc chutes were destroyed, the contact structures were damaged extensively, and the breaker frame and cubicle were also damaged. The main bus and bus compartment experienced severe arcing damage. The main contacts on all the phases were destroyed. Significant damage to two switchgear cubicles occurred. Ten feet of the feeder cable was destroyed. External thermal damage to the jackets of 4 of the 15 feeder cables was observed. Burn marks were observed on external cable conduits. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 100 Date: 05/15/2000 Location: Turbine Building Duration of Arc Fault: 4–8 s Means of Extinguishment: Fire Brigade, CO_2 extinguisher Suppression Time: 35 min	Equipment: 12 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 1 Fault Zone: BDUAT Bin 16.1-1	During operation at 100% power, a phase-to-phase arcing fault occurred on the 12 kV bus between the UAT and a nonvital switchgear. The cause of the fault could not be conclusively determined. The fault continued to be fed for 4–8 s by the decay of the main generator electrical field during generator coast-down, contributing to catastrophic failure of the bus bars. The fire brigade arrived at the switchgear room and determined that the fire was internal to the switchgear room and not associated with the UAT. Given the large amount of smoke, the fire brigade captain requested off-site fire brigade support. The fire brigade extinguished a small fire in the 12 kV bus duct with a CO_2 extinguisher within 17 minutes of arriving at the switchgear room.	Approximately 3 ft of the 12 kV bus bar was vaporized and approximately 6–9 in. of the exterior bus bars were missing. The bottom and top of the bus duct were melted for several feet, as were sections of the duct work on the perpendicular 12 kV bus sections at the tee connection. The ensuing fire burned an approximately 1 ft square hole in the bottom of a second 4 kV bus duct 4 in. above the 12 kV bus duct. The 4 kV bus bars and duct were covered with black soot, but the only conductor damage was a small piece of metal missing from the center bus bar and one outer bus bar, which is indicative of a single phase-to-phase fault. The floor beneath the fault contained a large slag pile, and a great deal of metal had splattered on the face of 12 kV nonvital switchgear, which were not damaged internally. Smoke patterns on the cabinet doors indicate that plastic components on the cabinet faces (e.g., gauge faces, identifier tags, and indicator lamp housings) ignited and burned during the event. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 106 Date: 02/03/2001 Location: Switchgear Room Duration of Arc Fault: 4–15 s Means of Extinguishment: Fire Brigade, Water Suppression Time: 31 min	Equipment: 4.16 kV Switchgear Arc Fault Location: Breaker Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 8 Fault Zone: 1 Bin 16.b	During a unit startup following a refueling outage, at approximately 39% power, a breaker faulted for an unknown cause and started a fire within the breaker cubicle upon switching from the RAT to the UAT. Fire brigade members unsuccessfully attempted to suppress the ensuing fire with fire extinguishers. The fire was eventually suppressed using water. Ionized gases and smoke diffused through cable passages between adjacent cubicles and entered the RAT feeder breaker cubicle. The fire consumed much of the breaker's nonmetallic parts and caused substantial melting of current-carrying components. Five cabinets in the bus were replaced/rebuilt, including the replacement of electrical equipment and cables that the fire either burned directly or damaged.	The entire switchgear bus was damaged. The back cabinet wall was blown open. Three trays above the cabinet were damaged, primarily by the ensuing fire. The trays were located 2 ft, 6 ft, and 7.5 ft above the top of the cabinet. A front cabinet located 4.5 ft away was also thermally damaged. Damage included doors and protective relays. Smoke penetrated other cabinets and required cleaning. Subdivision: HEAF
Incident Number: 112 Date: 08/03/2001 Location: Turbine Building Duration of Arc Fault: 4–15 s Means of Extinguishment: Fire Brigade Suppression Time: 90 min	Equipment: 4 kV Switchgear Arc Fault Location: Breaker Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 8 Fault Zone: 1 Bin 16.b	During an orderly startup of unit 1 following a reactor trip, at approximately 25% power, a breaker on a 4 kV switchgear failed because of overheating of the primary disconnect assemblies. Approximately 1.5 hours after the initial breaker failure, the plant fire brigade extinguished the fire with help from the local fire department.	The front of the cabinet was blown open. Several inches of the feed stabs were completely vaporized. The ensuing fire damaged an adjacent breaker. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 127 Date: 06/18/2004 Location: Yard: Main Transformer Low Voltage Bushing Box Duration of Arc Fault: 4–15 s Means of Extinguishment: Fire Brigade Suppression Time: 37 min	Equipment: 22 kV iso-phase bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 4 Fault Zone: IPBD Bin 16.2	A two-phase electrical fault-to-ground occurred on the 22 kV system. The B phase faulted to ground in the LV bushing box on top of the main transformer. The A phase faulted to ground in the surge arrester cubicle of the generator PT cabinet through the A-phase surge arrester. The C phase was involved 400 ms later (arcing and ionization from the B phase). The electrical grounds that initiated the event were cause by loose material in the B iso-phase bus duct as a result of the failed flexible connector that allows the iso-phase bus to thermally expand and contract.	Damage from this event was limited to major portions of the iso-phase bus and the LV main transformer bushings. The main transformer and the main generator were not damaged. Subdivision: HEAF
Incident Number: 10584 Date: 07/27/2008 Location: Cooling Towers Duration of Arc Fault: <2 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 4 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 7 Fault Zone: BDSAT Bin 16.1-1	During operation at mode 1, an arcing fault occurred on a 4 kV segmented bus duct. A current overload of the flexible connections at the expansion joints likely caused the fault.	Damage was identified as failed buswork between a cooling tower transformer and the cooling tower switchgear. Warping of the duct enclosure occurred. Subdivision: Arc Blast
Incident Number: 162 Date: 08/05/2009 Location: Turbine Building Duration of Arc Fault: 4–15 s Means of Extinguishment: Not specified Suppression Time: 21 min	Equipment: 6.9 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 3 Fault Zone: BDUAT Bin 16.1-1	During operation at 100% power, an electrical fault occurred on a 6.9 kV non-segregated bus. A relaxation of bolted connections on the center phase flexible link(s) caused by repeated thermal cycles over time likely caused the fault. The root cause for this event was identified as a failure to perform preventive maintenance tasks for torque checks of non-segregated bus links.	The explosion melted and removed approximately 4 ft of each of the three busses and 8 ft the bus duct. This bus duct hung at approximately 15 ft above finished floor. Shrapnel (molten aluminum) and debris were thrown in the general vicinity. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 50909 Date: 03/07/2010 Location: Yard Duration of Arc Fault: <0.75 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 13.8 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 8 Fault Zone: BD1 Bin 16.1-2	During operation at 100% power, an electrical fault occurred on a 13.8 kV non-segregated bus. The fault likely resulted from water intrusion made possible by the cracking of bus bar polymer insulation due to environmental factors.	The internal bus work was damaged, and the external protective structure was distorted from the fault. A large hole in the middle of the back side of the Calvert bus enclosure (facing the turbine building) and a smaller hole facing south toward the Unit 1 Operations Support building were observed. Subdivision: Arc Blast
Incident Number: 50910 Date: 03/28/2010 Location: Turbine Building Duration of Arc Fault: 20 s and 180 s Means of Extinguishment: Fire Brigade Suppression Time: 39* min *The suppression time for the first event is estimated using the description of other actions that took place during the HEAF event. The effect this assumed time has on the suppression rate calculation is insignificant; whether the suppression time was found to be 1 min or 60 min, the change in the suppression rate calculated per Section 5.4 would only change by ± 0.001.	Equipment: 4 kV Switchgear Arc Fault Location: Breaker Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 5 Fault Zone: 1 Bin 16.b	During operation in mode 1 at 99.5% power, a feeder cable to a 4 kV nonvital bus experienced an arcing fault. The following two counted HEAFs were associated with this event: 1) An initial fault on the 4 kV bus 5 supply due to a failure in cable insulation. 2) A second fault on the 4 kV bus 4 was caused by operators improperly resetting the main generator lockout relay with a trip signal still present and reinitiating a fault on the same breaker.	The initial fault caused electrical fires that damaged bus feeder cable above the bus 5 switchgear. There was evidence of some thermal impact to the ceiling approximately 5 ft above the switchgear and to the cables in a tray located approximately 3–5 ft horizontally from the fault location in the bus cable above bus 5. The second arc flash breached the rear of the cubicle in bus 4 and caused blast debris damage to surrounding components. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 50926 Date: 02/12/2011 Location: Cooling Tower Switchgear Building Duration of Arc Fault: 12 s Means of Extinguishment: Deenergized Suppression Time: 31 min	Equipment: 480V segmented bus duct Arc Fault Location: Safety Class: Non-1E Arc Electrode Material: Unknown EDS Configuration: 8 Fault Zone: BD2 Bin 16.1-2	During the process of raising reactor power (at approximately 20%) following refueling, an arcing fault occurred in a 480 V segmented bus duct. Due to significant damage to the bus, conclusive determination of the cause of the fault was limited; however, it was likely due to a relaxation of torque at the connection joint caused by repeated thermal cycles over time. A failure of the lockout relay to trip the circuit breaker extended the fault duration. The main control room received a smoke detector alarm in the cooling tower switchgear room. The fire brigade was dispatched. The breaker feeding the faulted bus had to be manually tripped and the smoke dissipated following the bus deenergization.	Significant bus, cable, and switchgear damage occurred. Subdivision: HEAF
Incident Number: 50935 Date: 06/07/2011 Location: Auxiliary Building Duration of Arc Fault: 41 s Means of Extinguishment: Automatic Halon System Suppression Time: N/A	Equipment: 480V Switchgear Arc Fault Location: Breaker Safety Class: 1E Arc Electrode Material: Copper and Aluminum EDS Configuration: 8 Fault Zone: 3 Bin 16.a	The plant was fully depressurized, operating in mode 5 during a refueling outage. An AC ground fault occurred in a load center. The most probable cause of the fault was a high-resistance connection on the line side of the load center circuit breaker cubicle. Automatic halon discharge suppressed the fire.	Catastrophic failure of the feeder breaker occurred. The fire produced a large quantity of soot and smoke. Conductive smoke caused arcing between the bus bars and island bus. Subdivision: HEAF
Incident Number: 51256 Date: 06/13/2013 Location: Reactor Building Duration of Arc Fault: 0.12 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 13.8 kV Switchgear Arc Fault Location: Breaker Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 8 Fault Zone: 1 Bin N/A	During operation in mode 4 at 0% power, an arcing fault occurred on a 13.8 kV feeder bus bar breaker. No conclusive evidence pointed to a single cause leading to the arcing fault. Equipment protective relay schemes operated as expected.	Damage was limited to the cubicle in which the fault initiated. Damaged components were replaced. Subdivision: Arc Flash

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 51194 Date: 07/03/2013 Location: Turbine Building Duration of Arc Fault: 0.75 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 13.8 kV Bus in Source Cabinet Arc Fault Location: Manual Load Interrupt Switch (Load Section) Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 8 Fault Zone: 1 Bin N/A	During operation at full power, an arcing fault on the disconnect bus bar into a cabinet blew the rear access door and shattered the front inspection window of the cabinet. The arcing fault was due to an uninsulated cable shield wire coming loose because of an age-related failure of the plastic cable ties.	The cabinet containing the faulted bus bar sustained damage consistent with a pressure event (bowed cabinet wall, rear door blown off, and broken inspection window). No other equipment was damaged. A support bar located in the path of the blown-off rear inspection door was damaged, but the adjacent cabinet was not damaged. No ensuing fire occurred. Subdivision: Arc Blast
Incident Number: 51199 Date: 07/26/2013 Location: Turbine Building Duration of Arc Fault: 10 s Means of Extinguishment: Fire Brigade Suppression Time: 29 min	Equipment: 25 kV isophase bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 8 Fault Zone: IPBD Bin 16.2	During operation at 100% power, an arcing fault occurred on the UAT iso-phase feed-through bushing and the main generator neutral connection box. The cause was electrical shorting resulting from a failed cooling backdraft damper blade entering the bus duct. The fire brigade suppressed the ensuing fires within 30 min.	Significant damage to the bus duct occurred. The fault ignited a small cable insulation and oil fire. Subdivision: HEAF
Incident Number: 51291 Date: 12/09/2013 Location: Turbine Building Duration of Arc Fault: About 6 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 6.9 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 3 Fault Zone: BDUAT Bin 16.1-1	During operation in mode 1, a failure in a fusible link attached to a 6.9 kV NSBD resulted in a phase-to-ground arcing fault. The protective relays did not function properly (lifted trip logic leads), resulting in the catastrophic failure of the UAT. The root cause of the fault is not conclusively known because the fusible link was vaporized during the fault. However, improper installation of the fusible links and subsequent degradation of the flex connections likely caused the fault. The fire brigade suppressed the UAT fire with a foam suppression agent.	The fault in the 6.9 kV non-segregated bus blew out and caused a phase-to-phase fault in the 4.16 kV bus duct located directly below the 6.9 kV bus duct. The failure extended to and caused an exposition/fire in the site UAT. Subdivision: HEAF

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: N/A Date: 02/07/2016 Location: Switchgear Area Duration of Arc Fault: 0.15 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 4.16 kV Switchgear Arc Fault Location: Bus Bar Cable Safety Class: Non-1E Arc Electrode Material: Copper EDS Configuration: 3 Fault Zone: 1 Bin N/A	During operation at 88% power in mode 1, a fault occurred in a 4.16 kV switchgear during an end-of-cycle coast-down. The fault occurred where cable insulation was found to be degraded.	Evidence of an electrical explosion was observed (cubicle door was deformed). No other damage was observed. No ensuing fire occurred. Subdivision: Arc Blast
Incident Number: 51764 Date: 01/17/2017 Location: Yard Duration of Arc Fault: 1 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 4.16 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 3 Fault Zone: BDSAT Bin 16.1-1	During operation at 100% power, an arcing fault occurred in a 4.16 kV NSBD. The fault was likely due to a degradation of insulation. Following annunciation of transformer undervoltage, an operator using thermal imaging reported discoloration and elevated temperatures of the bus duct.	Damage was limited to tracking along the bus support insulators. No equipment outside the bus duct was damaged. Subdivision: HEAF
Incident Number: N/A Date: 03/18/2017 Location: Turbine Building Duration of Arc Fault: 0.6 s Means of Extinguishment: Self-extinguish Suppression Time: N/A	Equipment: 4 kV Switchgear Arc Fault Location: Main Bus Bar Safety Class: 1E Arc Electrode Material: Copper EDS Configuration: 2 Fault Zone: 1 Bin N/A	An arcing fault occurred on the current-limiting reactor coil of a 4 kV switchgear. No flames were observed by initial responders. This event is notable in that a fire door credited as part of the fire barrier to an adjoining fire zone was found to have been damaged by the pressure wave caused by the blast.	Equipment damaged by this event was limited to the switchgear cubicle of origin. A worker who was inside the room during the event was injured, and a fire door separating an adjacent fire zone was damaged. No ensuing fire occurred. Subdivision: Arc Blast

Table A-1
Summary of HEAFs in the U.S. nuclear power industry, 1979 through 2021 (cont.)

Event Information	Initiating Electrical Component	Summary of Event	Event Zone of Influence
Incident Number: 51765 Date: 12/16/2020 Location: Turbine Building/Reactor Aux Building Wall Penetration Duration of Arc Fault: 15 s Means of Extinguishment: Multicycle sprinkler suppression system Suppression Time: N/A	Equipment: 6.9 kV segmented bus duct Arc Fault Location: N/A Safety Class: Non-1E Arc Electrode Material: Aluminum EDS Configuration: 6 Fault Zone: BDUAT Bin 16.1-1	During operation at 100% power, an arcing fault occurred in a 6.9 kV NSBD powered from the UAT 1B X winding that was a penetration between the turbine building and the reactor auxiliary building. The UAT differential protection immediately detected the phase-to-phase fault and initiated a main generator lockout and trip of the unit. This was a generator-fed HEAF. The root cause was an inadequate weathertight seal at the bus duct penetration throat, resulting in water intrusion and insulation degradation.	Significant damage to the bus duct occurred. Debris, soot, and slag impacted a nearby cable tray. The tray was cleaned and inspected. No cables were electrically damaged, but cables with outer jacket damage from molten slag were repaired through splicing. Subdivision: HEAF

Table A-2
Fire event data

Fire ID	Event Data	Location	Ignition Source	Power Mode	Fire Severity	Bin Designation	NSP Category	Suppression Time (minutes)
Old 434	08/02/1984	Plant-wide components	HEAF low-voltage electrical cabinet (480–1000V)	Power operation	CH	16.a	N/A	Excluded (halon discharge)
Old 575	03/19/1987	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	23
Old 922	07/10/1987	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	3
Old 678	03/02/1988	Plant-wide components	Bus duct	Power operation	CH	16.1-1	N/A	Excluded (self-extinguished)
Old 732	07/06/1988	Plant-wide components	HEAF MV electrical cabinet (>1000V)	Power operation	CH	16.b	HEAF	19
Old 947	01/03/1989	Plant-wide components	HEAF MV electrical cabinet (>1000V)	Power operation	CH	16.b	HEAF	46
Old 929	10/09/1989	Plant-wide components	Iso-phase bus duct	Power operation	CH	16.2	HEAF	68
20284	10/14/1991	Plant-wide components	Transformers	Refueling	U	23 [20]	Electrical	2
74	06/10/1995	Plant-wide components	HEAF MV electrical cabinet (>1000V)	Power operation	CH	16.b	HEAF	80
100	05/15/2000	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	35
106	02/03/2001	Plant-wide components	HEAF MV electrical cabinet (>1000V)	Power operation	CH	16.b	HEAF	31
112	08/03/2001	Plant-wide components	HEAF MV electrical cabinet (>1000V)	Power operation	CH	16.b	HEAF	90
127	06/18/2004	Plant-wide components	Iso-phase bus duct	Power operation	CH	16.2	HEAF	37
10584	07/27/2008	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	N/A
162	08/05/2009	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	21

[20] This event was binned as a HEAF (16.b) in NUREG-2169. After more details were received on this source, it was determined that this was a dry transformer (and not switchgear).

Fire ID	Event Data	Location	Ignition Source	Power Mode	Fire Severity	Bin Designation	NSP Category	Suppression Time (minutes)
50909	03/07/2010	Plant-wide components	Bus duct	Power operation	CH	16.1-2	HEAF	N/A
50910 Event 1	03/28/2010	Plant-wide components	HEAF MV electrical cabinet (>1000V)	Power operation	CH	16.b	HEAF	39
50910 Event 2	03/28/2010	Plant-wide components	HEAF MV electrical cabinet (>1000V)	Shutdown	CH	16.b	HEAF	24
50926	02/12/2011	Plant-wide components	Bus duct	Power operation	CH	16.1-2	HEAF	31
50935	06/07/2011	Plant-wide components	HEAF LV electrical cabinet (480–1000V)	Cold shutdown	CH	16.a	N/A	Excluded (halon discharge)
51199	07/26/2013	Plant-wide components	Iso-phase bus duct	Power operation	CH	16.2	HEAF	29
51291	12/09/2013	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	N/A
51764	01/17/2017	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	N/A
51765	12/16/2020	Plant-wide components	Bus duct	Power operation	CH	16.1-1	HEAF	N/A (sprinkler activation)

B
DISPOSITION OF MOTOR CONTROL CENTERS

NUREG/CR-6850, Supplement 1 [2], (FAQ 06-0017) provided the following guidance on considering HEAFs for motor control centers (MCCs):

> *Only MCCs with switchgear that is used to directly operate equipment such as load centers should be counted as HEAF sources.*

The working group concluded that the statement's original intent was to differentiate between an MCC and an LV switchgear (defined as a load center). The term "load center" has not been consistently defined; historically it was a marketing term for a plug-in breaker. Similarly, some manufacturers have labeled an LV switchgear as an MCC. Throughout this report, load centers are defined as LV switchgear where all supply and loads breakers are LV-powered circuit breakers. The latter are counted as Bin 16.a HEAFs.

MCCs are commonly supplied for smaller 480 VAC (and potentially 600 VAC) loads, where a combination MCCB, thermal overload (TOL), and National Electrical Manufacturer's Association (NEMA) motor starter (contactor) is housed in an individual compartment frequently referred to as an "MCC bucket." MCCs (and their buckets) are smaller and less expensive than load centers because load currents are significantly less than those of the upstream load center (e.g., smaller horsepower motors). MCCBs are for load and cable short circuit protection only and can only be manually switched locally because the NEMA motor starter/contactor is used to control motor stopping, starting, or reversing (e.g., motor-operated valve [MOV]). In many cases, the power supply breaker to the MCC is a remote load center circuit breaker. The MCC may not have a supply breaker (e.g., for operator tagging clearance purposes, the MCC is isolated at the load center circuit breaker). Therefore, all other MCC breakers are typically MCCBs with instantaneous settings.

In contrast, load centers are a form of switchgear used at the LV level (<1000 VAC). Circuit breakers in load centers are referred to as LVPCBs and resemble and operate similar to MV switchgear breakers. They can be remotely operated, have shunt trips, and have larger arc chutes to quench higher levels of fault current.

The control power arrangement for MCCs is different than that of load centers (LV switchgear). Load centers use separate, external dc power from the station batteries. MCC control power is self-powered. The MCC taps two of the three phases of the 480 VAC power circuit and reduces the control voltage to 120 VAC via a control power transformer (CPT). A small number of MCCs have been identified in U.S. NPPs that use a LVPCB for the MCC primary and alternate supply. These breakers are local and integral to the MCC. These breakers do not contain an instantaneous element for coordination purposes with the downstream load breakers. These MCCs are supplied from an intermediary load center and are not directly supplied from the step-down transformer; therefore, they should be treated as MCCs and not load centers.

Arc faults have occurred in MCCs in U.S. NPP operating experience; however, none have been observed at the severity of HEAFs in load centers or switchgear. The many likely reasons for this include the following:

- Load MCCB IOC (50) settings significantly limit fault energy.
- MCCBs do not require external control power to initiate overcurrent protection and are generally more reliable.
- Load MCCBs have two backup breakers (MCC supply and load center supply).
- If a supply breaker exists in an MCC, it has at least one backup breaker (load center breaker).
- Less fault energy is available at the entry level of MCCs.

The limited fault energy and design difference of MCCs compared to load centers (LV switchgear) are factors in the absence of MCC HEAFs. This is consistent with the guidance in NUREG/CR-6850, Supplement 1 [2], (FAQ 06-0017) to not include MCCs in the consideration of HEAF sources. Load centers (LV switchgear) as differentiated in the above discussion are considered HEAF sources.

C
EXPERT PANEL FOR MEDIUM VOLTAGE SWITCHGEAR HEAFS

C.1 Objective and Scope

MV switchgear HEAFs (Bin 16.b) in Zone 1 and Zone 2 of the EDS require expert judgment to establish certain scenario probabilities. The HEAF events corresponding to Zones 1 and 2 were initially examined together for this expert judgment activity. During the HEAF operating experience review, the working group determined that the majority of events occurred in Zone 1 (see explanation and basis in Section 5.2.2.1) and assigned the ignition frequency to Zone 1 and Zone 2 based strictly on operating experience (86% for Zone 1, 14% in Zone 2). Contrary to NUREG/CR-6850, switchgear are no longer counted by vertical section; instead they are counted by switchgear bank (see explanation and basis in Section 5.2.2.2). To determine the probabilities of HEAFs within the switchgear bank, an expert judgment process is used to determine the end state likelihood. Expert judgment is used to define the split fractions where the HEAF is likely to occur within the switchgear. This appendix further describes the concepts, expert panel input, discussion, and results.

C.2 Expert Panel Composition

The expert panel consisted of experts in PRA, fire protection engineering, and electrical engineering. The following working group members supported the expert panel:

- T. Dinh, NRC-NRR
- K. Fleischer, retired NextEra
- J.S. Hyslop, NRC-NRR
- D. Lovelace, Jensen Hughes
- P. S. Lovvorn, TVA
- A. Lindeman, EPRI
- N. Melly, NRC-RES
- G. Taylor, NRC-RES

C.3 Expert Panel Input

On the PRA method subgroup call on October 7, 2020, the working group decided to obtain expert input to determine the likelihood of HEAFs within the switchgear bank. Prior to this call, event trees were developed describing the possible HEAF end states for Zone 1 and Zone 2 MV switchgear. An Excel sheet was distributed (see Figure C-1) for experts to document the numbers and basis assigned for both the vertical section and ZOI event tree headings.

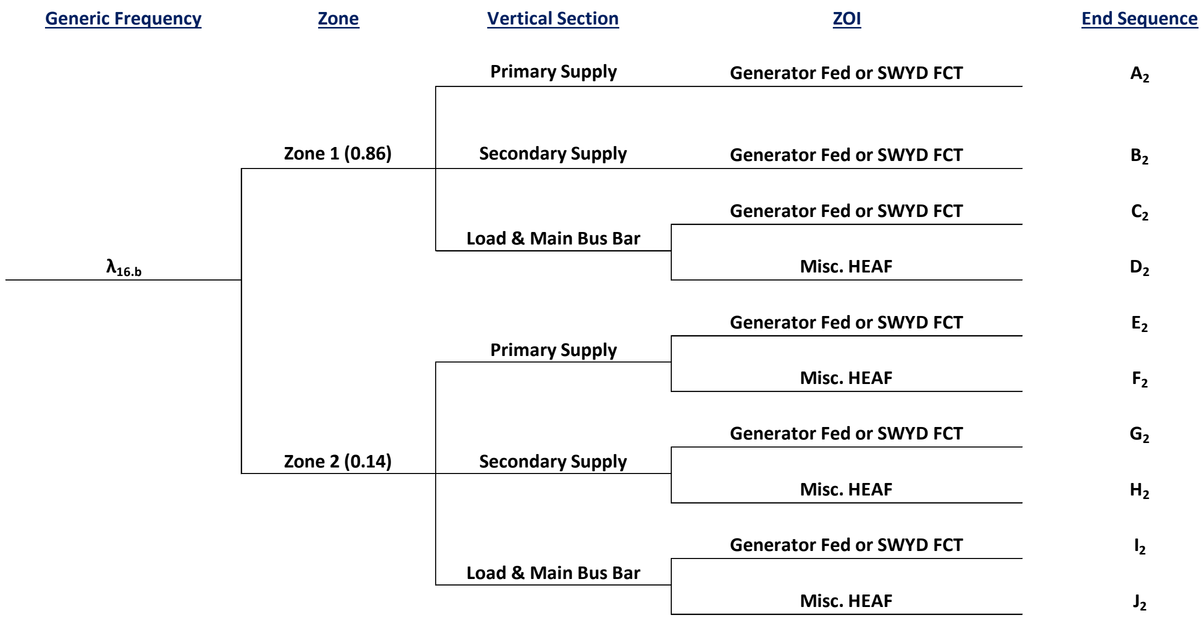

Figure C-1
Initial event tree sent out for working group expert panel

C.4 First Panel Meeting

On October 14, 2020, the PRA method subgroup met to discuss each member's input and basis. Each working group member supporting the expert panel was requested to fill out the event tree in Figure C-1 and provide a basis for their estimates. Table C-1 reports the initial numbers provided by each working group member. Table C-2 provides additional documentation for the numbers reported.

Table C-1
Initial input received from working group members (WGM)

Top Event or End State	WGM 1	WGM 2	WGM 3	WGM 4	WGM 5	WGM 6	WGM 7	WGM 8
Vertical Section in Zone 1	0.6/0.2/0.2*	0.8/0.2*	0.9/0.1*	0.567/0.283/0.15*	0.75/0.25	0.57/0.29/0.14*	0.8/0.2*	0.85/0.15*
Power Transformer/SBL (Zone 1)	0.25/0.75	Not provided	0.1/0.9	0.0525/0.9475	Not provided	Not provided	0.1/0.9	0.667/0.333
End State A	0.6 or 0.2	Not calculated	Not calculated	0.567	Not calculated	0.57	0.4	0.425
End State B	0.2 or 0.6	Not calculated	Not calculated	0.283	Not calculated	0.29	0.4	0.425
End State C	0.05	Not calculated	0.01	0.008	Not calculated	0.014	0.02	0.1
End State D	0.15	Not calculated	0.09	0.14	Not calculated	0.126	0.18	0.05
Vertical Section in Zone 2	0.4/0.4/0.2	0.8/0.2*	0.9/0.1*	0.567/0.283/0.15*	0.75/0.25	0.45/0.45/0.1	0.8/0.2*	0.85/0.15*
Power Transformer/SBL (Zone 2)	0.025/0.975 and 0/1.0	Not provided	Not provided	0.0275/0.9725	Not provided	0.01/0.99	0.03/0.97	0.5/0.5 and 0.333/0.667
End State E	0.01	Not calculated	Not calculated	0.016	Not calculated	0.0045	0.012	0.2125
End State F	0.39	Not calculated	Not calculated	0.55	Not calculated	0.4455	0.388	0.2125
End State G	0.01	Not calculated	Not calculated	0.008	Not calculated	0.0045	0.012	0.2125
End State H	0.39	Not calculated	Not calculated	0.28	Not calculated	0.4455	0.388	0.2125
End State I	0	Not calculated	Not calculated	0.004	Not calculated	0.001	0.006	0.05
End State J	0.2	Not calculated	Not calculated	0.15	Not calculated	0.099	0.194	0.1
Notes	*Primary supply gets larger frequency	*Primary feed gets the supply frequency	*Primary feed gets the supply frequency	*Primary supply gets larger frequency	The supply split is determined by the plant-specific feed (UAT or SAT)	*UAT/SAT/load split based on OPEX	*Supply split evenly	*Supply split evenly

Table C-2
Basis for input provided in Table C-1

Expert	Part of Event Tree	Basis or Explanation
WGM 1	General	Zone 1 end states should be different based on the normal supply or feed to the switchgear. If supplied from the SAT, there should be a higher fraction of fires assigned to the SAT (but the UAT side should also see a fraction of fires to account for switching alignments). Likewise, if normally supplied by the UAT, the opposite is true. So, I made two splits (one based on UAT normally aligned and one based on SAT normally aligned). This concept allows the methodology to account for actual plant lineups as noted in the EPRI EDS HEAF whitepaper (a design fed off the SAT is less likely to see a generator-fed fault). Most Zone 1 experience is likely to be in the supply cubicle due to switching, past operating experience, and in some cases, single-point vulnerabilities.
	Zone 1 – Normally supplied by UAT	End state A (Generator-fed fault): 0.6 (Qualitative ranking: highest; one breaker away from generator-fed fault) End state B (FCT duration): 0.2 (Qualitative ranking: high; one breaker away from SAT fault) End states C and D: Load vertical section: 0.2 (remainder of vertical section to sum to 1), ZOI split fraction (0.25 Gen Fed/FCT duration/0.75 SBL) End State C: 0.05 (Qualitative ranking: low; 2 breakers away from generator-fed fault) End State D: 0.15 (Qualitative ranking: medium; fault can occur in main bus bar, which would require supply breaker to interrupt)
	Zone 1 – Normally supplied by SAT	Same as above except that SAT supply: 0.6 and UAT supply 0.2. End States C and D are same.
	Zone 2	End state E: 0.01 (Zone 2 supply fault interrupted by Zone 1—2 (possibly 3) breakers away from gen-fed fault) End state F: 0.39 (Zone 2 SBL) End state G: 0.01 End state H: 0.39 End state I: 0 (unlikely to see a generator-fed fault this far down in Zone 2) End state J: 0.2

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
WGM 2	General	Assumptions: Still splitting frequency by bank Using Bayes with a non-informed prior and OPEX data results in similar estimates. Rounded for convenience.
	Zone 1 and Zone 2 supply	Supply (including both UAT and SAT): 80% Loads: 20% Modified event tree because I do not feel that we should specify the fraction of frequency that goes to the specific supply. Leave that up to the plant. If their normal configuration is powered from the SAT, then the frequency goes there. If there is some split between the SAT/UAT or if we need to account for fast transfer failures, then we could specify the method to address. I don't see much value in assigning x% of frequency to supply a component that is not operational for the majority of the time.
WGM 3	General	1. Agree with WGM 2 idea of treatment of UAT/SAT on vertical section top event. 2. 90/10 split reflects strong preference for supply overload for vertical section top event. Based on earlier discussions, feel like expert judgment should be sorted into very high likelihood, very low likelihood, or really uncertain. 3. Unsure about Zone 2 ZOI split. Working group is split on event characterization with respect to duration for Zone 2. 4. For Zone 1 ZOI split, according to discussions, SBL for load is very dominant and I have assigned it very high likelihood. 5. My understanding is that generator-fed or FCT duration means large HEAF; SBL means small HEAF.
	Vertical section top event	Supply (including both UAT and SAT): 90% Loads: 10%
	ZOI top event	ZOI branch between C and D is 10% generator-fed or SWYD FCT, and 90% short duration
WGM 4	General	Duration discussion: I would like to see the working group, for now, limit the ZOI end states to either short duration (breach up to something like 4 seconds) and long duration (bolted fault current greater than 4 seconds). Until we see the ZOIs, we really do not know the practical usefulness of breaking up ZOIs any more than this. Once the ZOI information is available, then we could make better judgments about the usefulness of different ZOI end states.

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
WGM 4	Vertical section top event (applicable for Zone 1 and 2)	Supply (UAT): 56.67%; assuming this is the normal supply. The normal supply breaker should get more frequency than the alternate. The HEAF frequency for switchgear supply breakers is largely dependent on the breaker operations. The switchgear is likely to be taken out of service without transferring to alternate for maintenance. This configuration change would operate the normal supply breaker without operating the alternate supply breaker. My engineering judgment is a 2:1 split. Using an 85% supply to 15% load split, the normal supply is given 0.85 × 2/3 for the frequency split. NOTE: It should be noted that this event tree is an example for Zone 2 with a normal from the UAT and a single alternate from the SAT. If there are more or less supplies, the frequency must be apportioned accordingly. Supply (SAT): 28.33%; assuming this is the alternate supply. The normal supply breaker should get more frequency than the alternate. The HEAF frequency for switchgear supply breakers is largely dependent on the breaker operations. The switchgear is likely to be taken out of service without transferring to alternate for maintenance. This configuration change would operate the normal supply breaker without operating the alternate supply breaker. My engineering judgment is a 2:1 split. Using an 85% supply to 15% load split, the alternate supply is given 0.85 × 1/3 for the frequency split. Loads: 15%; the HEAF OPEX is dominated by supply breaker events. Using an 85% supply to 15% load split based on OPEX and engineering judgment.
	ZOI top event (end states C and D)	Zone 1 loads – generator fed: 5.25%; in order for the downstream breaker to experience a long-duration HEAF, the upstream breaker must fail to interrupt the fault fast enough to prevent the long-duration HEAF. The upstream breaker is typically set higher than the downstream breaker to achieve proper selective coordination and, therefore, does not provide 100% redundant protection. Thus, the likelihood is not solely limited to the breaker random-failure probability. The delay time for the supply breaker to trip if the load breaker fails is difficult to predict and depends on multiple factors: 1. Supply breaker protection available – Many utilities have board differential protection. This protection checks whether the current flowing into a board should equal the summation of all the currents flowing out of the board. If a switchgear has board differential protection and that protection is not failed by the fault or by random failure, the fault would be interrupted very quickly (cycles) and there would be no HEAF. For cases where board differential is successful, those events are already excluded from the base HEAF frequency. Therefore, the board differential protection availability is not considered further. It is assumed that faults within the board differential protection, where available, do not produce a HEAF end

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
WGM 4	ZOI top event (end states C and D) (cont.)	state. Therefore, the supply breaker protection that is being relied upon here is the 50 instantaneous and/or 51 (time overcurrent) where available. So, the first consideration is the load breaker may have a 50 and 51 trip device, but the supply breaker may not have a 50 trip device and only 51 protection. If the supply breaker has both 50 and 51 protection, the likelihood of a long duration HEAF, in theory, would be lower. The factors below assume only a 51 device is available on the upstream breaker. *Supply breaker protection settings – The 51 trip protection setting is set higher than the load breakers to achieve proper selective coordination. How low the supply breaker protection can be set is limited by the clearing time of the load protection device and a safety margin or it may be limited by the need to start and accelerate the largest connected load on top of the board running load so that there are not spurious trips of the supply breaker. For the time delta comparison between the supply and the larger loads, a time delay of 2–3 seconds for a bolted fault can be expected based on sample reviews. It is expected that available supply breaker protection would prevent a long duration HEAF unless there is a non-optimal setting for the supply breaker protection or significantly different shaped curves where faults of different impedance might have more significant delays. Engineering judgment used to establish this factor at 2.5%. 2. Failure of the supply breaker protection = random failure 0.25% [NUREG/CR-6928, Table 5-13] + HEAF induced failure 2.5% [engineering judgment] = 2.75% Zone 1 loads – SBL: 94.75%; the load breaker SBL is assigned the remainder of the frequency that is not attributed to the long duration.
	ZOI top event (Zone 2 end states)	Top branch (representing generator-fed, FCT duration type faults): 2.75%; in order for the downstream breaker to experience a long-duration HEAF, the upstream breaker must fail to interrupt the fault fast enough to prevent the long-duration HEAF. The upstream breaker is typically set higher than the downstream breaker to achieve proper selective coordination and, therefore, does not provide 100% redundant protection. Thus, the likelihood is not solely limited to the breaker random failure probability. The delay time for the supply breaker to trip if the load breaker fails is difficult to predict and depends on multiple factors: 1. Supply breaker protection available – Many utilities have board differential protection. This protection checks whether the current flowing into a board should equal the summation of all the currents flowing out of the board. If a switchgear has board differential protection and that protection is not failed by the fault or by random failure, the fault would be interrupted very quickly (cycles) and there would be no HEAF. For cases where board differential is successful,

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
WGM 4	ZOI top event (Zone 2 end states) (cont.)	those events are already excluded from the base HEAF frequency. Therefore, the board differential protection availability is not considered further here. It is assumed that faults within the board differential protection, where available, do not produce a HEAF end state. Therefore, the supply breaker protection that is being relied upon here is the 50 instantaneous and/or 51 (time overcurrent) where available. So, the first consideration is the load breaker may have a 50 and 51 trip device, but the supply breaker may not have a 50 trip device and only 51 protection. If the supply breaker has both 50 and 51 protection, the likelihood of a long duration HEAF, in theory, would be lower. The factors below assume only a 51 device is available on the upstream breaker. *Supply breaker protection settings – The 51 trip protection setting will be set higher than the load breakers to achieve proper selective coordination. How low the supply breaker protection can be set is limited by the clearing time of the load protection device and a safety margin or it may be limited by the need to start and accelerate the largest connected load on top of the board running load so that there are not spurious trips of the supply breaker. For the time delta comparison between the supply and the larger loads, a time delay of 2–3 seconds for a bolted fault can be expected based on sample reviews. It is expected that available supply breaker protection would prevent a long duration HEAF unless there is a non-optimal setting for the supply breaker protection or significantly different shaped curves where faults of different impedance might have more significant delays. Engineering judgment used to establish this factor at 2.5%. 2. Failure of the supply breaker protection = random failure 0.25% [NUREG 6928, Table 5-13]. NOTE: HEAF-induced failure not included as there is an upstream breaker in Zone 2 not influenced by the Zone 3 HEAF = 0.25% Estimate = 2.5% + 0.25% = 2.75% Bottom branch (representing short duration faults): 97.25%; the load breaker short duration is assigned the remainder of the frequency that is not attributed to the long duration.
WGM 5	General	I recommend apportioning the supply/load frequency in a 75/25 split because we have so little data. Usually when we have extremely small data sets, we use a uniform distribution. That would mean a 50/50 split. But we have expert opinion and some data that says the supply cabinet is more likely to have a HEAF. So, I moved to a 75/25 split. I'm uncomfortable with more “precision” because the data set is so small that a new HEAF will skew things a lot. The supply split will be determined by the plant-specific feed type (UAT or SAT).

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
WGM 6	General	1. Use of OPEX and EDS system protection considered (Note: differential (87) not credited as these would screen out as HEAFs due to rapid operation of circuit breaker fault clearing). 2. Zone of switchgear is selected based on its normal EDS alignment during station operations. 3. Loads should be expanded to "MBB & Loads."
	Vertical section (Zone 1)	Supply (UAT): 57%; 4 events were UAT-fed EDS alignments / 7 total MV SWGR events = 57% Supply (SAT): 29%; 2 events were on SAT EDS alignments / 7 total MV SWGR events = 29% [2nd FEDB 732 event] (original/normal alignment was Zone 2, FEDB 50910 2nd event: HEAF fault location transferred from original "normal" alignment Zone 2 (Bus 5) to Zone 1 (Bus 4: Bkr 52/54) MBB & Loads: 14%; 1/7 main bus bars (1st FEDB 732 event)
	Vertical section (Zone 2)	Supply (UAT): 45%; even split between UAT/SAT. A fault can originate equally on any bus supply breaker regardless of zone. Supply (SAT): 45% MBB & Loads: 10%; no OPEX supports MBB fault on Zone 2 switchgear. However, it did on Zone 1 switchgear and Mfg./model/construction similarities can be used a 90/10 split between supply and load
	ZOI (same for both Zone 1 and Zone 2)	Generator Fed/FCT: 1% Short Duration: 99%; short duration should be reserved where an upstream bus supply circuit breaker must be credited as a "backup" and can take nominally 2 to 3 seconds to clear a downstream fault on the main bus bars or backup to a failed load circuit breaker. **Takes two protective layer failures: No OPEX supports two independent circuit breaker/scheme failures, FEDB 50910 backup protection operated "twice" and a total of six successful circuit breaker operation demands. Based on electrical distribution system protection scheme reliability and supporting reactor operating years, split fraction should be heavily favored towards "short duration," around 99/1% split.

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
WGM 6	Notes on end sequences in Zone 2	E_2, G_2, I_2: Initially considered circuit breaker reliability and shows it screens below 1E-06. However, the number is too high (3E-02) to have two independent circuit breaker failures below 1E-06. However, out of all the U.S. Nuclear Reactor operating hours, there has been no documented double circuit breaker failures that resulted in a HEAF. 7 MV SWGR HEAFs are single circuit breaker failures (except FEDB 732 where no circuit breaker failures occurred (two independent circuit breakers operated successfully). The circuit breaker failure probability seems too high. The circuit breaker reliability should be based on circuit breaker failures that caused a HEAF (fail to open only, not close) With no double circuit breaker failure HEAFs, the split fraction should weigh heavily in the “short duration” end sequence. Some reasons for this: 1. 4 MV SWGR Generator-fed faults were bus transfer events, which included the successful operation of other circuit breakers 2. FEDB 732, no circuit breaker failures. 2 independent circuit breakers operated successfully. 3. FEDB 50910 was a failure at a system level that placed a 6 demands on 3 circuit breakers that all operated successfully (other than circuit breaker 52/24, which was a latent/passive failure), no other circuit breakers failed to operate when demanded (open/close) -) First event circuit breakers that operated successfully: --)Three circuit breakers (52/20 [open], 52/7 [open], 52/19 [close]) operated successfully as part of the bus transfer ---) Circuit breaker 52/19 operated twice (closed, then opened to clear fault) -) Second Event: Consequences of Generator Lockout (86) relay ---) Circuit Breaker 52/19 again successfully closes, then opens to clear the fault Note that circuit breaker 52/19 operated four times within a matter of four hours, with 2 of those being fault clearing demands (including “close & latch”). In other words, the “backup” protection worked twice (52/19).

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
WGM 6	Supplemental notes	Short Duration: If we haven't defined this (and we're going to adopt), then we should consider: o) Load (Zone 1 or Zone 2): One level of protection failure (load circuit breaker fails) and the bus supply circuit breaker successfully (w/no instantaneous [50] element) operates as a backup, but still result in a "short duration" (not supported by any OPEX). o) Bus "supply" circuit breaker works as designed (clears the fault, no protection failure) but because it has no instantaneous element (50) it does not clear instantaneously and may result in a "short duration" HEAF -) Marginally supported by FEDB 732 (2nd event). A circuit breaker was closed in on a preexisting fault requiring the circuit breaker: a) Forward motion to close and latch b) Sense the fault: No instantaneous (50) element, so there is going to be a delay depending where the inverse-time current relay is set c) Reverse operation and re-open to clear the fault Short duration is what is reasonably expected for selectively coordinated EDS Zone 1/Zone 2 (Range: 2 to 3 s [or less]) Class 1E vs. Non-Class 1E: Given OPEX and oversight of the 1E over non-1E, the frequencies should be different (higher for non-1E). It may be appropriate for the practitioner to have a decision path that is for either Class 1E or non-Class 1E.
WGM 7	Vertical section top event	Utilizing the OPEX events that have occurred in the supply sections versus load section to inform the 80/20 split. In order for the arc flash to raise to the level of a HEAF, it requires a delay in the supply breaker from tripping for faults on the main bus bar or at the load breaker, for faults downstream of the load breaker it requires a failure of that breaker and then is dependent on the tripping time of the supply breaker. The tripping time for the supply breaker in cases of faults vary between plants, with some being quick enough to not raise to the level of a HEAF.
	Zone 1 – ZOI split	The 90/10 split is derived from the events in understanding that a generator-fed event is unlikely, but plausible. For cases where a fault is initiated at the load breaker or main bus bar, then it would require a failure of the supply breaker to trip. This would correspond closer to the breaker failure probability, however there is a chance that the HEAF may prevent the breaker from working by damaging control circuitry or other common causes. Therefore, the split is set at an order of magnitude higher than the common cause failure (CCF) for MV SWGR breakers failing to operate on demand.

Table C-2
Basis for input provided in Table C-1 (cont.)

Expert	Part of Event Tree	Basis or Explanation
	Zone 2 – ZOI split	The 97/03 split is derived from the from the CCF of MV switchgear breakers failing to operate on demand. In order to have a generator-fed HEAF at the Zone 2 level, both breakers in the Zone 1 switchgear and possibly any breakers in the Zone 2 switchgear are required to fail. There is independence in the breakers in Zone 1 from the initiating event of the arc fault; however, there maybe be some common cause characteristics between the switchgear from a random failure standpoint. Therefore, the split of 97/03 is applied instead of the split of 99.75/0.25.
WGM 8	General	1) Supply UAT and SAT equally likely noting the prevalence for the arc to initiate during switching 85/15 2) “Short duration” faults must still comport with initiating frequency definitions—suggest duration be in excess of 2 s or we consider setting a minimum energy level corresponding with short duration. These events will have a limited potential to damage targets external to the initiating component unless targets are close. 3) I have no strong physical evidence to create a basis for the generator-fed vs. short duration faults for zone 2. The frequency value of 22% was based on operating experience for a high energy long duration fault (not necessarily generator fed, i.e., FEDB 50910); however, the energy output would fall into the same classification as a generator-fed event. There still was some uncertainty on the Zone 2 nature of the FEDB 50910 event as well as the total energy output so I adjusted the split between a true generator-fed event and the short duration event on a 50/50 split. I don’t think skewing the consequence towards non-consequential events based on breaker alignments or breaker failure probability is justified based on the initiating frequency. If there are truly short duration events that do occur at the Zone 2 which are impacted by breakers, they will be binned as arc flash events and appropriately put into Bin 15. In my opinion, if there is an argument to make an aggressive Zone 2 adjustment to short duration non-consequential events, there would be an equal argument to put all frequency of a HEAF into Zone 1 to begin with.
	Vertical section split in Zone 1	Supply UAT and SAT equally likely (85/2 = 42.5) noting the prevalence for the arc to initiate during switching.

C.4.1 Summary of Discussion from 10/14/2020 Call

The meeting started with a discussion of the definition of SBL HEAFs (as opposed to long-duration generator-fed HEAFs, which have been well defined). This discussion helped calibrate the working group to a similar definition for non-generator-fed HEAF events. WGM 7 discussed that the time duration would be anywhere between 0.5 s through 3–4 s for events at bolted fault conditions. The FEDB 732 event was roughly 1.15 s. Events that are longer than this (e.g., 2–3 s) would have larger ZOIs. WGM 4 brought up the point about the difference between short duration faults and faults fed off the SAT. WGM 7 pointed out that approximately 10 units’ SATs have FCTs in excess of 4 s, per the EPRI survey [43]. WGM 8 stated that the generator-fed faults are likely to have consequences similar to the FEDB 112 operating experience and that potentially HEAFs with aluminum can be larger in ZOI. Switchgear fed off the SAT can be either shorter or longer duration (more closely resembling generator-fed faults). The working group agreed that the group needs to better define short-duration HEAFs so that everyone is working off the same definition. The working group also agreed that this discussion may have to be reevaluated once the group knows more about the threshold of when an exothermic aluminum reaction occurs and the size of ZOIs at different durations and/or currents.

Next, discussion moved to the event tree for MV switchgear (see Figure C-1). WGM 8 asked about the lower range of the miscellaneous duration, 0.5 s. WGM 7 said this represented a cabinet breach from an arc—a cabinet breach that occurs between 0.5 and 0.6 s into the event, based on videos from the full-scale testing. WGM 1 stated that Bin 16 is to capture the higher-consequence HEAF events, and some Bin 15 events may have cabinet breach without rising to the level of a HEAF (arc blast/flash with secondary ensuing fire). WGM 7 clarified that this is not the door opening, but breach by burning through the cabinet from the arc. The working group agreed to revisit the threshold for the lower end of the HEAF range.

At this point, the working group went back to the table of values from each member's input. WGM 7 presented the results at a high level (see Table C-1) and noted that the estimates from each member were generally similar. WGM 1 had a higher estimate than most working group members for end state C (generator-fed fault in Zone 1 load cubicle). WGM 1 said this was based on a definition of small HEAFs and the difficulty of defining those events. WGM 6 clarified that getting to a generator-fed fault in end state C requires load breaker and supply breaker failure to clear the fault (or the fault can occur in the main bus bar or breaker stabs). WGM 1 said that based on the team discussion, the estimate will shift to a higher probability for end state D.

Discussion of individual estimates and rationale

WGM 1: Started analyzing numbers and determined that one number would not be generic for all the plants due to differences in normal alignment (either fed from SAT or UAT). Assumed two sources with each receiving 20% of the frequency, and then applied an additional 40% to normal alignment (normal alignment had 60% of frequency, alternate had 20%). Supply breakers for Zone 1 (either UAT/SAT) could be single-point vulnerabilities, and therefore, since only one failure has to occur, this is more likely. Having a generator-fed fault in the load sections was the least likely scenario, so assigned that 5%. Would like better understanding of plants that have switchgear fed from the SAT, how often are they aligned to the UAT (and susceptible to a generator-fed fault). In Zone 2, had hard time imagining what these faults would be like, but relied on operating experience, and most likely to see faults of miscellaneous durations in this zone. 1% for generator-fed/FCT faults in the Zone 2 supply (end states E and G) and 0 for the load (end state I).

WGM 2: Assigned 80% of the Zone 1 frequency amongst the supply sections. Proposed that of the 80% it could be split up based on plant configurations. Perhaps 30% (15% UAT/15% SAT) of the 80% is predetermined by the methodology, and the remainder of the 50% is up to the plant based on their electrical lineups based on past historical data.

> WGM 4 states that it might not matter the alignments, but how much switching you do. Does the plant switch between the normal and alternate supply? Or just the normal? How often?
>
> WGM 2: Do we know when the HEAFs occurred? If during switching? 3 of 4 bus transfer events were during standard routine operations switching buses from SAT to UAT during

> power ascension. Fourth event during grid transient in switchyard (occurred during unsupervised bus transfer).
>
> WGM 6: There is switching of SAT breakers during operation (e.g., during diesel generator surveillance). Also, after the FEDB 74 event, INPO put out INPO SER 19-95 [50], to recommend against unsupervised bus transfer schemes. Unsupervised means simultaneous trip of the UAT breaker and simultaneous close of the SAT breaker. Since the breaker will open faster than the closing breaker, this inherently provides the appropriate dead time so there are not two sources on the bus at the same time. This works most of the time, but in the FEDB 74 event it didn't. INPO recommended supervised bus transfers, which means sync check relays or early B contact (motion is in place and on the way to successful opening).

WGM 4: Tried to think through Zone 2 load breaker scenarios and to get a generator-fed fault, the fault must not detected be by the supply breaker. Supply breaker can randomly fail, but the HEAF itself in the load breaker compartment could render supply breaker inoperable due to collateral damage from load breaker compartment. Supply breaker is not redundant to load breaker (has to be set higher), so there is some potential for supply breaker to not interrupt quickly enough. Given we haven't seen long-duration fault in a load breaker and random breaker failure probability was too generous, introduced a factor for Zone 2 supply where the breaker doesn't open either due to nonoptimal settings or collateral damage. Put this factor as 2.5% (low but not impossible)—also 10 times more likely than random.

WGM 7: Similar thinking as WGM 4 in Zone 2. Medium-voltage breaker failure probabilities for internal events are on the order of a low E-03, and the common cause occurrence factors for failure to open are on the order of a low E-02. These probabilities rely on failures independent of the fire. For HEAFs occurring at the Zone 2 level there is at least one breaker (can be two) independent of the HEAF-initiating switchgear to prevent it from being a long-duration generator-fed HEAF. General review of operating experience shows that the majority of switchgear HEAFs initiate at the breakers, so there exists a possible common cause concern with the breaker failure mechanism that initiated the HEAF in Zone 2 and the independent breaker in the Zone 1 supply switchgear (similar switchgear model, maintenance, etc.). A one-order-of-magnitude adjustment was applied to the independent breaker failure probability, and the factor of 3% was determined as the split. For HEAFs initiating within load vertical sections at the Zone 1 level, there is a potential (unlikely due to general switchgear design, but still plausible) for the supply breaker in this switchgear to fail to trip due to damaging control circuitry or other common causes during the time-delay characteristic of the overcurrent relays. The factor of 10% was determined for the split; this was judged based on the likelihood being higher than the value determined for Zone 2.

The group then discussed the two HEAFs in FEDB 50910, the power flow alignments and the implications on the event tree, and types of HEAFs occurring in Zone 1/Zone 2.

C.5 Second Panel Meeting

On October 21, 2020, the subgroup met to continue discussion on the definition of the miscellaneous/short-HEAF (later renamed SBL) durations to ensure a common understanding between the working group. A summary of the discussion is as follows:

WGM 8: Questioned the working group on the difference between generator-fed and short-duration HEAFs. Is this short-duration HEAF nonconsequential? Need more definition on end state D.

> WGM 7: Modelers and testing should feed in insights to the definition of short duration/misc. HEAFs. Miscellaneous means HEAFs not directly fed from either SAT or UAT. Somewhere between FEDB 732 and FEDB 50910 event.
>
> WGM 6: Looked at time-current-characteristic (TCC) curves, given a fault in first breaker, how long does it take for second breaker to interrupt fault? Range was between 1 to 3 s per the plants sampled. Used values of bolted faults and at 65%, 75%, and 85% of bolted fault. OPEX that is not generator-fed are instances where the bus supply breaker has to interrupt, and this may take some time because it does not have an instantaneous element (0.8–2.4 s). Where you have to rely on a backup breaker (primary fails), the timing is more like 0.2–5 s. There is going to be some overlap.
>
> WGM 8: FEDB 50910 fault was not a generator-fed event but was longer than 1–4 seconds. Need to keep this in mind when we give these parameters to the modelers for ZOI.
>
> WGM 7: 80% of the plants will likely be in the 2–3 s range. There may be a few outliers with nonoptimal settings or poor coordination.
>
> WGM 1: May have to iterate once we finalize miscellaneous HEAF duration to make sure the frequency and consequences (from the model) are what is intended. Miscellaneous HEAF may be represented as a distribution since the durations, currents, and energies may all be different.
>
> WGM 8: Need to make sure we are properly treating the difference between Bin 15 (thermal fires) and Bin 16 (HEAFs). Bin 16 is HEAF with potential to damage external targets at time 0. Lower threshold is FEDB 732 at 1.15 s for HEAF bin. This had melted holes in the cabinet.
>
> WGM 6: Discussed differences in non-Class 1E and Class 1E switchgear, such as daily surveillance for DC control power.
>
> Action: EPRI to send out definition of short-/miscellaneous-duration HEAFs to working group to ensure consistent definition within the working group. Table C-3 reproduces this below.

Table C-3
ZOI definition and durations in MV switchgear (developed in 2020)

HEAF Description	Duration*	End State Name
<u>SAT or UAT alignment</u> • Bus supply (cross-tie) primary protection works OR • Primary protection fails; however, next-level upstream bus supply (or cross-tie) circuit breaker operates to clear the fault**	0.8–4.5 s	MISC HEAF (formerly: short duration)
<u>SAT alignment only:</u> Protection failure requiring reliance upon the SAT switchyard transformer backup TOC (51) protection to clear the fault • Zone 1: one breaker fails • Zone 2: two breakers fail	0.8–5 s	Backup SWYD FCT (formerly: FCT duration)
<u>Generator-fed faults:</u> • Zone 1: one breaker fails • Zone 2: two breakers fail	4–10 s	Gen-fed HEAF (formerly: generator fed)

* The durations shown in this table are solely when viewing the speed of the protection system and not the OPEX or its consequences (real or potential). This is supported by review of four nuclear station protection and coordination calculations, sample TCC curves, the EPRI HEAF survey [43], and IEEE C57.109 [27]). Note: Instantaneous (50) relay elements are not credited.
** "Primary protection fails" takes into consideration that the Zone 2 frequency split based on one of seven events in the OPEX may include some of the first level of protection works (breaker failure probability); therefore, the end state may rely on the Zone 2 supply breaker to trip.

C.6 Third Panel Meeting

The group met again on October 26, 2020 to continue discussing the split fraction and basis.

WGM 8: Asked to discuss more about the relationship and differences in Zone 2 between Class 1E and non-Class 1E equipment.

WGM 6: Discussed EDS lineups in simplified one-line diagrams to generically explain scenarios that start with a load fault, and sequential breaker failures and resulting energies. Started with system voltages but then also looked at arc voltages from NEA/CSNI/R (2017)7 [7]. Average of 880V used to calculate arc energy. Fault current of 30,000A.

> WGM 2: Clarified that Table 4-1 is the generator voltage, so arc voltage will be lower than that.

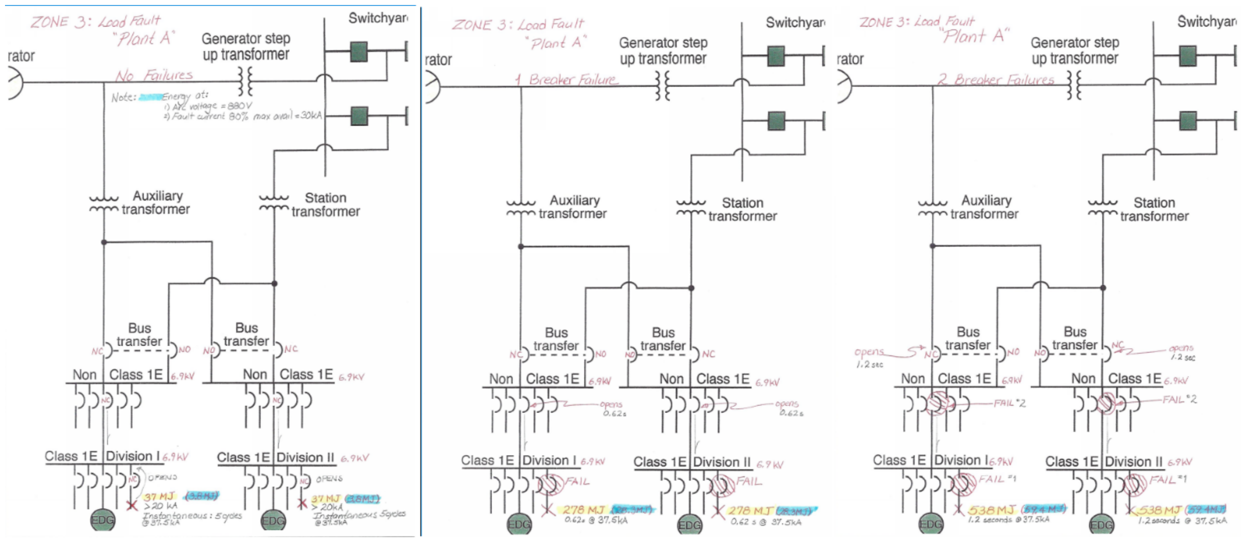

Figure C-2
Zone 2 load fault exercise in FCTs

Xs indicate load fault (e.g., service water pump motor) in Zone 2.

- Fault and load breaker opens in five cycles (fault energy limited 3.8 MJ). Not a HEAF.
- Fault and first breaker (load breaker) fails to interrupt. Now bus supply breaker is called to open and does so within 0.5 s. (fault energy 28 MJ)
- Fault with two breaker failures (load breaker and bus supply breaker). Next breaker that can operate is first out breaker from either SAT or UAT (Zone 1 supply breaker), which opens in 1.2 s (fault energy 59 MJ).
- Fault with three breaker failures (load breaker, bus 2 supply breaker, and bus 1 supply breaker failure), which now relies on the backup protection for the yard transformers.
    - For UAT, lockout goes to switchyard breakers and generator field breaker. Generator-fed fault 4 s (179 MJ before generator-fed fault).
    - For SAT, set at 3.9 s (fault energy 175 MJ), immediately trips switchyard circuit breaker and clears fault without generator-fed fault.

Durations are set by inverse time relay curves for 51 relay (not just available fault current).

If analyzed as a bus fault, just take out one breaker, but values the same as just covered.

WGM 8: Do we have a basis for the Class 1E supply breaker being more reliable (such that we can limit the probability of generator-fed faults in Zone 2/Class 1E)?

WGM 7: Example applicable to both Class 1E and non-Class 1E buses, with exception that the timing might be different.

WGM 8: Do we need different split for Class 1E / non-Class 1E? Given care, maintenance, etc., for Class 1E systems?

WGM 7: When implementing this, more likely during normal operations that the Zone 1 Class 1E is going to be powered by the SAT (as opposed to the UAT). If pushing frequency more towards normal supply, this may show the applicable differences. For Zone 2, larger weight of Class 1E equipment versus non-Class 1E equipment.

WGM 8 challenged WGM 4 if the estimates would change if talking about Class 1E vs. non 1E systems.

WGM 4: Zone 2 has additional upstream breakers that can interrupt the fault that should not be in original ZOI. But those breakers are not redundant (not set to interrupt at same time) and may interrupt with a delay. Factored into estimate for nonoptimal setting. There is some art in where to set that upstream breaker—depends on the largest starting motor load on top of running motors and might have to be set higher to accommodate that. There are some sweet spots for setting this and some optimization, but not always there. For Class 1E/non-Class 1E, maintenance strategies for Class 1E are more rigorous and design analysis is more rigorous. Some non-Class might not be as well maintained. Would have a hard time quantifying the difference between Class/non-Class.

WGM 1: If we treat Class 1E differently in Zone 2, we would have to treat it differently in Zone 1.

WGM 6: Discussed some of the potential reasons why Class 1E systems may be more reliable:

- Technical specifications periodic surveillance (30 days/90 days) to ensure continued operability.
- Technical specifications for operability are met and documented.
- Action request/work order priority for Class 1E equipment is higher.
    - Senior Reactor Operator has to do action request work order screening.
- Quality of maintenance (Quality Assurance hold points, dual verification, critical acceptance criteria, relay setting calibrations to Generic Letter 96-01 requirements, DC control power).
- Less deferrals for preventative maintenance in Class 1E equipment.

WGM 8: Should we have two sets of numbers in the event tree? One for Class 1E (lower probability of generator-fed fault) and one for non-Class 1E (higher probability of generator-fed fault)?

The working group agreed that the Class 1E buses/breakers are more reliable but agreed that they did not have the data to further split them up. The working group agreed to update the numbers based on previous discussions.

C.7 Fourth Panel Meeting

The working group met again on October 28 to discuss the revised expert input. After the previous call, the working group members were able to adjust their initial estimates for final aggregation. Table C-4 shows the final input.

Table C-4
Final input received from working group members

	WGM 1	WGM 2	WGM 3	WGM 4	WGM 5	WGM 6	WGM 7	WGM 8
Vertical Section in Zone 1	0.65/0.2/0.15*	0.5/0.3/0.2	0.6/0.3/0.1	0.567/0.283/0.15*	0.57/0.29/0.14	0.57/0.29/0.14*	0.567/0.283/0.15*	0.567/0.283/0.15*
Gen Fed or SWYD/SBL (Zone 1)	0.05/0.95	0.1/0.9	0.1/0.9	0.0525/0.9475	0.1/0.9	0.1/0.9	0.1/0.9	0.1/0.9
End State A	0.559	0.430	0.516	0.488	0.490	0.490	0.488	0.488
End State B	0.172	0.258	0.258	0.243	0.249	0.249	0.243	0.243
End State C	0.006	0.017	0.009	0.005	0.012	0.012	0.009	0.009
End State D	0.123	0.155	0.077	0.081	0.108	0.108	0.077	0.077
Vertical Section in Zone 2	0.65/0.2/0.15*	0.5/0.3/0.2	0.6/0.3/0.1	0.567/0.283/0.15*	0.45/0.45/0.1	0.45/0.45/0.1	0.567/0.283/0.15*	0.567/0.283/0.15*
Gen Fed or SWYD/SBL HEAF (Zone 2)	0.05/0.95 and 0/1.0	0.1/0.9	0.1/0.9 and 0.05/0.95	0.0275/0.9725	0.1/0.9 and 0.05/0.95	0.01/0.99	0.03/0.97	0.1/0.9 and 0.05/0.95
End State E	0.005	0.007	0.008	0.002	0.006	0.001	0.002	0.008
End State F	0.086	0.063	0.076	0.077	0.057	0.062	0.077	0.071
End State G	0.001	0.004	0.004	0.001	0.006	0.001	0.001	0.004
End State H	0.027	0.038	0.038	0.039	0.057	0.062	0.038	0.036
End State I	0.000	0.003	0.001	0.000	0.001	0.000	0.000	0.001
End State J	0.021	0.025	0.013	0.014	0.013	0.014	0.014	0.013
Notes	*Primary supply gets larger frequency	*Primary supply gets larger frequency	*Primary supply gets larger frequency	*Primary supply gets larger frequency Credited HEAF breaker failure probability	*Primary supply gets larger frequency	*UAT/SAT/load split based on OPEX	*Primary supply gets larger frequency	*Primary supply gets larger frequency

C.7.1 Zone 1 Vertical Section Top Event

WGM 1, WGM 2, WGM 4, WGM 6, WGM 7, and WGM 8 each reported different estimates to differentiate between the primary and alternate supply (the primary supply feed received a higher probability).

> WGM 3 and WGM 5 did not split this out, and both reported that they did not provide updated numbers at the time of the call. WGM 3 had split 90% to the supply but recommended an equitable split between the two supply sections. After discussions WGM 3 agreed with biasing the split fraction toward the primary supply sections.
>
> WGM 2: Stated that the 0.5 value is for the primary and 0.3 for the backup/alternate supply.
>
> WGM 6: Used OPEX to come up with this vertical section split.
>
> WGM 1: Revised primary supply fraction from 0.6 to 0.65, to partition more of the frequency in the supply cabinets versus the load sections. Believe the supply section is the most likely location for a HEAF.

After this discussion, these estimates were aggregated and presented at the next meeting. WGM 3 and WGM 5 will submit three numbers to have input consistent with the rest of the working group.

C.7.2 Zone 1 Load ZOI Top Event (Generator Fed/FCT versus Miscellaneous HEAF)

Most estimates are between 5 and 10% for generator-fed/FCT HEAF.

> WGM 1: Incorporated random breaker failure probability plus some margin to come up with 5/95 split.
>
> WGM 2: Looked at PhD dissertation for interdependencies and common cause failures for reconfiguration systems (e.g., telecom/electrical distribution systems). Went through failure modes for each and had several examples, including a circuit breaker for a distribution system. Saw a lot of analogies between his work and our work, so drew on his research for my estimates. Used 10/90 split.

WGM 1 asked if there was a scenario in which the plant always runs from the SAT and would never run from the UAT. Should that plant postulate generator-fed faults?

> WGM 6: They shouldn’t. There are some plants where the Class 1E buses do not connect to a UAT. For balance of plant, this may not be the case (may be aligned to UAT).
>
> WGM 3: The probability still has to sum to 1, so it would just go into another sequence.
>
> WGM 7: If switchgear only had one supply, the analyst would sum the supply frequency and use that value.
>
> WGM 4: Likewise, if there is more than one alternate, going to need to split the alternate probability among the alternates. Zone 1 may only have one alternate, but Zone 2 you may have more than one alternate.
>
> WGM 7: How about EDG cubicles? Won’t be running during normal operation, so keep them as a load?

WGM 4 challenged that assumption: The protection scheme and everything about them is more similar to a supply but agree they won't be running. The EDG does get tied to grid about once per month. Could this be an alternate supply?

WGM 6: Primary and backup are the normal supplies and didn't think too much of EDG for HEAF. EDG is not going to produce the same amount of power as an off-site source, so probably have a smaller ZOI.

Several members discussed that the EDG is potentially more similar to a load than a supply. This discussion was tabled for now.

After this discussion, the working group decided to aggregate the estimates for the Zone 1 load ZOI split.

C.7.3 Zone 2 Vertical Section Top Event

The working group discussed the likelihood of HEAFs within Zone 2 switchgear (supply and load sections).

WGM 1: For vertical section, are we going to use the same splits? As we get further down the EDS, it is harder and harder to imagine generator-fed faults.

WGM 6 has different values for Zone 1 versus Zone 2, but everyone else had the same values for Zone 2. WGM 6 had a different breakdown, and their reasoning was there was not much OPEX in Zone 2, so they did an equal split.

WGM 1: Explain the connection between Zone 1 and Zone 2. Are there multiple sources/supplies? Answer: Depends on the plant. To be in Zone 2, the normal feed has to be from Zone 1, but there could be alternate feeds that come directly from a yard transformer (some newer Zone 2 switchgear). WGM 4 agreed and discussed that we need good guidance on how to apply this situation correctly in the PRA.

C.7.4 Zone 2 ZOI Top Event

WGM 8: Used two different numbers between supply (used 90/10 split based on engineering judgment). When I got to the load, there is an additional breaker that can prevent the HEAF, and although potentially co-located, halved previous estimate (95/5). Generator-fed fault in load section even smaller due to the additional breaker.

WGM 4: Doesn't the vertical section split account for supply versus load?

WGM 8 scoped out the supply/load separation based on OPEX but used more judgment/extra breaker for the ZOI portion.

WGM 6: Remember the loads also includes the main bus bar as well (so in these cases the load breaker is downstream of the fault and cannot interrupt).

WGM 1: If in Zone 2 load, assigned a 0% chance of having a generator-fed fault. Likely in 1E-7 range for likelihood in this branch. In addition to the initiating HEAF/breaker failure, you would need at least two additional breakers to fail to get a generator-fed HEAF.

Working group agreed that load centers aren't susceptible to generator-fed faults, so felt comfortable removing this from the load branch.

WGM 8: We may go through this activity and determine that this might wash out and the analyst may not have to postulate.

WGM 7: A generator-fed fault/FCT fault in branch I is one entire train of the medium-voltage EDS system not functioning.

End states are aggregated, and once estimates are known the working group can decide if it makes sense for the analyst to postulate this failure.

The working group can also revisit crediting the “bonus breaker,” which could be one way the working group can support not analyzing generator-fed HEAFs in Zone 2.

C.8 Fifth Panel Meeting/Final Estimates

The working group met again on November 2 to discuss the aggregated results. The results were presented for both the average and the median. The working group chose to select the average value. Figure C-3 and Figure C-4 show the event tree with vertical section and end state probabilities.

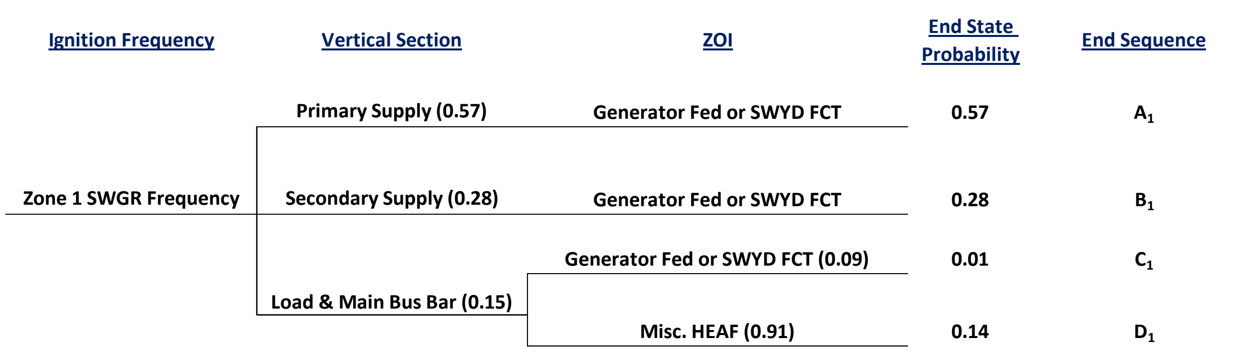

Figure C-3
Zone 1 event tree

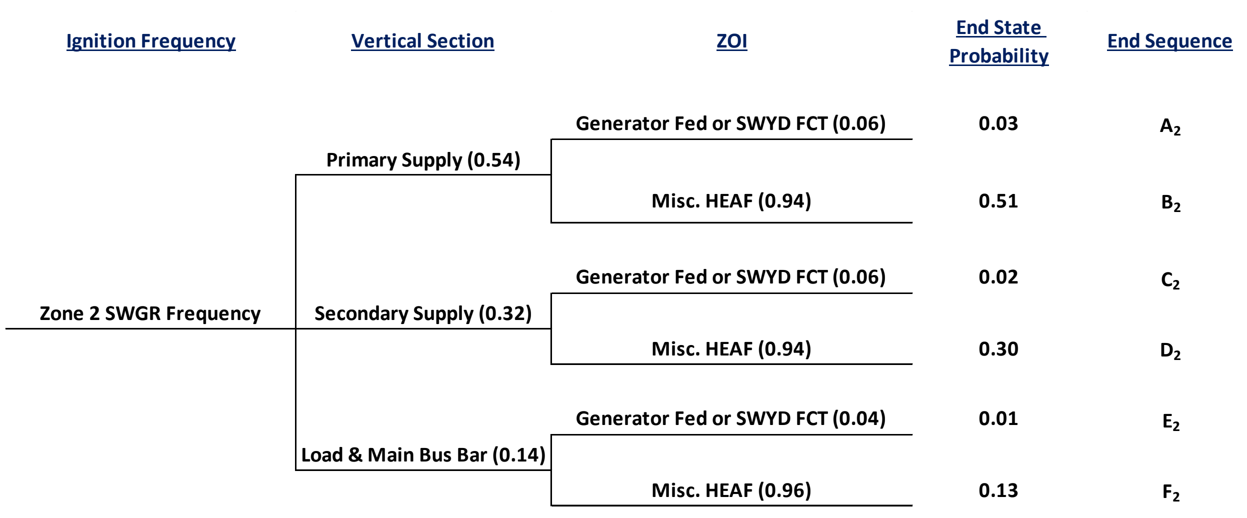

Figure C-4
Zone 2 event tree

D
FDS SUMMARY OF THE ENERGETIC HEAF ZOI

D.1 Introduction

This appendix describes the process used to develop the ZOIs in Sections 7–9 of this report. The process used the ZOIs calculated from FDS simulations of LV switchgear, MV switchgear, and NSBD. The FDS modeling report [16] provides a detailed description of the FDS modeling approach, the inputs, and the outputs. The WG reviewed the results of these FDS simulations in combination with industry data on FCTs [43] to establish a series of end states for screening and configuration-specific ZOIs. These end states correspond to the event trees and ZOI tables in Sections 7–9 of this report.

The documentation process for the energetic-phase ZOIs begins with the FDS results as summarized in the FDS ZOI report [16]. Significant observations that the working group used to develop end states are then identified and linked to specific FDS simulations considered when developing the energetic ZOIs. The general process that the working group used involved a review of predicted energetic ZOIs associated with an end state, and the selection of a representative value within this group of FDS simulation results in units of feet. This value was then rounded up, in increments of 0.5 ft.

In most cases, the WG developed up to four types of energetic ZOIs for 15 MJ/m² and 30 MJ/m² fragility targets, depending on the equipment involved. The types are as follows:

- Screening ZOIs, which consist of a single ZOI distance uniformly applied to all faces of the switchgear enclosures or NSBDs. The screening ZOIs are provided for a range of SAT and UAT FCTs and are only developed for MV switchgear.
- HEAFs fed by an auxiliary power transformer (configuration-specific ZOIs), which consist of an array of ZOI distances for different switchgear or NSBD faces. These ZOIs are provided for a range of SAT and UAT FCTs.
- HEAFs interrupted by the switchgear bus supply breaker (configuration-specific ZOIs), which consist of an array of ZOI distances for different switchgear or NSBD faces. These ZOIs are provided for a range of bus supply breaker clearing times.
- ZOI refinements that use a defined subset of the FDS simulation results associated with the breaker style used with MV switchgear.

The resulting energetic ZOIs are provided in feet in Sections 7, 8, and 9. This appendix provides the energetic ZOIs in meters. Several examples are selected for each switchgear type and NSBD configuration to illustrate the development of specific energetic ZOIs from the identified FDS simulation end state grouping.

D.2 Load Centers

Section 7 of this report provides ZOIs for load centers. The ZOIs are grouped as follows:

- End or interior location
- Upper or lower elevation

The primary difference between an end location and an internal location is that internal-location HEAFs do not have side ZOIs. The vertical location distinguishes where the ZOI initiates from vertically in the load center.

D.2.1 FDS Results for Load Centers

A total of 10 unique baseline FDS input files and simulations were developed for the LV switchgear enclosures. The simulations evaluated a range of fault locations and bus-bar material compositions, using a 90 MJ arc energy power profile, as described in Section 7.2.

D.2.1.1 FDS-Predicted Energetic ZOIs

Table D-1 summarizes the FDS results for the 10 load center HEAF simulations. These results are as provided in the FDS ZOI report [16]. The FDS ZOI report provides 24 sensitivity scenarios for the load centers using alternate fault power profiles; the working group did not directly use them to determine the ZOIs and they are not shown in Table D-1.

Table D-1
Summary of load center energetic ZOIs predicted by FDS [16]

Scenario Summary						ZOI Distance (m)									
						15 MJ/m² Target Fragility					30 MJ/m² Target Fragility				
Scenario Designator[1]	Bus Bar Material	Arcing Fault Duration (s)	Arc Location	Arc Elevation	Arc Energy (MJ)	Back	Left	Right	Top	Front	Back	Left	Right	Top	Front
LV-BASE-1	Aluminum	41	Breaker	Mid-height	90	None[2]	None	0.74	None	None	None	None	0.47	None	None
LV-BASE-2	Aluminum	41	Breaker	Top	90	None	None	0.77	0.48	None	None	None	0.49	0.25	None
LV-BASE-3	Aluminum	41	Bus bar comp.	Mid-height	90	None	None	0.77	None	None	None	None	0.49	None	None
LV-BASE-4	Aluminum	41	Bus bar comp.	Top	90	0.06	None	0.75	0.72	None	None	None	0.47	0.43	None
LV-BASE-5	Aluminum	41	Breaker to bus bar comp.[3]	Mid-height	90	None	None	0.71	None	None	None	None	0.43	None	None
LV-BASE-6	Aluminum	41	Breaker to bus bar comp.	Top	90	None	None	0.71	0.50	None	None	None	0.43	0.23	None
LV-BASE-7	Copper	41	Breaker	Mid-height	90	None	None	0.70	None	None	None	None	0.43	None	None
LV-BASE-8	Copper	41	Breaker	Top	90	None	None	0.73	0.43	None	None	None	0.46	0.20	None
LV-BASE-9	Copper	41	Bus bar comp.	Mid-height	90	None	None	0.75	None	None	None	None	0.47	None	None
LV-BASE-10	Copper	41	Bus bar comp.	Top	90	0.05	None	0.73	0.71	None	None	None	0.46	0.42	None

[1]The FDS input designator is not the same as the input file name but uniquely corresponds to a single FDS input file. Refer to Appendix C of the FDS ZOI report for the corresponding input file nomenclature designator [16].

[2]None means there is no external ZOI.

[3]Fault begins at the breaker and migrates to the bus bar compartment.

D.2.1.2 FDS Simulation Results Observations

The FDS ZOI report identifies several significant findings that simplify the number of ZOIs to characterize the hazard as follows [16]:

- The bus-bar material composition does not have a significant effect on the energetic. The ZOIs are within the uncertainty range for copper and aluminum bus-bar simulations for a given fault location, fault type, and fault energy.
- The energetic ZOI results are sensitive to the distance between the target and the arc location and to the number of enclosure boundaries between the arc and the target.

Based on these observations, the working group developed ZOIs for load centers that are applicable to an end or internal location, elevation, and 15 MJ/m² and 30 MJ/m² fragility targets. Screening ZOIs and refinements are not applied to load centers due to the simplicity of the overall results.

D.2.2 Load Center Energetic ZOI Mapping

The energetic ZOIs for load centers are mapped to specific FDS results. This mapping allows the working group to review subsets of the FDS results that correspond to a ZOI. The ZOIs are grouped by arc location within the switchgear, as Figure 7-2 shows. The mapping to the FDS simulations is listed as follows:

- Location A: LV-BASE-5 and LV-BASE-6
- Locations B and C: LV-BASE-5
- Location D: LV-BASE-6, with side ZOIs set to zero
- Locations E and F: LV-BASE-5, with side and vertical ZOIs set to zero

These simulations most closely represent the type of HEAFs expected in load centers. The remaining eight baseline FDS simulations are used to confirm that these ZOIs are reasonable for other types of configurations, given the arc power profile.

D.2.3 Determination of Load Center Energetic ZOIs

As noted in Section D.1, the general process used by the working group involved a review of predicted energetic ZOIs associated with an end state, and the selection of a representative value within this group of FDS simulation results in units of feet. This value was then rounded up, in increments of 0.5 ft.

The process is illustrated using the FDS simulation results for Location A with a 15 MJ/m² target fragility. Table D-2 lists the ZOIs as calculated by FDS.

Table D-2
FDS simulation results applicable to load center with a 15 MJ/m² target fragility

FDS Simulation	ZOI (m (ft))				
	Back	Left	Right	Top	Front
LV-BASE-5	None	None	0.71 (2.4)	None	None
LV-BASE-6	None	None	0.71 (2.4)	0.50 (1.6)	None
Maximum	None	**None**	**0.71 (2.4)**	**0.50 (1.6)**	None
WG ZOI (End Location)	**None**	**0.76 (2.5)**		**0.61 (2.0)**	**None**

The back and front of the LV switchgear do not have external ZOIs, based on the results in Table D-2. The maximum right or left ZOI dimensions are 0.73 m (2.4 ft), which is rounded to 0.76 m (2.5 ft). The maximum top ZOI dimension is 0.51 m (1.7 ft), which is rounded to 0.61 m (2.0 ft). The same process was used to determine the ZOIs for the 30 MJ/m² fragility targets.

The intermediate-location ZOIs are equal to the end-location ZOIs, but the right and left ZOIs are set to zero (no external ZOI). The final ZOIs for the LV switchgear are provided in English units in Table 7-1 and in SI units in Appendix E (Table E-1).

D.3 MV Switchgear

Section 8 of this report provides ZOIs for MV switchgear. The ZOIs are grouped as follows:

- Screening ZOIs for 15 MJ/m² and 30 MJ/m² fragility targets (Table 8-2)
- Zone 1 ZOIs for 15 MJ/m² and 30 MJ/m² fragility targets (Table 8-3 and Table 8-4)
- Zone 2 ZOIs for 15 MJ/m² and 30 MJ/m² fragility targets (Table 8-5 and Table 8-6)

The Zone 1 and Zone 2 ZOIs include end states based on the type of switchgear, the arc location within the switchgear, and the applicable FCT.

D.3.1 FDS Simulation Results for MV Switchgear

A total of 48 unique FDS input files and simulations were developed for the MV switchgear enclosures. The simulations evaluated a range of fault locations, switchgear types, fault types, fault energies, and bus-bar material compositions, as Table 8-1 summarizes.

D.3.1.1 FDS-Predicted Energetic ZOIs

Table D-3 summarizes the FDS simulation results for the 48 MV switchgear HEAF scenarios. These results are as provided in the FDS ZOI report [16]. Note that the primary cable compartment bus bar is denoted as PCCBB.

Table D-3
Summary of MV switchgear energetic ZOIs predicted by FDS [16]

Scenario summary						ZOI Distance (m)									
						15 MJ/m² Target Fragility					30 MJ/m² Target Fragility				
Scenario Designator[1,2]	Bus Bar Mat-erial	Stiff (s)	Decay (s)	Arc Location	Arc Energy (MJ)	Back	Left	Righ t	Top	Front	Back	Left	Right	Top	Front
MV-GE-1	Al	2	0	Main bus bar	68	None	0.17	0.17	0.08	0.19	None	None	None	None	None
MV-GE-2	Al	2	0	PCCBB load	68	0.56	None	None	None	None	0.30	None	None	None	None
MV-GE-3	Al	2	0	PCCBB supply	68	None	0.08	0.08	None	None	None	None	None	None	None
MV-GE-4	Al	4	0	Main bus bar	135	None	0.64	0.63	0.30	0.61	None	0.35	0.34	0.08	0.27
MV-GE-5	Al	4	0	PCCBB load	135	0.95	0.39	0.41	0.28	None	0.61	0.16	0.18	0.06	None
MV-GE-6	Al	4	0	PCCBB supply	135	None	0.46	0.50	0.28	None	None	0.21	0.24	0.07	None
MV-GE-7	Al	5	0	Main bus bar	169	None	0.77	0.79	0.39	0.77	None	0.45	0.46	0.15	0.39
MV-GE-8	Al	5	0	PCCBB load	169	1.11	0.56	0.55	0.44	None	0.74	0.29	0.29	0.18	None
MV-GE-9	Al	5	0	PCCBB supply	169	None	0.59	0.65	0.43	None	None	0.32	0.36	0.19	None
MV-GE-10	Al	0	15	Main bus bar	132	None	0.64	0.63	0.41	0.55	None	0.34	0.34	0.16	0.22
MV-GE-11	Al	0	15	PCCBB load	132	0.92	0.57	0.55	0.38	None	0.59	0.29	0.27	0.11	None
MV-GE-12	Al	0	15	PCCBB supply	132	None	0.57	0.57	0.41	None	None	0.28	0.29	0.14	None
MV-GE-13	Al	3	15	Main bus bar	233	None	0.96	0.95	0.63	0.94	None	0.65	0.63	0.33	0.53

Table D-3
Summary of MV switchgear energetic ZOIs predicted by FDS [16]

Scenario summary						ZOI Distance (m)									
						15 MJ/m² Target Fragility					30 MJ/m² Target Fragility				
Scenario Designator[1,2]	Bus Bar Mat-erial	Stiff (s)	Decay (s)	Arc Location	Arc Energy (MJ)	Back	Left	Righ t	Top	Front	Back	Left	Right	Top	Front
MV-GE-14	Al	3	15	PCCBB load	233	1.21	0.81	0.81	0.70	None	0.89	0.49	0.49	0.38	None
MV-GE-15	Al	3	15	PCCBB supply	233	None	0.89	0.85	0.70	0.05	None	0.56	0.52	0.38	None
MV-GE-16	Al	5	15	Main bus bar	300	None	1.09	1.09	0.74	1.13	None	0.79	0.78	0.41	0.69
MV-GE-17	Al	5	15	PCCBB load	300	1.39	0.93	0.93	0.87	None	1.04	0.60	0.61	0.52	None
MV-GE-18	Al	5	15	PCCBB supply	300	None	0.96	0.97	0.86	0.31	None	0.66	0.70	0.51	None
MV-GE-19	Cu	2	0	Breaker stabs	68	None	0.05	0.08	None	0.15	None	None	None	None	None
MV-GE-20	Cu	2	0	Main bus bar	68	None	0.11	0.14	0.18	0.14	None	None	None	None	None
MV-GE-21	Cu	2	0	PCCBB load	68	0.50	None	None	None	None	0.26	None	None	None	None
MV-GE-22	Cu	2	0	PCCBB supply	68	None	None	None	None	None	None	None	None	None	None
MV-GE-23	Cu	4	0	Breaker stabs	135	None	0.58	0.55	None	0.48	None	0.30	0.27	None	0.14
MV-GE-24	Cu	4	0	Main bus bar	135	None	0.63	0.59	0.48	0.55	None	0.33	0.30	0.21	0.21
MV-GE-25	Cu	4	0	PCCBB load	135	0.89	0.54	0.50	0.37	None	0.56	0.23	0.23	0.09	None

Table D-3
Summary of MV switchgear energetic ZOIs predicted by FDS [16] (cont.)

Scenario summary						ZOI Distance (m)									
						15 MJ/m² Target Fragility					30 MJ/m² Target Fragility				
Scenario Designator[1,2]	Bus Bar Mat-erial	Stiff (s)	Decay (s)	Arc Location	Arc Energy (MJ)	Back	Left	Right	Top	Front	Back	Left	Right	Top	Front
MV-GE-26	Cu	4	0	PCCBB supply	135	None	0.53	0.52	0.30	None	None	0.26	0.26	0.06	None
MV-GE-27	Cu	5	0	Breaker stabs	169	None	0.71	0.71	None	0.60	None	0.40	0.40	None	0.24
MV-GE-28	Cu	5	0	Main bus bar	169	None	0.76	0.73	0.59	0.68	None	0.41	0.41	0.29	0.32
MV-GE-29	Cu	5	0	PCCBB load	169	1.02	0.66	0.63	0.54	None	0.67	0.33	0.33	0.22	None
MV-GE-30	Cu	5	0	PCCBB supply	169	None	0.67	0.68	0.50	None	None	0.38	0.38	0.20	None
MV-GE-31	Cu	0	15	Breaker stabs	132	None	0.63	0.63	None	0.48	None	0.34	0.34	None	0.13
MV-GE-32	Cu	0	15	Main bus bar	132	None	0.62	0.62	0.49	0.51	None	0.32	0.33	0.21	0.18
MV-GE-33	Cu	0	15	PCCBB load	132	0.87	0.59	0.60	0.42	None	0.55	0.30	0.31	0.13	None
MV-GE-34	Cu	0	15	PCCBB supply	132	None	0.59	0.59	0.45	None	None	0.30	0.30	0.16	None
MV-GE-35	Cu	3	15	Breaker stabs	233	None	0.93	0.92	None	0.77	None	0.61	0.58	None	0.38
MV-GE-36	Cu	3	15	Main bus bar	233	None	0.93	0.92	0.79	0.87	None	0.60	0.58	0.44	0.48
MV-GE-37	Cu	3	15	PCCBB load	233	1.17	0.86	0.85	0.78	None	0.81	0.51	0.51	0.41	None
MV-GE-38	Cu	3	15	PCCBB	233	None	0.87	0.87	0.78	None	None	0.53	0.53	0.41	None

Table D-3
Summary of MV switchgear energetic ZOIs predicted by FDS [16] (cont.)

Scenario summary						ZOI Distance (m)									
						15 MJ/m² Target Fragility					30 MJ/m² Target Fragility				
Scenario Designator[1,2]	Bus Bar Mat-erial	Stiff (s)	Decay (s)	Arc Location	Arc Energy (MJ)	Back	Left	Right	Top	Front	Back	Left	Right	Top	Front
				supply											
MV-GE-39	Cu	5	15	Breaker stabs	300	None	1.03	1.02	None	0.93	None	0.74	0.72	None	0.50
MV-GE-40	Cu	5	15	Main bus bar	300	None	1.04	1.05	0.96	1.04	None	0.74	0.75	0.57	0.62
MV-GE-41	Cu	5	15	PCCBB load	300	1.28	0.96	0.96	0.98	None	0.94	0.65	0.64	0.56	None
MV-GE-42	Cu	5	15	PCCBB supply	300	None	0.99	0.97	0.95	0.19	Non e	0.68	0.67	0.55	None
MV-ABB-1	Cu	2	0	Breaker stabs	68	None	0.34	0.31	None	None	None	0.12	0.10	None	None
MV-ABB-2	Cu	4	0	Breaker stabs	135	None	0.76	0.77	None	None	None	0.45	0.47	None	None
MV-ABB-3	Cu	5	0	Breaker stabs	169	None	0.92	0.90	None	None	None	0.59	0.57	None	None
MV-ABB-4	Cu	0	15	Breaker stabs	132	None	0.76	0.76	None	None	None	0.45	0.45	None	None
MV-ABB-5	Cu	3	15	Breaker stabs	233	None	1.05	1.05	None	None	None	0.74	0.74	None	None
MV-ABB-6	Cu	5	15	Breaker stabs	300	0.12	1.22	1.21	None	None	None	0.90	0.89	None	None

[1]The MV-GE-# designation corresponds to an MV GE vertical-lift circuit breaker switchgear style and the MV-ABB-# designation corresponds to an MV ABB horizontal-draw-out switchgear style circuit breaker.

[2]The FDS input designator is not the same as the input file name but uniquely corresponds to a single FDS input file. Refer to the FDS ZOI report for the corresponding input file nomenclature designator [16].

D.3.1.2 FDS Simulation Results Observations

The FDS ZOI report identified several significant findings that simplify the number of ZOIs required to characterize the hazard potential of the HEAF [16]. Those findings are as follows:

- The dominant parameter affecting the energetic ZOIs in MV switchgear was the total arc energy.
- A secondary parameter was the switchgear type (vertical-lift breaker style or horizontal-draw-out style).
- The bus-bar material composition does not have a significant effect on the energetic ZOI. The ZOIs are within the uncertainty range for copper and aluminum bus-bar simulations for a given fault location, fault type, and fault energy.
- The energetic ZOI results are sensitive to the distance between the target and the arc location and to the number of enclosure barriers and boundaries between the arc and the target.

Based on these observations, the working group developed configuration-specific and screening end states for different arc energies corresponding to both SAT and UAT power sources, with the results for copper and aluminum bus-bar compositions consolidated. The working group also defined refinements for SBL and vertical-lift circuit breakers given these observations, the latter of which was a means of incorporating the location-specific sensitivity into the energetic ZOIs.

D.3.2 MV Switchgear Energetic ZOI End State Mapping

The energetic ZOI end states developed by the working group are mapped to specific FDS simulation results. This mapping allowed the working group to review subsets of the FDS simulation results that correspond to an event tree branch end state when developing the ZOIs.

D.3.2.1 Screening Energetic ZOI End State Mapping

Although the screening energetic ZOIs do not have end state designators defined in Section 8, a fixed number of end states are selected using site-specific inputs. These end states correspond to ranges of SAT and UAT FCTs. Table D-4 summarizes these end states for Zone 1 and Zone 2. The scenario mapping applies to both 15 MJ/m² and 30 MJ/m² fragility targets. The basic mapping strategy for the SAT and UAT FCTs is as follows:

- SAT FCTs between 0 and 4.00 s correspond to FDS simulations with a constant current (stiff) duration of 4 s (or less).
- SAT FCTs over 4.01 s correspond to FDS simulations with a constant current duration of 5 s.
- UAT FCTs between 0 and 0.50 s correspond to FDS simulations with a 0 s constant-current duration and a 15 s generator-fed fault.
- UAT FCTs between 0.51 and 2.0 s interpolate the results for UAT FCTs of 0–0.50 s and 2.01–3.0 s, both followed by a 15 s generator-fed fault.
- UAT FCTs between 2.01 and 3.0 s correspond to FDS simulations with a 3 s constant-current duration and a 15 s generator-fed fault.

- UAT FCTs over 3.01 s correspond to FDS simulations with a 5 s constant-current duration and a 15 s generator-fed fault.

Note that the screening ZOIs provided in Section 8 combine the 0–4.00 s SAT and the 0–0.50 s UAT end states because the ZOIs are the same; however, the ZOIs for these end states were based on different simulations as shown in Table D-4.

Table D-4
Zone 1 and Zone 2 MV switchgear screening energetic ZOI end state mapping to FDS simulations

SAT or UAT fault clearing time range	Applicable FDS Simulations
0–4.00 s (SAT)	MV-GE-1 through MV-GE-6 MV-GE-19 through MV-GE-26 MV-ABB-1, MV-ABB-2
4.01+ s (SAT)	MV-GE-7 through MV-GE-9 MV-GE-27 through MV-GE-30 MV-ABB-3
0–0.50 s (UAT[1])	MV-GE-10 through MV-GE-12 MV-GE-31 through MV-GE-34 MV-ABB-4
0.51–2.00 s (UAT[1])	None, ZOIs are interpolated
2.01–3.00 s (UAT[1])	MV-GE-13 through MV-GE-15 MV-GE-35 through MV-GE-38 MV-ABB-5
3.01+ s (UAT[1])	MV-GE-16 through MV-GE-18 MV-GE-39 through MV-GE-42 MV-ABB-6

[1]UAT fault into a generator-fed fault.

D.3.2.2 Configuration-Specific Energetic ZOI End States

The configuration-specific ZOIs for Zone 1 and Zone 2 switchgear use end states to characterize event tree branches that correspond to faults located at the normal supply, the secondary supply, and load vertical sections (including the main bus bar). The end states are essentially equivalent to the SAT and UAT end states described in Section D.3.2.1 for the screening ZOIs. Table D-5 summarizes the end states and the corresponding FDS simulations for the configuration-specific ZOIs.

Table D-5
MV switchgear configuration-specific energetic ZOI end state mapping to FDS simulations

End state Designator[1]	Power Source and Duration	Arc Energy (MJ)	Applicable FDS Simulations
GF	UAT[2] (0–0.50 s)	132	MV-GE-10 through MV-GE-12 MV-GE-31 through MV-GE-34 MV-ABB-4
SAT2	SAT (0–2.00 s)	68	MV-GE-1 through MV-GE-3 MV-GE-19 through MV-GE-22 MV-ABB-1
SAT3	SAT (2.01–3.00 s)	101	None, ZOIs are interpolated between SAT2 and SAT4 end states
SAT4	SAT (3.01–4.00 s)	135	MV-GE-4 through MV-GE-6 MV-GE-23 through MV-GE-26 MV-ABB-2
SATMAX	SAT (4.01+ s)	169	MV-GE-7 through MV-GE-9 MV-GE-27 through MV-GE-30 MV-ABB-3
UAT2	UAT[2] (0.51–2.00 s)	200	None, ZOIs are interpolated
UAT3	UAT[2] (2.01–3.00 s)	233	MV-GE-13 through MV-GE-15 MV-GE-35 through MV-GE-38 MV-ABB-5
UATMAX	UAT[2] (3.00+ s)	300	MV-GE-16 through MV-GE-18 MV-GE-39 through MV-GE-42 MV-ABB-6

[1]The ZOI tables provided in Section 8 append the target fragility threshold to each end state designator.
[2]UAT faults into a generator-fed fault.

D.3.2.3 Supply Breaker Limited Energetic ZOI End States

The ZOI end states that correspond to the SBL duration are a subset of the configuration-specific ZOI end states described in Section D.3.2.2. Three end states correspond to 2 s, 3 s, and 4 s arc durations. These are nominally equivalent to the configuration-specific ZOI end states SAT2, SAT3, and SAT4, respectively, that are summarized in Table D-5. Table D-6 summarizes these end states and the applicable FDS simulation results.

Table D-6
MV switchgear SBL energetic ZOI end state mapping to FDS simulations

End state Designator[1]	Power Source and Duration	Arc Energy (MJ)	Applicable FDS Simulations
SBL4	SAT (3.01–4.00 s)	135	MV-GE-4 through MV-GE-6 MV-GE-23 through MV-GE-26 MV-ABB-2
SBL2	SAT (0–2.00 s)	68	MV-GE-1 through MV-GE-3 MV-GE-19 through MV-GE-22 MV-ABB-1
SBL3	SAT (2.01–3.00 s)	101	None, ZOIs are interpolated between SBL2 and SBL4 end states

[1]The ZOI tables provided in Section 8 append the target fragility threshold to each end state designator.

D.3.2.4 Vertical-Lift Circuit Breaker Refinement Energetic ZOI End States

The vertical-lift circuit breaker refinement represents a subset of the configuration-specific and SBL energetic ZOI FDS simulations that incorporates both the fault location (supply or load) and the switchgear type (vertical-lift) applicable to Zone 1 and Zone 2 MV switchgear. There are no end state designators uniquely applicable to the vertical-lift circuit breaker style refinement energetic ZOIs. The configuration-specific end state designators are used for both load and supply fault locations, though the ZOIs that correspond to these end states may be different.

FDS Summary of the Energetic HEAF ZOI

Table D-7 summarizes the applicable FDS simulations for the vertical-lift circuit breaker refinement to the ZOIs.

Table D-7
MV switchgear vertical-lift circuit breaker refinement energetic ZOI end state mapping to FDS simulations

Fault Location	End state Designator[1]	Power Source and Duration[2]	Arc Energy (MJ)	Applicable FDS Simulations
Normal supply and secondary supply	GF	UAT (0–0.50 s)	132	MV-GE-10, MV-GE-12 MV-GE-31, MV-GE-32, MV-GE-34
	SAT2	SAT (0–2.00 s)	68	MV-GE-1, MV-GE-3 MV-GE-19, MV-GE-20, MV-GE-22
	SAT3	SAT (2.01–3.00 s)	101	None, ZOIs are interpolated
	SAT4	SAT (3.01–4.00 s)	135	MV-GE-4, MV-GE-6 MV-GE-23, MV-GE-24, MV-GE-26
	SATMAX	SAT (4.01+ s)	169	MV-GE-7, MV-GE-9 MV-GE-27, MV-GE-28, MV-GE-30
Supply breaker limited	SBL4	SAT (3.01–4.00 s)	135	MV-GE-4 through MV-GE-6 MV-GE-23 through MV-GE-26 MV-ABB-2
	SBL2	SAT (0–2.00 s)	68	MV-GE-1, MV-GE-2 MV-GE-19, MV-GE-21, MV-GE-22
	SBL3	SAT (2.01–3.00 s)	101	None, ZOIs are interpolated between SBL2 and SBL4 end states
Main bus bar or load breaker	GF	UAT (0–0.50 s)	132	MV-GE-10, MV-GE-11 MV-GE-31, MV-GE-33, MV-GE-34
	UAT2	UAT (0.51–2.00 s)	200	None, are ZOIs interpolated
	UAT3	UAT (2.01–3.00 s)	233	MV-GE-13, MV-GE-14 MV-GE-35, MV-GE-37, MV-GE-38
	UATMAX	UAT (3.00+ s)	300	MV-GE-16, MV-GE-17 MV-GE-39, MV-GE-41, MV-GE-42
	SAT2	SAT (0–2.00 s)	68	MV-GE-1, MV-GE-2 MV-GE-19, MV-GE-21, MV-GE-22
	SAT3	SAT (2.01–3.00 s)	101	None, ZOIs are interpolated between SAT2 and SAT4 end states
	SAT4	SAT (3.01–4.00 s)	135	MV-GE-4, MV-GE-5 MV-GE-23, MV-GE-25, MV-GE-26
	SATMAX	SAT (4.01+ s)	169	MV-GE-7, MV-GE-8 MV-GE-27, MV-GE-29, MV-GE-30

[1]The ZOI tables provided in Section 8 append the target fragility threshold to each end state designator.

D.3.3 Determination of the MV Switchgear Energetic ZOIs

As noted in Section D.1, the working group's general process involved a review of predicted energetic ZOIs associated with an end state, and selection of a representative value within this group of FDS simulation results in units of feet. This value was then rounded up in increments of 0.5 ft (15 cm). This section provides an illustration of this process for the screening, configuration-specific, and refinement energetic ZOIs. The overall ZOIs are provided in Sections 8.4 through 8.6, and all end states considered are in Section 8 of this report. Note that the screening ZOIs were determined using the configuration-specific ZOIs rather than separately reviewing the FDS results because the configuration-specific ZOIs use all FDS results. This ensures a consistent rounding system between the screening and configuration-specific ZOIs. As such, the configuration-specific ZOIs are discussed before the screening ZOIs in this section.

D.3.3.1 Determination of the Configuration-Specific Energetic ZOIs

The configuration-specific ZOIs are determined from the FDS simulation results as grouped in Table D-5. These ZOIs are provided for the back, left/right, top, and front for 15 MJ/m² and 30 MJ/m² target fragilities. To illustrate the process, the energetic ZOIs for the SAT2 end state with a 15 MJ/m² target fragility is assessed. Based on Table D-5, the following FDS simulation results apply:

- MV-GE-1 through MV-GE-3
- MV-GE-19 through MV-GE-22
- MV-ABB-1

Table D-8 summarizes the FDS-predicted ZOIs applicable to this end state, as determined using the data provided in Table D-6. The ZOIs for end state SAT2 were determined using the data provided in Table D-8 with the FDS results for the left and right faces combined. Generally, the maximum value in feet was rounded up to the nearest 0.5 ft increment, unless the maximum value was an outlier or the value in feet was slightly higher than the lower 0.5-ft increment. For end state SAT2, the maximum value for the back, left/right, top, and front faces is rounded up to the nearest 0.5 ft increment, as Table D-8 shows. This process was applied to all end states listed in Table D-5.

Table D-8
FDS simulation results applicable to configuration-specific end state SAT2 with a 15 MJ/m² target fragility

FDS simulation	ZOI (m (ft))				
	Back	Left	Right	Top	Front
MV-GE-1	None	0.17 (0.56)	0.17 (0.56)	0.08 (0.26)	0.19 (0.62)
MV-GE-2	0.56 (1.8)	None	None	None	None
MV-GE-3	None	0.08 (0.26)	0.08 (0.26)	None	None
MV-GE-19	None	0.05 (0.16)	0.08 (0.26)	None	0.15 (0.49)
MV-GE-20	None	0.11 (0.36)	0.14 (0.46)	0.18 (0.59)	0.14 (0.46)
MV-GE-21	0.50 (1.6)	None	None	None	None
MV-GE-22	None	None	None	None	None
MV-ABB-1	None	0.34 (1.1)	0.31 (1.1)	None	None
Maximum	**0.56 (1.8)**	**0.34 (1.1)**	**0.31 (1.1)**	**0.18 (0.59)**	**0.19 (0.62)**
WG ZOI	**0.61 (2.0)**	**0.46 (1.5)**		**0.61 (2.0)**	**0.30 (1.0)**

D.3.3.2 Determination of the Screening Energetic ZOIs

The screening energetic ZOIs are determined from the maximum configuration-specific energetic ZOI dimensions across all faces for the applicable end state. A simple example to illustrate this process uses the results from Section D.3.3.1. Based on Table D-4, the Zone 1 MV switchgear screening ZOI for an SAT with an FCT between 0 and 2.00 s uses the same FDS simulations as end state SAT2, which Table D-8 summarizes. The working group determined the screening energetic ZOIs use the maximum ZOI dimension across all faces, or 2.0 ft (0.61 m) for this case. This process was applied to all screening ZOIs.

D.3.3.3 Determination of the Vertical-Lift Circuit Breaker Refinement Energetic ZOIs

The vertical-lift circuit breaker refinement energetic ZOIs are determined using the FDS results applicable to the vertical-lift circuit breaker style switchgear and are further divided into load and supply groupings (see Table D-7). The basic process described in Section D.3.3.1 is applied using the FDS simulation groupings listed in Table D-7. As an example, consider the ZOIs for the UAT3 end state with a fault in the main bus bar or load breaker (load fault), applicable to a vertical-lift circuit breaker refinement with a 15 MJ/m² target fragility. Based on Table D-7, the following FDS results apply:

- MV-GE-13
- MV-GE-14
- MV-GE-35
- MV-GE-36
- MV-GE-37

Table D-9 summarizes the FDS-predicted ZOIs applicable to this end state, as determined using the data in

Table D-7. The ZOIs for end state UAT3 applicable to the vertical-lift circuit breaker style refinement with an arc on the load side were determined using the data provided in Table D-9 with the FDS results for the left and right faces combined. Similar to the example provided in Section D.3.3.1, the maximum value in feet was rounded up to the nearest 0.5-ft increment, unless the maximum value was an outlier or the value in feet was slightly higher than the lower 0.5-ft increment. For end state UAT3 with the vertical-lift style circuit breaker refinement, the maximum value for the top face is rounded up to the nearest 0.5-ft increment, and the maximum value for the back, left/right, and front faces is rounded down to the nearest 0.5-ft increment in Table D-9. This process is applied to all end states listed in Table D-7.

Table D-9
FDS simulation results applicable to the vertical-lift circuit breaker style refinement with a load fault, end state of UAT3, and a 15 MJ/m² target fragility

FDS simulation	ZOI (m (ft))				
	Back	Left	Right	Top	Front
MV-GE-13	None	0.96 (3.1)	0.95 (3.1)	0.63 (2.1)	0.94 (3.1)
MV-GE-14	1.21 (4.0)	0.81 (2.7)	0.81 (2.7)	0.70 (2.3)	None
MV-GE-35	None	0.93 (3.1)	0.92 (3.0)	None	0.77 (2.5)
MV-GE-36	None	0.93 (3.1)	0.92 (3.0)	0.79 (2.6)	0.87 (2.8)
MV-GE-36	1.17 (3.8)	0.86 (2.8)	0.85 (2.8)	0.78 (2.6)	None
Maximum	**1.21 (4.0)**	**0.96 (3.1)**	**0.95 (3.1)**	**0.79 (2.6)**	**0.94 (3.1)**
WG ZOI	**1.2 (4.0)**	**0.91 (3.0)**		**0.91 (3.0)**	**0.91 (3.1)**

D.3.4 Summary of the MV Switchgear Energetic ZOIs

Table 8-2 (English units) and Table E-2 (SI units) provide the screening energetic ZOIs for the MV switchgear. Similarly, Table 8-3 through Table 8-6 (English units) and Table E-3 and Table E-6 (SI units) provide the full set of configuration-specific and refinement ZOIs.

D.4 Non-Segregated Bus Ducts

Section 9 of this report provides energetic ZOIs for NSBDs. Six zones are defined for bus ducts: IPDB, BDUAT, BDSAT, BD1, BD2, and BDLV. With the exception of IPDB (the guidance does not change) the remaining five zones contain a total of 14 end states.

D.4.1 FDS Results for Non-Segregated Bus Ducts

A total of 58 unique FDS input files were developed for the NSBDs. The simulations evaluated a range of fault energies, duct geometries, bus-bar material compositions, and duct material compositions. Table D-10 summarizes the FDS simulation results for the 57 NSBD HEAF scenarios (accounting for one failed simulation). These results are as provided in the FDS ZOI report [16].

Table D-10
Summary of NSBD ZOIs predicted by FDS [16]

Scenario Summary							ZOI (m)									
							15 MJ/m² Target Fragility					30 MJ/m² Target Fragility				
HEAF ID[1]	Duct	Bus Bar Mat-erial	Stiff (s)	Deca y (s)	Duct Geom-etry	Arc Ene-rgy (MJ)	Back	Front	Right	Above	Belo w	Back	Front	Right	Above	Belo w
NSBD-1	Steel	Al	1	0	Straight	34	None	None	N/A[2]	None	None	None	None	N/A	None	None
NSBD-2	Steel	Al	2	0	Straight	68	0.30	0.30	N/A	0.23	None	0.13	0.13	N/A	0.08	None
NSBD-3	Steel	Al	4	0	Straight	135	0.60	0.58	N/A	0.47	0.37	0.36	0.34	N/A	0.28	0.17
NSBD-4	Steel	Al	5	0	Straight	169	0.71	0.69	N/A	0.58	0.52	0.44	0.42	N/A	0.36	0.28
NSBD-5	Steel	Al	0	15	Straight	133	0.68	0.68	N/A	0.66	0.59	0.42	0.42	N/A	0.41	0.32
NSBD-6	Steel	Al	3	15	Straight	233	0.98	1.00	N/A	0.85	0.90	0.62	0.63	N/A	0.57	0.54
NSBD-7	Steel	Al	5	15	Straight	300	1.15	1.13	N/A	0.95	1.07	0.73	0.72	N/A	0.65	0.67
NSBD-8	Al	Al	1	0	Straight	34	0.14	0.14	N/A	0.15	None	None	None	N/A	None	None
NSBD-9	Al	Al	2	0	Straight	68	0.40	0.39	N/A	0.38	0.21	0.20	0.20	N/A	0.19	None
NSBD-10	Al	Al	4	0	Straight	135	0.69	0.68	N/A	0.64	0.58	0.42	0.41	N/A	0.40	0.33
NSBD-11	Al	Al	5	0	Straight	169	0.79	0.79	N/A	0.74	0.69	0.50	0.50	N/A	0.48	0.41
NSBD-12	Al	Al	3	15	Straight	233	1.04	1.04	N/A	0.93	1.03	0.66	0.66	N/A	0.62	0.64
NSBD-13	Al	Al	5	15	Straight	300	1.21	1.21	N/A	1.05	1.18	0.77	0.77	N/A	0.72	0.76
NSBD-14	Steel	Cu	1	0	Straight	34	None	None	N/A	None	None	None	None	N/A	None	None
NSBD-15	Steel	U	2	0	Straight	68	0.31	0.29	N/A	0.28	None	0.14	0.12	N/A	0.10	None
NSBD-16	Steel	Cu	4	0	Straight	135	0.61	0.65	N/A	0.71	0.20	0.37	0.40	N/A	0.43	None
NSBD-17	Steel	Cu	5	0	Straight	169	0.73	0.76	N/A	0.84	0.33	0.46	0.48	N/A	0.53	0.14
NSBD-18	Steel	Cu	0	15	Straight	132	0.69	0.70	N/A	0.76	0.44	0.43	0.44	N/A	0.47	0.21
NSBD-19	Steel	Cu	3	15	Straight	233	1.03	1.00	N/A	1.09	0.79	0.66	0.64	N/A	0.71	0.47
NSBD-20	Steel	Cu	5	15	Straight	300	1.17	1.19	N/A	1.30	0.95	0.75	0.77	N/A	0.87	0.59
NSBD-21	Al	Cu	1	0	Straight	34	0.19	0.19	N/A	0.17	None	None	0.06	N/A	None	None
NSBD-22	Al	Cu	2	0	Straight	68	0.37	0.42	N/A	0.47	0.17	0.20	0.2	N/A	0.24	None
NSBD-23	Al	Cu	4	0	Straight	135	0.69	0.71	N/A	0.83	0.49	0.44	0.45	N/A	0.52	0.25
NSBD-24	Al	Cu	5	0	Straight	169	0.82	0.85	N/A	0.97	0.64	0.53	0.54	N/A	0.62	0.36
NSBD-25	Al	Cu	0	15	Straight	132	0.77	0.76	N/A	0.86	0.64	0.49	0.49	N/A	0.54	0.36
NSBD-26	Al	Cu	3	15	Straight	233	1.04	1.08	N/A	1.20	0.96	0.67	0.69	N/A	0.79	0.60
NSBD-27	Al	Cu	5	15	Straight	300	1.22	1.24	N/A	1.37	1.10	0.80	0.81	N/A	0.93	0.71
NSBD-28	Steel	Al	2	0	Tee	68	N/A	0.27	N/A	0.24	None	N/A	0.12	N/A	0.10	None
NSBD-29	Steel	Al	4	0	Tee	135	N/A	0.58	N/A	0.45	None	N/A	0.35	N/A	0.27	None
NSBD-30	Steel	Al	5	0	Tee	169	N/A	0.69	N/A	0.55	None	N/A	0.43	N/A	0.34	None

Table D-10
Summary of NSBD ZOIs predicted by FDS [16] (cont.)

Scenario Summary							ZOI (m)									
							15 MJ/m² Target Fragility					30 MJ/m² Target Fragility				
HEAF ID[1]	Duct	Bus Bar Mat-erial	Stiff (s)	Decay (s)	Duct Geom-etry	Arc Ene-rgy (MJ)	Back	Front	Right	Above	Below	Back	Front	Right	Above	Below
NSBD-31	Steel	Al	0	15	Tee	132	N/A	0.67	N/A	0.63	None	N/A	0.42	N/A	0.39	None
NSBD-32	Steel	Al	3	15	Tee	233	N/A	0.97	N/A	0.85	None	N/A	0.62	N/A	0.56	None
NSBD-33	Steel	Al	5	15	Tee	300	N/A	1.15	N/A	0.94	None	N/A	0.73	N/A	0.64	None
NSBD-34	Al	Al	2	0	Tee	68	N/A	0.43	N/A	0.38	None	N/A	0.22	N/A	0.20	None
NSBD-35	Al	Al	4	0	Tee	135	N/A	0.71	N/A	0.58	None	N/A	0.44	N/A	0.36	None
NSBD-36	Al	Al	5	0	Tee	169	N/A	0.82	N/A	0.66	None	N/A	0.52	N/A	0.41	None
NSBD-37	Al	Al	0	15	Tee	132	N/A	0.76	N/A	0.71	None	N/A	0.48	N/A	0.44	None
NSBD-38	Al	Al	3	15	Tee	233	N/A	1.09	N/A	0.93	0.22	N/A	0.68	N/A	0.61	None
NSBD-39	Al	Al	5	15	Tee	300	N/A	1.25	N/A	1.03	0.47	N/A	0.80	N/A	0.69	0.10
NSBD-40	Steel	Cu	2	0	Tee	68	N/A	0.27	N/A	0.30	None	N/A	0.11	N/A	0.12	None
NSBD-41	Steel	Cu	4	0	Tee	135	N/A	0.50	N/A	0.66	None	N/A	0.28	N/A	0.39	None
NSBD-42	Steel	Cu	5	0	Tee	169	N/A	0.66	N/A	0.82	None	N/A	0.40	N/A	0.51	None
NSBD-43	Steel	Cu	0	15	Tee	132	N/A	0.69	N/A	0.73	None	N/A	0.43	N/A	0.44	None
NSBD-44	Steel	Cu	3	15	Tee	233	N/A	0.95	N/A	1.08	None	N/A	0.61	N/A	0.70	None
NSBD-45	Steel	Cu	5	15	Tee	300	N/A	1.12	N/A	1.29	None	N/A	0.71	N/A	0.86	None
NSBD-46	Al	Cu	2	0	Tee	68	N/A	0.38	N/A	0.41	None	N/A	0.20	N/A	0.21	None
NSBD-47	Al	Cu	4	0	Tee	135	N/A	0.69	N/A	0.77	None	N/A	0.44	N/A	0.47	None
NSBD-48	Al	Cu	5	0	Tee	169	N/A	0.83	N/A	0.92	None	N/A	0.53	N/A	0.58	None
NSBD-49	Al	Cu	0	15	Tee	132	N/A	0.77	N/A	0.85	None	N/A	0.49	N/A	0.52	None
NSBD-50	Al	Cu	3	15	Tee	233	N/A	1.06	N/A	1.15	None	N/A	0.67	N/A	0.75	None
NSBD-51	Al	Cu	5	15	Tee	300	N/A	1.24	N/A	1.36	0.20	N/A	0.81	N/A	0.91	None
NSBD-52	Al	Al	2	0	Elbow	68	0.44	0.44	0.40	N/A	0.46	0.24	0.24	0.20	N/A	0.24
NSBD-53	Al	Al	4	0	Elbow	135	0.75	0.75	0.71	N/A	0.82	0.48	0.48	0.45	N/A	0.51
NSBD-54	Al	Al	5	0	Elbow	169	0.88	0.88	0.85	N/A	0.96	0.56	0.56	0.54	N/A	0.61
NSBD-55	Al	Al	0	15	Elbow	132	0.76	0.77	0.77	N/A	0.81	0.49	0.49	0.50	N/A	0.51
NSBD-56	Al	Al	3	15	Elbow	233	1.10	1.10	1.09	N/A	1.15	0.70	0.70	0.70	N/A	0.75
NSBD-57	Al	Al	5	15	Elbow	300	1.28	1.28	1.28	N/A	1.34	0.83	0.83	0.82	N/A	0.89

[1]The FDS input designator is not the same as the input file name but uniquely corresponds to a single FDS input file. Refer to the FDS ZOI report for the corresponding input file nomenclature designator [16].

[2]N/A indicates the presence of a physical bus duct in that direction for that HEAF simulation. For example, the straight-duct HEAF simulations have the duct running left to right in the FDS model; therefore, the right direction of the arc is inside the initiating component.

D.4.1.2 FDS Simulation Results Observations

The FDS ZOI report identifies several significant findings that simplify the number of energetic ZOIs that are required to characterize the HEAF's hazard potential [16]. The findings are as follows:

- The dominant parameter affecting the energetic ZOIs in NSBDs was the total arc energy.
- A secondary parameter was the duct housing material (aluminum or steel).
- The bus-bar material composition does not have a significant effect on the energetic ZOI. The ZOIs are within the uncertainty range for copper and aluminum bus-bar simulations for a given fault type and energy.
- The geometry of the duct (straight, elbow, or tee) does not have a significant effect on the energetic ZOI.

Based on these observations, the working group developed end states for different arc energies corresponding to both SAT and UAT power sources and with the results for duct geometries and copper/aluminum bus-bar compositions consolidated.

D.4.2 Energetic ZOI End State Mapping

The energetic ZOI end states developed by the working group are mapped to specific FDS results. This mapping allows the working group to review subsets of the FDS results that correspond to an event tree branch end state when developing the energetic ZOIs. Due to duct symmetry, there are no screening ZOIs; ZOIs are applied to all faces of the duct. The scenario mapping applies to both 15 MJ/m² and 30 MJ/m² fragility targets. Table D-11 summarizes the end state mapping. The basic mapping strategy for the SAT and UAT FCTs is as follows:

- SAT FCTs between 0 and 0.50 s are interpolated from the results for a constant current (stiff) duration of 1 s and an assumption that a 0 s stiff source has no external ZOI.
- SAT FCTs between 0.51 and 1.00 s correspond to FDS simulations with a constant-current (stiff) duration of 1 s.
- SAT FCTs between 1.01 and 1.50 s interpolate the results for SAT FCTs of 0.51–1.00 s and 1.51–2.00 s.
- SBL or SAT FCTs between 1.51 and 2.00 s correspond to FDS simulations with a constant-current duration of 2 s.
- SAT FCTs between 2.01 and 3.00 s interpolate the results for SAT FCTs of 1.51–2.00 s and 3.01–4.00 s.
- SAT FCTs between 3.01 and 4.00 s correspond to FDS simulations with a constant-current duration of 4 s.
- SBL FCTs over 4.01 s correspond to FDS simulations with a constant-current (stiff) duration of 5 s.
- UAT FCTs between 0 and 0.50 s correspond to FDS simulations with a 0 s constant-current duration and a 15 s generator-fed fault.
- UAT FCTs between 0.51 and 2.0 s interpolate the results for UAT FCTs of 0–0.50 s and 2.01–3.0 s and a 15 s generator-fed fault.

- UAT FCTs between 2.01 and 3.0 s correspond to FDS simulations with a 3 s constant-current duration and a 15 s generator-fed fault.
- UAT FCTs over 3.01 s correspond to FDS simulations with a 5 s constant-current duration and a 15 s generator-fed fault.

Table D-11
NSBD energetic ZOI end state mapping to FDS simulations

End state	SAT or UAT fault clearing time	Duct material	Applicable FDS simulations
BDSAT0.5 BDSBL0.5	SAT: 0–0.50 s SBL: 0–0.50 s		Interpolated
BDSAT1 BDSBL1	SAT: 0.51–1.00 s SBL: 0.51–1.00 s	Steel	BD-1, BD-14
		Aluminum	BD-8, BD-21
BDSAT1.5 BDSBL1.5	SAT: 1.01–1.50 s SBL: 1.01–1.50 s		Interpolated
BDSAT2 BDSBL2* BDLV	SAT:1.51–2.00 s SBL: Z2 generic* (≥ 2 s) and 1.51-2.00s Low voltage	Steel	BD-2, BD-15, BD-28, BD-40
		Aluminum	BD-9, BD-22, BD-34, BD-46, BD-52
BDSAT3 BDSBL3	SAT:2.01–3.00 s SBL:2.01–3.00 s		Interpolated
BDSAT4 BDSBL4*	SAT:3.01–4.00 s SBL: Z1 generic* (≥ 4 s)	Steel	BD-3, BD-16, BD-29, BD-41, BD-53
		Aluminum	BD-10, BD-23, BD-35, BD-47
BDSATMAX	SAT: ≥ 4.01 s UAT: 0–0.5 s + GF	Steel	BD-4, BD-17, BD-30, BD-42, BD-54
		Aluminum	BD-11, BD-24, BD-36, BD-48
BDGenFed	UAT: 0.51–2 s + GF UAT: 2.01–3 s + GF	Steel	BD-5, BD-18, BD-31, BD-43, BD-55
		Aluminum	BD-25, BD-37, BD-49,
BDGF2	UAT: ≥3 s + GF		Interpolated
BDGF3	SAT: ≥ 4.01 s UAT: 0–0.5 s + GF	Steel	BD-6, BD-19, BD-32, BD-44, BD-56
		Aluminum	BD-12 BD-26, BD-38, BD-50
BDGFMAX	UAT: 0.51–2 s + GF	Steel	BD-7, BD-20, BD-33, BD-45, BD-57
		Aluminum	BD-13, BD-27, BD-39, BD-51

D.4.3 Determination of NSBD Energetic ZOIs

As noted in Section D.1, the working group's general process involved reviewing predicted energetic ZOIs associated with an end state and selecting a representative value within this group of FDS simulation results in units of feet. The maximum value in feet was rounded up to the nearest 0.5 ft increment unless the maximum value was an outlier or the value in feet was slightly higher than the lower 0.5 ft increment. This section provides an illustration of this process.

D.4.3.1 Determination of the NSBD Energetic ZOIs

The NSBD energetic ZOIs are determined from the FDS results as grouped in Table D-11. These ZOIs are provided for the back, front, top, and bottom (and right, in the case of elbows) for 15 MJ/m² and 30 MJ/m² target fragilities; however, a single value is used to represent the ZOI in all directions. To illustrate the process, the energetic ZOIs for the BDSAT2 end state with a 15 MJ/m² target fragility is assessed. Based on Table D-11, the following FDS results apply for a steel duct enclosure:

BD-2, BD-15, BD-28, BD-40

The following FDS results apply for an aluminum duct enclosure:

BD-9, BD-22, BD-34, BD-46, BD-52

The FDS-predicted ZOIs applicable to this end state are summarized in Table D-12 for steel duct housings and Table D-13 for aluminum duct housings, using the data in Table D-11. The energetic ZOIs for end state BDSAT2 were determined using the data in Table D-10. Generally, the maximum value in feet was rounded up to the nearest 0.5 ft increment, unless the maximum value was an outlier or the value in feet was slightly higher than the lower 0.5 ft increment. This process was applied to all end states listed in Table D-11.

Table D-12
FDS simulation results applicable to end state BDSAT2 with a 15 MJ/m² target fragility and steel duct housing

FDS simulation	ZOI (m (ft))				
	Back	Front	Right	Above	Below
BD-2	0.30 (0.98)	0.30 (0.98)	N/A	0.23 (0.75)	None
BD-15	0.31 (1.02)	0.29 (0.95)	N/A	0.28 (0.92)	None
BD-28	N/A	0.27 (0.89)	N/A	0.24 (0.79)	None
BD-40	N/A	0.27 (0.89)	N/A	0.30 (0.98)	None
Maximum	**0.31 (1.02)**	**0.30 (0.98)**	**N/A**	**0.30 (0.98)**	**0**
WG ZOI	**0.30 (1.0)**				

Table D-13
FDS simulation results applicable to end state BDSAT2 with a 15 MJ/m² target fragility and aluminum duct housing

FDS simulation	ZOI (m (ft))				
	Back	Front	Right	Above	Below
BD-9	0.40 (1.31)	0.39 (1.28)	N/A	0.38 (1.25)	0.21 (0.69)
BD-22	0.37 (1.21)	0.42 (1.38)	N/A	0.47 (1.54)	0.17 (0.56)
BD-34	N/A	0.43 (1.41)	N/A	0.38 (1.25)	None
BD-46	N/A	0.38 (1.25)	N/A	0.41 (1.34)	None
BD-52	0.44 (1.44)	0.44 (1.44)	0.40 (1.31)	N/A	0.46 (1.51)
Maximum	**0.44 (1.44)**	**0.44 (1.44)**	**0.40 (1.31)**	**0.47 (1.54)**	**0.46 (1.51)**
WG ZOI	**0.46 (1.50)**				

D.4.3.2 Determination of the NSBD Energetic ZOIs for FCTs of Less Than 1.5 s

The shortest FDS simulation in the original set of runs was 2 s. After a review of SAT FCTs, a significant number of SAT FCTs fell between 0.0 and 1.5 s, and using a 2 s fault would be excessively conservative. To provide a better resolution of faults with short clearing times, four additional FDS simulations were run with a 1 s fault duration. Table D-14 summarizes the subsequent binning and ZOI determination for short clearing times.

Table D-14
ZOI determination for FCTs of 2 s or less

FCT Bin	Duct Housing	ZOI (m (ft))		Rationale
		30 MJ/m² Target Fragility	15 MJ/m² Target Fragility	
0.0–0.5 s	Steel	0	0	In FDS, aluminum ducts were observed to breach between 0.2 and 0.3 s. Arc termination before or immediately after the breach is not expected to produce a ZOI external to the duct.
	Aluminum	0	0	
0.51–1.0 s	Steel	0	0	This bin's ZOIs are based on the additional 1 s FDS runs. In the FDS simulations, steel ducts were observed to breach at approximately 1 s. No external ZOI is expected if the arc terminates before or immediately after duct breach.
	Aluminum	0.15 (0.5)	0.15 (0.5)	
1.01–1.5 s	Steel	0.15 (0.5)	0.15 (0.5)	This bin's ZOIs are interpolated between the 0.51–1.0 s and the 1.51–2.0 s rows. For the 30 MJ/m² fragility targets, the interpolation results in 0.08 m (0.25 ft) and 0.23 m (0.75 ft) for steel and aluminum ducts, respectively. At a 0.5-ft (0.15-m) resolution, these are rounded up to 0.5 ft (0.15 m) and 1.0 ft (0.30 m).
	Aluminum	0.30 (1.0)	0.30 (1.0)	
1.51–2.0 s	Steel	0.30 (1.0)	0.15 (0.5)	This bin's ZOIs are based on the 2 s FDS runs (see Table D-12).
	Aluminum	0.46 (1.5)	0.30 (1.0)	

D.4.4 Summary of the NSBD Energetic ZOIs

The full set of energetic ZOIs for the NSBDs are provided in Table 9-2 (English units) and Table E-7 (SI units).

E
ZOI TABLES IN SI UNITS

E.1 Purpose

This appendix provides the ZOI tables in SI units for load centers, MV switchgear, and NSBDs.

E.2 Load Center ZOIs

The LV switchgear ZOIs in SI units are in Table E-1. The corresponding English unit table is Table 7-1.

Table E-1
Load center ZOIs in SI units

Load center supply breaker location and target fragility	Arc Energy (MJ)	Back/Front	External Side (m)	Top (m)
A – end location, upper elevation: 15 MJ/m²	90	None	0.76	0.61
A – end location, upper elevation: 30 MJ/m²	90	None	0.45	0.30
B and C – end location, lower elevation: 15 MJ/m²	90	None	0.76	None
B and C – end location, lower elevation: 30 MJ/m²	90	None	0.45	None
D – interior, upper elevation: 15 MJ/m²	90	None	None	0.61
D – interior, upper elevation: 30 MJ/m²	90	None	None	0.30
E and F – interior, lower elevation: 15 MJ/m²	90	None	None	None
E and F – interior, lower elevation: 30 MJ/m²	90	None	None	None

E.3 Medium Voltage Switchgear ZOIs

E.3.1 Screening ZOIs

The screening ZOIs for MV switchgear are provided in SI units in Table E-2. The corresponding English unit table is Table 8-2.

Table E-2
Screening ZOIs for MV switchgear in SI units

SAT fault clearing time	SAT arc energy (MJ)	UAT fault clearing time into generator-fed fault	UAT arc energy (MJ)	15 MJ/m^2 target fragility (m)	30 MJ/m^2 target fragility (m)
SAT (0–4.00 s)	135	UAT (0–0.50 s)	132	0.91	0.61
SAT (4.01+ s)	169	UAT (0.51–2.00 s)	200	1.1	0.76
		UAT (2.01–3.00 s)	233	4	1.2
		UAT (3.01+ s)	300	4.5	1.4

E.3.2 Configuration-Specific and Refinement ZOIs

The configuration-specific and refinement ZOIs for MV switchgear are provided in SI units in Table E-3 and Table E-4 (Zone 1 switchgear) and in Table E-5 and Table E-6 (Zone 2 switchgear). The corresponding English unit tables are Table 8-3 and Table 8-4 (Zone 1 switchgear) and Table 8-5 and Table 8-6 (Zone 2 switchgear).

Table E-3
Configuration-specific ZOIs for Zone 1 – 15 MJ/m² target fragility (SI units)

Zone 1 – 15 MJ/m² Target Fragility				Default ZOI dimensions (inclusive of horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift style circuit breakers			
Fault Location	Power Source and Duration	Arc Energy (MJ)	End State	Left/Right (m)	Front (m)	Back (m)	Top (m)	Left/Right (m)	Front (m)	Back (m)	Top (m)
Normal supply (0.57) secondary supply (0.28)	UAT: Generator fed	132	GF-15	0.76	0.61	0.91*	0.46	0.61	0.61	None	0.46
	SAT: 0–2.00 s	68	SAT2-15	0.46	0.30	0.61*	0.30	0.15	0.30	None	0.30
	SAT: 2.01–3.00 s	101	SAT3-15	0.61	0.46	0.76*	0.46	0.46	0.46	None	0.46
	SAT: 3.01–4.00 s	135	SAT4-15	0.76	0.61	0.91*	0.46	0.61	0.61	None	0.46
	SAT: ≥4.01 s	169	SATMAX-15	0.91	0.76	1.1*	0.61	0.76	0.76	None	0.61
Loads: SBL (0.14)	SBL: Z1 generic (≥4 s)	135	SBL4-15	0.76	0.61	0.91*	0.46	0.61	0.61	None	0.46
	SBL: ≥2 s	68	SBL2-15	0.46	0.30	0.61*	0.30	0.15	0.30	None	0.30
	SBL: 2.01–3 s	101	SBL3-15	0.61	0.46	0.76*	0.46	0.46	0.46	None	0.46
Loads fed by normal supply (0.01)	UAT: 0–0.5 s + GF	132	GF-15	0.76	0.61	0.91*	0.46	0.61	0.61	0.91**	0.46
	UAT: 0.51–2 s + GF	200	UAT2-15	0.91	0.76	1.1*	0.76	0.76	0.76	1.1**	0.76
	UAT: 2.01–3 s + GF	233	UAT3-15	1.1	0.91	1.2*	0.91	0.91	0.91	1.2**	0.91
	UAT: ≥3 s + GF	300	UATMAX-15	1.2	1.1	1.4*	1.1	1.1	1.1	1.4**	1.1
	SAT: 0–2.00 s	68	SAT2-15	0.46	0.30	0.61*	0.30	0.15	0.30	0.61**	0.30
	SAT: 2.01–3.00 s	101	SAT3-15	0.61	0.46	0.76*	0.46	0.46	0.46	0.76**	0.46
	SAT: 3.01–4.00 s	135	SAT4-15	0.76	0.61	0.91*	0.46	0.61	0.61	0.91**	0.46
	SAT: ≥4.01 s	169	SATMAX-15	0.91	0.76	1.1*	0.61	0.76	0.76	1.1**	0.61

GF= generator fed

*For horizontal-draw-out-style supply circuit breaker cubicles and load circuit breaker cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to no back ZOI (left/right/front/top dimensions the same).

**For the vertical-lift circuit breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% no back ZOI (left/right/front/top dimensions the same).

Table E-4
Configuration-specific ZOIs for Zone 1 – 30 MJ/m² target fragility (SI units)

Zone 1 – 30 MJ/m² Target Fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	Power Source and Duration	Arc Energy (MJ)	End State	Left/Right (m)	Front (m)	Back (m)	Top (m)	Left/Right (m)	Front (m)	Back (m)	Top (m)
Normal supply (0.57) secondary supply (0.28)	UAT: Generator fed	132	GF-30	0.46	0.30	0.61*	0.30	0.30	0.30	None	0.30
	SAT: 0–2.00 s	68	SAT2-30	0.15	None	0.30*	None	None	None	None	None
	SAT: 2.01–3.00 s	101	SAT3-30	0.30	0.15	0.46*	0.15	0.15	0.15	None	0.15
	SAT: 3.01–4.00 s	135	SAT4-30	0.46	0.30	0.61*	0.30	0.30	0.30	None	0.30
	SAT: ≥4.01 s	169	SATMAX-30	0.61	0.61	0.76*	0.30	0.46	0.61	None	0.30
Loads: SBL (0.14)	SBL: Z1 generic (≥4 s)	135	SBL4-30	0.46	0.30	0.61*	0.30	0.30	0.30	None	0.30
	SBL: ≥2 s	68	SBL2-30	0.15	None	0.30*	None	None	None	None	None
	SBL: 2.01–3 s	101	SBL3-30	0.30	0.15	0.46*	0.15	0.15	0.15	None	0.15
Loads fed by normal supply (0.01)	UAT: 0–0.5 s + GF	132	GF-30	0.46	0.30	0.61*	0.30	0.30	0.30	0.61**	0.30
	UAT: 0.51–2 s + GF	200	UAT2-30	0.61	0.46	0.76*	0.46	0.46	0.46	0.76**	0.46
	UAT: 2.01–3 s + GF	233	UAT3-30	0.76	0.61	0.91*	0.61	0.61	0.61	0.91**	0.61
	UAT: ≥3 s + GF	300	UATMAX-30	0.91	0.76	1.1*	0.76	0.76	0.76	1.1**	0.76
	SAT: 0–2.00 s	68	SAT2-30	0.15	None	0.30*	None	None	None	0.30**	None
	SAT: 2.01–3.00 s	101	SAT3-30	0.30	0.15	0.46*	0.15	0.15	0.15	0.46**	0.15
	SAT: 3.01–4.00 s	135	SAT4-30	0.46	0.30	0.61*	0.30	0.30	0.30	0.61**	0.30
	SAT: ≥4.01 s	169	SATMAX-30	0.61	0.61	0.76*	0.30	0.46	0.61	0.76**	0.30

GF= generator fed

*For horizontal-draw-out-style supply circuit breaker cubicles and load circuit breaker cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to no back ZOI (left/right/front/top dimensions the same).

**For the vertical-lift circuit breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% no back ZOI (left/right/front/top dimensions the same).

Table E-5
Configuration-specific ZOIs for Zone 2 – 15 MJ/m² target fragility (SI units)

Zone 2 – 15 MJ/m² Target Fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	**Power Source and Duration**	**Arc Energy (MJ)**	**End State**	**Left/Right (m)**	**Front (m)**	**Back (m)**	**Top (m)**	**Left/Right (m)**	**Front (m)**	**Back (m)**	**Top (m)**
Refinement Level 1: Primary, secondary, and loads: 0.05 **Refinement Level 2:** Normal supply: 0.03 Secondary supply: 0.02	UAT: 0–0.5 s + GF	132	GF-15	0.76	0.61	0.91*	0.46	0.61	0.61	0.91**	0.46
	UAT: 0.51–2 s + GF	200	UAT2-15	0.91	0.76	1.1*	0.76	0.76	0.76	1.1**	0.76
	UAT: 2.01–3 s + GF	233	UAT3-15	1.1	0.91	1.2*	0.91	0.91	0.91	1.2**	0.91
	UAT: ≥ 3 s + GF	300	UATMAX-15	1.2	1.1	1.4*	1.1	1.1	1.1	1.4**	1.1
	SAT: 0–2.00 s	68	SAT2-15	0.46	0.30	0.61*	0.3	0.15	0.30	None	0.30
	SAT: 2.01–3.00 s	101	SAT3-15	0.61	0.46	0.76*	0.46	0.46	0.46	None	0.46
	SAT: 3.01–4.00 s	135	SAT4-15	0.76	0.61	0.91*	0.46	0.61	0.61	None	0.46
	SAT: ≥ 4.01 s	169	SATMAX-15	0.91	0.76	1.1*	0.61	0.76	0.76	None	0.61
Refinement Level 1: Zone 1 SBL: 0.95 **Refinement Level 2:** Zone 1 SBL Normal supply: 0.51 Secondary supply: 0.30 Loads: 0.01	SBL: Z1 generic (≥ 4s)	135	SBL4-15	0.76	0.61	0.91*	0.46	0.61	0.61	None	0.46
	SBL: ≥ 2 s	68	SBL2-15	0.46	0.30	0.61*	0.30	0.15	0.30	None	0.30
	SBL: 2.01–3 s	101	SBL3-15	0.61	0.46	0.76*	0.46	0.46	0.46	None	0.46
Refinement Level 2: Zone 2 SBL (loads): 0.13	SBL: Z2 generic (≥2 s)	68	SBL2-15	0.46	0.30	0.61*	0.30	0.15	0.30	None	0.30

GF= generator fed
*For horizontal-draw-out-style supply cubicles and load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to a no-back ZOI (left/right/front/top dimensions the same).
**For the vertical-lift breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI in the table, 80% to the no-back ZOI (left/right/front/top dimensions the same).

Table E-6
Configuration-specific ZOIs for Zone 2 – 30 MJ/m² target fragility (SI units)

Zone 2 – 30 MJ/m² Target Fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	**Power Source and Duration**	**Arc Energy (MJ)**	**End State**	**Left/Right (m)**	**Front (m)**	**Back (m)**	**Top (m)**	**Left/ Right (m)**	**Front (m)**	**Back (m)**	**Top (m)**
Refinement Level 1: Primary, secondary, and loads: 0.05 **Refinement Level 2:** Normal supply: 0.03 Secondary supply: 0.02	UAT: 0–0.5 s + GF	132	GF-30	0.46	0.30	0.61*	0.30	0.30	0.30	0.61**	0.30
	UAT: 0.51–2 s + GF	200	UAT2-30	0.61	0.46	0.76*	0.46	0.46	0.46	0.76**	0.46
	UAT: 2.01–3 s + GF	233	UAT3-30	0.76	0.61	0.91*	0.61	0.61	0.61	0.91**	0.61
	UAT: ≥ 3 s + GF	300	UATMAX-30	0.91	0.76	1.1*	0.76	0.76	0.76	1.1**	0.76
	SAT: 0–2.00 s	68	SAT2-30	0.15	None	0.30*	None	None	None	None	None
	SAT: 2.01–3.00 s	101	SAT3-30	0.30	0.15	0.46*	0.15	0.15	0.15	None	0.15
	SAT: 3.01–4.00 s	135	SAT4-30	0.46	0.30	0.61*	0.30	0.30	0.30	None	0.30
	SAT: ≥4.01 s	169	SATMAX-30	0.61	0.61	0.76*	0.30	0.46	0.61	None	0.30
Refinement Level 1: Zone 1 SBL: 0.95 **Refinement Level 2:** Zone 1 SBL Normal supply: 0.51 Secondary supply: 0.30 Loads: 0.01	SBL: Z1 generic (≥ 4s)	135	SBL4-30	0.46	0.30	0.61*	0.30	0.30	0.30	None	0.30
	SBL: ≥ 2 s	68	SBL2-30	0.15	None	0.30*	None	None	None	None	None
	SBL: 2.01–3 s	101	SBL3-30	0.30	0.15	0.46*	0.15	0.15	0.15	None	0.15
Refinement Level 2: Zone 2 SBL (loads): 0.13	SBL: Z2 generic (≥2 s)	68	SBL2-30	0.15	None	0.30*	None	None	None	None	None

GF= generator fed
*For horizontal-draw-out-style supply circuit breaker cubicles and load circuit breaker cubicles, the following fraction can be applied to the back direction: 20% to the ZOI shown in the table, 80% to the no-back ZOI (left/right/front/top dimensions the same).
**For the vertical-lift circuit breaker load cubicles, the following fraction can be applied to the back direction: 20% to the ZOI in the table, 80% to the no-back ZOI (left/right/front/top dimensions the same).

E.4 Non-Segregated Bus Duct ZOIs

Table E-7 provides the NSBD ZOIs in SI units. The corresponding English unit table is Table 9-2.

Table E-7
Non-segregated bus duct ZOIs (SI units)

End state	Power transformer and fault clearing time	Bus duct enclosure material and target fragility			
		Steel enclosure with target fragility of 15 MJ/m^2 (m)	Steel enclosure with target fragility of 30 MJ/m^2 (m)	Aluminum enclosure with target fragility of 15 MJ/m^2 (m)	Aluminum enclosure with target fragility of 30 MJ/m^2 (m)
BDSAT0.5 BDSBL0.5	SAT: 0–0.50 s SBL: 0–0.50 s	0	0	0	0
BDSAT1 BDSBL1	SAT: 0.51–1.00 s SBL: 0.51–1.00 s	0	0	0.15	0.15
BDSAT1.5 BDSBL1.5	SAT: 1.01–1.50 s SBL: 1.01–1.50 s	0.15	0.15	0.30	0.30
BDSAT2 BDSBL2 BDLV	SAT:1.51–2.00 s SBL: Z2 generic* (≥ 2 s) and 1.51-2.00s Low voltage	0.30	0.15	0.46	0.30
BDSAT3 BDSBL3	SAT:2.01–3.00 s SBL:2.01–3.00 s	0.61	0.30	0.76	0.46
BDSAT4 BDSBL4	SAT:3.01–4.00 s SBL: Z1 generic* (≥ 4 s)	0.76	0.46	0.91	0.61
BDSATMAX	SAT: ≥ 4.01 s	0.91	0.61	1.07	0.61
BDGenFed	UAT: 0–0.5 s + GF	0.76	0.46	0.91	0.61
BDGF2	UAT: 0.51–2 s + GF	1.07	0.61	1.22	1.07
BDGF3	UAT: 2.01–3 s + GF	1.22	1.07	1.22	1.07
BDGFMAX	UAT: ≥3 s + GF	1.37	0.91	1.52	0.91

GF= generator fed

*For the SBL end state, an optional refinement can be made by calculating the FCT of the primary supply breaker for the MV switchgear feeding the NSBD following the steps in Section 6.4. The appropriate end state (BDSBL0.5, BDSBL1, BDSBL1.5, BDSBL2, or BDSBL3) should be selected based on the FCT.

F
TARGET FRAGILITY FOR EQUIPMENT NOT ADDRESSED IN THE FRAGILITY REPORT

F.1 Introduction

During the development of the target fragility thresholds for electrical cables, bus ducts, and electrical cable protective features in the HEAF fragility report [15], the working group deferred the characterization of the failure threshold(s) and guidance for equipment that can also be a fire PRA target. The list of equipment includes:

- Cable bus ducts, cable wireways, and junction boxes
- Battery chargers
- Dry-type transformers
- Inverters
- Load centers
- Motor control centers
- Motor-generator sets
- Switchgear

The purpose of this appendix is to develop guidance based on the current state of knowledge for the equipment listed above. This guidance is intended for equipment in proximity to the HEAF source. This appendix does not address integral equipment immediately adjacent to the HEAF source, such as a vertical section of switchgear next to the failing section (see Section 6 for treatment).

F.2 Background

F.2.1 Equipment Definitions

Most of the electrical equipment is well-defined. The following definitions are provided for specific equipment related to cable routing:

Cable bus duct: An assembly of insulated conductors with fittings and conductor terminations in a completely enclosed, ventilated protective metal housing. The assembly is designed to carry fault current and to withstand the magnetic forces of such current. Cable bus shall be permitted at any voltage or current for which the spaced conductors are rated. Cable bus is ordinarily assembled at the point of installation from components furnished or specified by the manufacturer in accordance with instructions for the specific job [51].

Cable wireway: Sheet-metal troughs with hinged or removable covers for housing and protecting electric wires and cable and in which conductors are laid in place after the wireway has been installed as a complete system [51]. Sometime referred to as "cable troughs."

Junction box: A fully enclosed metal box containing terminals for joining or splicing cables. For a complete definition of a junction box, please refer to FAQ 13-0006 [52].

F.2.2 Testing

Between 2014 and 2016, the NRC performed HEAF experiments as part of an international program to better understand the HEAF phenomena and confirm existing fire PRA guidance [1,2]. As part of the program, several experiments involving aluminum resulted in the deposition of a conductive white material on the surfaces of the test cell and KEMA Labs power supply bus bars. The material deposition decreased the insulation resistance between the power supply phases and, in at least one instance, required significant decontamination efforts to return the power supply to service [7]. The electrical system impacted was the uninsulated MV power system (bus bars) in the KEMA Labs test cell. This open-air configuration of bus bars is not typical in NPPs.

Based on the observations from the OECD program, the NRC fielded additional experimentation during a subsequent series of experiments [42] to evaluate, in part, the HEAF byproduct's conductive nature. The fielded instrumentation included air breakdown strength, air conductivity, and surface deposit analysis. These instruments were placed at various locations (between 5 ft [1.5 m] and 13 ft [4.0 m]) and orientations (typically on the axis of the arc jet) to evaluate the HEAF environment over a diverse range of conditions. These sensors were placed in open air to evaluate the phenomenon in what is believed to be a conservative manner. The open-air configuration provides direct exposure to the HEAF byproducts, whereas in the field, most electrical equipment is housed within electrical enclosures with varying ventilation configurations. Housing the electrical equipment provides a barrier between the HEAF byproduct and the targeted electrical equipment not present in the experimental design. As such, the approach taken was to promote the occurrence of the phenomenon. If the phenomenon is not observed in this configuration, then a high confidence would exist for similar results in a more typical enclosed environment. If the complement of this outcome were to occur, then more realistic testing would be required to better understand the influence on the phenomenon. The results [42] from the open-air configuration concluded that,

> For the experimental conditions and locations investigated, the results indicated that HEAF byproduct dispersed into the air causing equipment arc over, referred to as flashover, was unlikely at the measurement locations. This conclusion may not hold for locations closer to the source.
>
> Surface conductivity measurements of HEAF byproduct surface deposition showed a decrease in resistance compared to pre-experimental conditions. For the experimental conditions and locations investigated, the result indicated that an impact on plant safety equipment is not likely. The impact of surface deposition, however, is highly dependent on the design, configuration, location, and sensitivity of the equipment.

The results from the measurements taken during testing suggest that the change in air-particulate conductivity due to the effluent from the HEAF does not cause subsequent equipment failures from flashovers. The test results were not definitive to completely exclude the surface conductivity concern.

A higher level of confidence can be assured for actual plant electrical equipment because target conductors are surrounded by enclosures with limited ventilation or ventilation configurations that limit the ingress of the HEAF byproduct. However, the measurement results are dependent on the location and configuration as well as the level of conductivity required to cause equipment failure from changes in surface conductivity. There is limited understanding on the applicability of this failure mode in the field.

F.2.3 Operating Experience

From a review of HEAF operating experience, no events were reported where targets near the HEAF initiator were breached as a result of the HEAF thermal energy or failed as a result of HEAF byproduct deposition. Two HEAF events have been reported where combustion products from the post-HEAF ensuing fire (soot, black smoke) migrated through the switchgear and resulted in operation of a live bus protection (i.e., breaker trip). This phenomenon of heavy smoke serving as a medium for arc propagation is referred to as flashover in this appendix. The two events are summarized below.

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The NRC Special Inspection Report [53] documents that “Soot and combustion products from the fire caused an unexpected phase-to-phase fault on non-segregated bus duct conductors between open bus-tie breaker BT-1B4A and island bus 1B3A-4A.” Specifically, “Combustion products from the fire in load center 1B4A migrated across normally open bus-tie breaker BT-1B4A into the non-segregated bus duct, shorting all three electrical phases.” NRC Information Notice 2017-04 also states that combustion products from the fire caused the second 1B3A-4A fault [6].

The event showed heavy deposit of soot and black smoke from the ensuing fire that migrated throughout the load center. The load center outer enclosure was not breached and no evidence of gray or white residue (i.e., aluminum oxide) was observed or reported outside of the load center’s bus supply circuit breaker outer enclosure.

The language of the NRC Special Inspection Report quoted above can be misinterpreted to mean that the flashover generated by the soot and combustion byproduct occurred in the NSBD. However, the flashover occurred across the bus duct connection points to the bus-tie breaker within the switchgear. This connection point was three vertical sections from where the HEAF initiated.

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This is the only other event where the combustion products from the fire caused a fault—in this instance, on the RAT’s exposed energized bus stabs located two circuit breaker cubicles away from the bus supply circuit breaker cubicle.

Per Information Notice 2002-01, failure of the 4.16 kV breaker's C-phase main contacts to fully close caused the fault. This resulted in arcing and a production of a thick, dark, ionized smoke. The breaker was a Brown Bovari Type HK three-pole, MV ac power circuit breaker rated for 3000A (continuous) and 350 MVA (interrupting). Off-site power was lost when ionized smoke (which is conductive) diffused through holes (through which wires passed) and conduits between adjacent cubicles. This shorted the energized incoming terminals of the off-site power supply from the RAT. The fault blew open the cubicle door of the off-site supply circuit breaker and blew off an insulating boot that covered the A-phase bus bar. The high-voltage supply breakers upstream of the RAT opened to clear the fault. This interrupted non-vital off-site power to the unit.

F.2.4 Summary of OPEX insights

No reported HEAF events caused secondary consequential failure of equipment outside the HEAF initiator due to thermal damage or direct HEAF jet byproducts for equipment listed in Section F.1. Two HEAF events reported secondary consequential faults from thick, dark ionized smoke. These faults occurred within the set of interconnected vertical sections/enclosures within a switchgear or load center bus. The OPEX does not demonstrate subsequent failures of nearby equipment as a direct result of the HEAF-generated byproduct.

F.3 Discussion

The evidence presented in Section F.2 suggests that subsequent failure of electrical equipment in the vicinity of the HEAF due to the particulate concern is not likely. In addition, air-conductivity and air-breakdown measurements taken during testing do not indicate conditions suitable to induce electrical failure. Although conductivity measurements combined with the failed testing facility equipment (exposed open-air power conductors) may suggest potential equipment failures, the distinct differences between the test equipment and the field application (enclosed conductors) and correlation of the test result to equipment response does not support a firm conclusion. Therefore, testing results and insights from OPEX are interpreted as suggesting that equipment failure by particle interaction depends on the specific field configuration and event characteristics. The range of configurations that may influence equipment failure caused by HEAF byproducts is difficult to predict. Based on the information known to the working group, at this time, no empirical or operational data supports development of a ZOI for surface conductivity until more data (testing or OPEX) is available to prove otherwise.

The thermal hazard posed by a HEAF is the most likely mechanism to induce failure to targets. The thermal hazard has the potential to breach enclosed equipment. Once enclosure breach occurs, the components within the target equipment are directly exposed to the HEAF. The analysis performed in the fragility report [15] evaluated this failure progression for bus ducts, electrical cable conduit, and electrical cable trays with bottom and top covers. From that analysis, the working group provided specific failure thresholds for enclosure materials (steel or aluminum) and electric cable characteristics (cable-jacket type).

One difference between the targets evaluated in the target fragility report [15] and the targets identified here is ventilation. Bus ducts have limited ventilation or breathers, and cable conduits are not ventilated. Ventilation configurations for the electrical equipment identified can vary substantially from that assumed in the fragility report [15]. Switchgear, load centers, motor control centers, dry-type transformers, motor-generator sets, battery chargers, and inverters are commonly ventilated to provide cooling to the equipment contained within the electrical enclosure. Depending on the design, cable bus ducts can be ventilated. The type, location, and configuration of the electrical enclosure ventilation varies by manufacturer and by equipment type. Some equipment offers large and open ventilation in which the components within the enclosure are visible through the vents, while others have more limited and restrictive ventilation configuration. Because of these variations in electrical enclosure ventilation openings, the working group consensus is that vents could impact the conclusions from previous fragility evaluations [15].

Based on this information, the working group developed a qualitative approach to use existing fragility thresholds for equipment where limited ventilation exists and to use a more conservative fragility threshold for equipment with open ventilation. Along with the ZOI estimates developed by the working group, the criteria for determining the threshold are primarily dependent on whether ventilation openings in the electrical enclosures will limit the exposure. Section F.4.2 presents detail on this approach.

F.3.1 Cable Bus Ducts, Cable Wireways, and Electrical Junction Boxes

In the target fragility report [15], heat transfer calculations for electrical raceway conduit and electrical raceway cable tray covers were conducted to evaluate the thermal shielding and protection provided by the raceway systems. That report showed that the raceway systems provide some initial protection from the arcing phase of the HEAF, and the sustained elevated temperature of the raceway system (conduit or tray covers) over an extended period of time acts as an additional radiation source, contributing to cable thermal damage. Based on this and other insights documented in the fragility report, the working group concluded that not enough information was available to determine any recommended change to the current cable failure criteria.

Cable bus ducts, cable wireways (troughs), and electrical junction boxes have attributes that are similar to the cable trays with covers and cable conduits previously evaluated by the working group [54]. As such, the working group recommends that the fragility thresholds developed for cable protective devices in the fragility report [15] can be extended to cable bus ducts, cable wireways, and junction boxes.

F.3.2 Electrical Equipment

Switchgear, load centers, MCCs, dry-type transformers, battery chargers, inverters, and motor-generator sets are present in commercial NPPs in a variety of shapes, sizes, and configurations. From an equipment failure/damage point of view, two design attributes influence HEAF impact on electrical equipment targets: ventilation and enclosure material.

All electrical equipment has some ventilation that circulates external air through the enclosure to remove excess heat. In naturally ventilated enclosures, ventilation is commonly located at the top and bottom elevations to allow buoyance and stack principles to effectively create a unidirectional flow of air. In mechanically ventilated enclosures, typically one or more fans pull air out of or into the enclosure. In some designs, air ductwork within the enclosure is also used to allocate the air distribution within the enclosure and minimize hot spots. Vents can be located on any side of the enclosure, including the top and bottom. No standards define the design configuration of enclosure ventilation, other than to limit ventilation opening size to prevent objects from penetrating the enclosure and possibly contacting live parts [54][55] or to ensure that ambient thermal conditions are met [56].

From the information presented to the working group and their discussion, ventilation system design will have a primary influence on the ability of the HEAF thermal energy to enter the enclosure and potentially cause equipment failure. Limited ventilation will minimize the heat transfer from convective and conductive heating, while open ventilation will not provide the same level of shielding from these heating mechanisms and allows possible direct thermal-radiation exposure. Review of field installations identified a variety of common configurations, which Sections F.3.2.1 and F.3.2.2 summarize. These configurations are presented as illustrative examples to help categorize the ventilation configuration for electrical enclosures found in the field and correlate fire PRA guidance on the treatment of assumed equipment failure/damage. Additionally, because many types of electrical enclosures have ventilation on the top of the enclosure, vents on the top of the enclosure should also be considered (particularly for the bus duct HEAF waterfall).

F.3.2.1 Designs That Minimize Exposure (Limited Ventilation)

F.3.2.1.1 Louver Vents

Louver vents provide openings in the enclosure while maintaining protection from accidental entry of dirt, dripping water, or foreign objects. Louvers are press-formed from sheet metal. This results in a raised window with protection from three sides and an opening on one side (bottom). Figure F-1
1 provides photographs of electrical enclosures with louver vents. Based on the limited entry that louver vents provide, the working group considers equipment with louver vents as limited ventilation. Note that louvered vents do not require filters (see section F.3.2.1.2) to be classified as limited ventilation.

Figure F-1
Photos of louvers on enclosures

F.3.2.1.2 Filtered Vents

In certain applications, air filters (typically replaceable or reusable) or fine mesh screens (typically permanent) are used in addition to the vent. They provide an added layer of protection against any external contaminants that could enter the enclosure and are viewed as adding a layer of protection against the HEAF concern. As such, the working group considers vents with filters as a limited-ventilation configuration. Figure F-2 through Figure F-5 present examples.

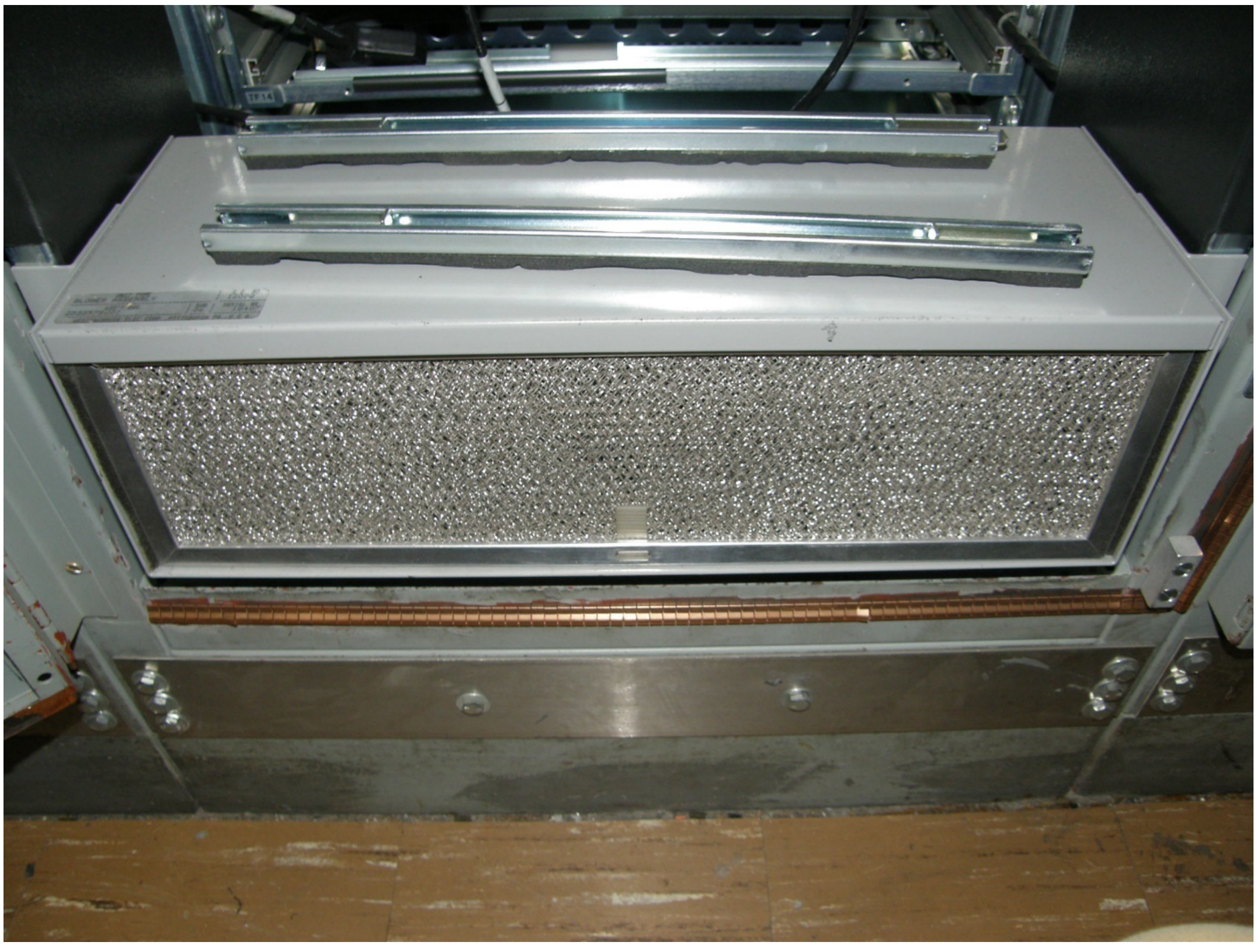

Figure F-2
Internal filter (shown with door open, filter surface area covers door vent area)

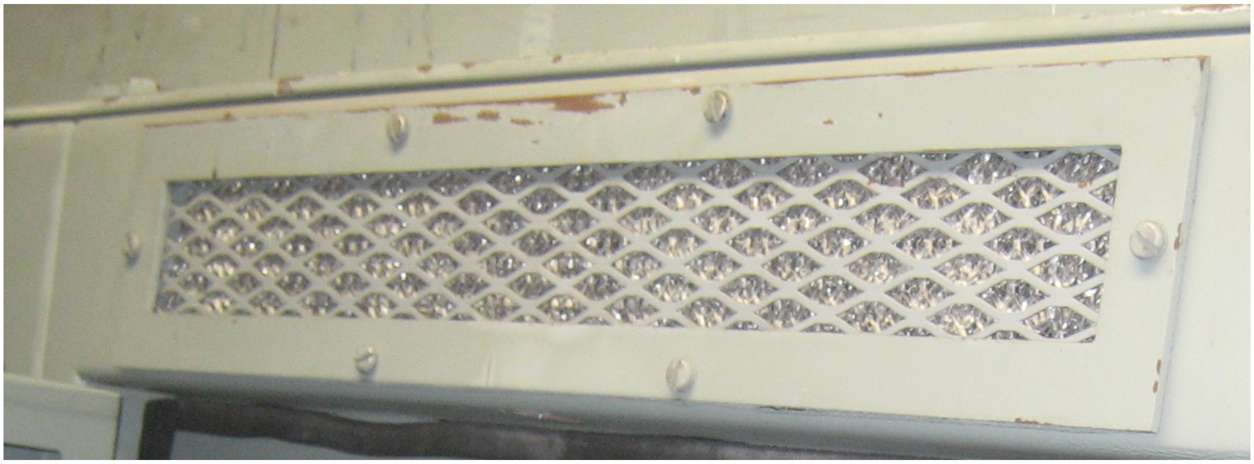

Figure F-3
Expanded metal vents with filters

Figure F-4
External filter (shown on top of enclosure)

Figure F-5
Vent screen (on internal side of door vent)

F.3.2.1.3 Other Configurations

The guidance on configurations that minimize exposure have been limited to specific design features in openings and vents, which should constitute the majority of conditions encountered in the field. Other relatively small openings (e.g., drill holes, holes with missing bolts, gaps in a steel enclosure at the seams) or sizes smaller than those of an individual opening within punched or extended vents (as described in Section F.3.2.1) should be treated as a design that impedes ingress.

F.3.2.2 Designs That Do Not Impede Ingress

F.3.2.2.1 Open-Punched and Expanded-Metal Vents

Unlike louver vents, which do not remove material during the manufacturing process, open vents created by punching metal from the sheet provide a less efficient means of limiting HEAF energy ingress to components within the enclosure. In many instances, the enclosure contents are viewable from the enclosure exterior. As such, the working group concludes that open vents may not limit HEAF thermal energy from impacting the target equipment and should be classified as open ventilation. Figure F-6 though Figure F-8 provide photographs of open vents for different configurations. These examples are not inclusive of all designs found in the field.

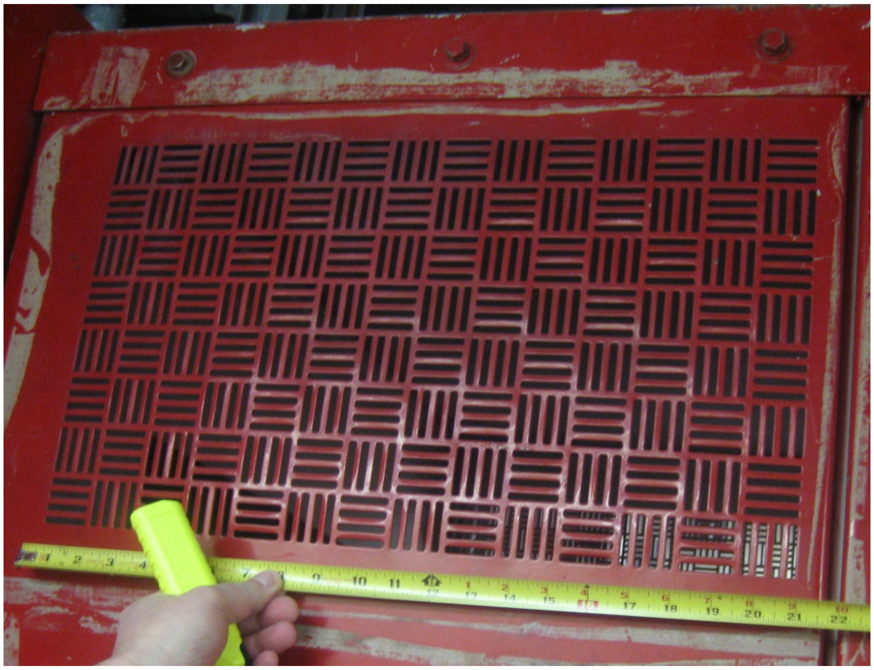

Figure F-6
Photo of open parquet vents (switchgear)

Figure F-7
Photo of open rounded-rectangular vent (LV switchgear)

Figure F-8
Photo of open rectangular vents (inverter)

Expanded-metal vents are similar to open-punched vents, except the manufacturing process is different. Here the material is not removed from the sheet; instead, a break expands the material to make the opening. While the manufacturing processes differ, the open-area configuration is similar to that of open-punched vents and is classified accordingly as open ventilation. Figure F-9 and Figure F-10 show examples of expanded-metal vents.

Figure F-9
Photo of expanded-metal vents on air-cooled transformer

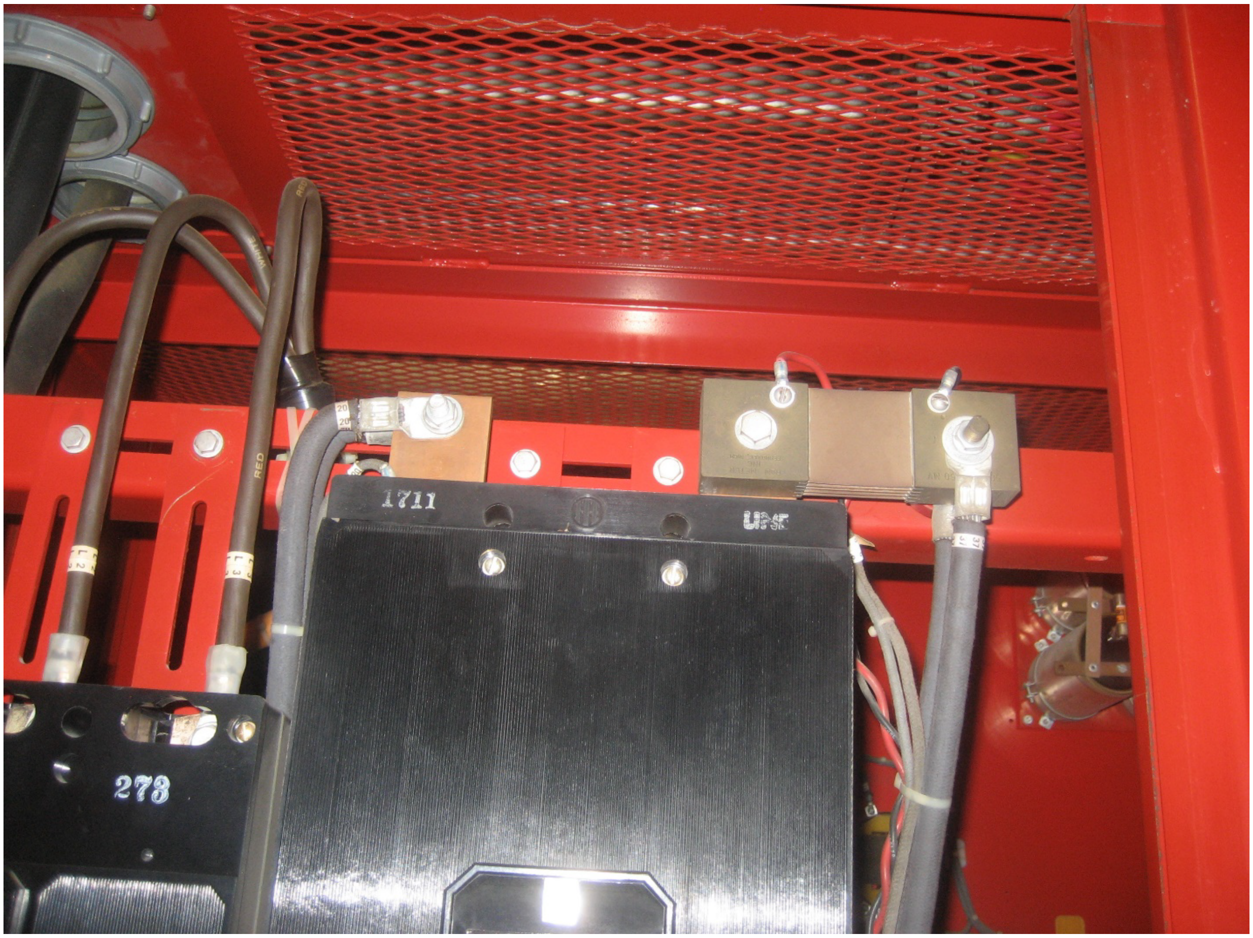

Figure F-10
Photo of expanded-metal vent on top of a switchgear enclosure viewed from inside the enclosure

F.3.2.2.2 Non-Enclosed Equipment

Although rare, configurations exist where electrical equipment is not contained within an electrical enclosure. These configurations are more likely to be in LV communication or instrumentation rooms than in rooms containing electrical distribution equipment. However, if electrical equipment targets are not within an enclosure, they should be considered open ventilation and subject to the impact of HEAF thermal damage. Figure-11 provides a photograph of an open-air instrumentation rack.

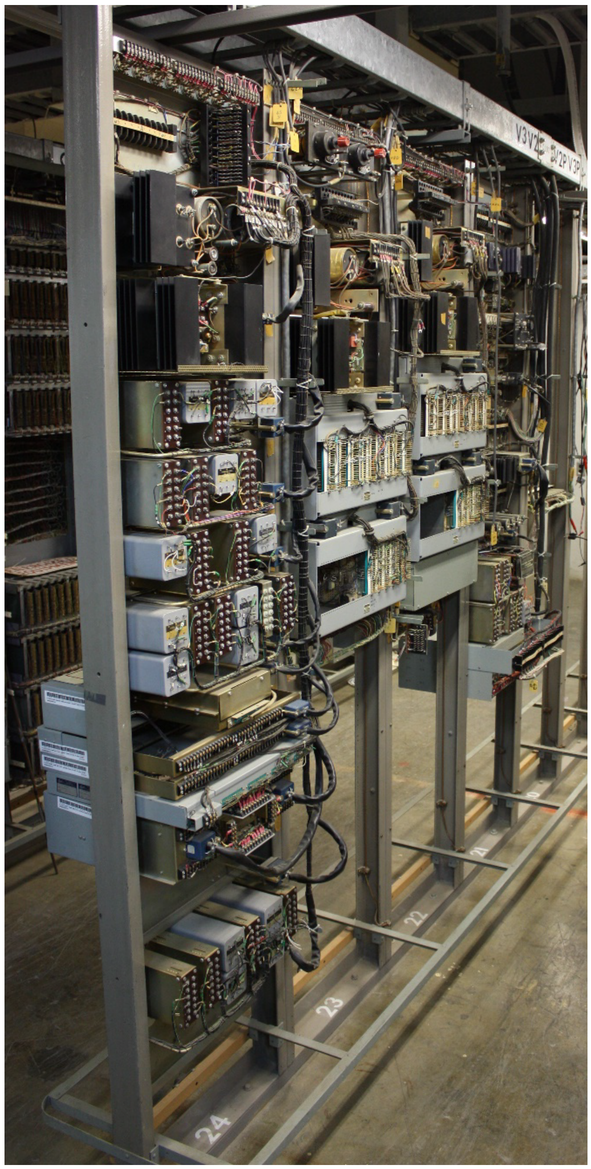

Figure F-11
Open-air instrumentation (not enclosed)

F.4 Guidance

F.4.1 Cable Bus Ducts, Cable Wireways, and Junction Boxes Targets

Cable bus ducts, cable wireways, and junction boxes should be treated consistently with the treatment of thermoplastic jacketed and thermoset jacketed cables, as described in Section 4 of RIL 2022-01 [15]). See Section F.3.1 for the technical basis.

F.4.2 Other Electrical Equipment Targets

The following guidance is provided for battery chargers, dry transformers, inverters, load centers, motor control centers, motor generator sets, and switchgear.

1. Determine the scenario-specific ZOI by identifying the HEAF location (e.g., supply breaker elevation, vertical section[s], length of bus duct, bus duct transition point, and so on) and the energetic-blast ZOI (see Section 7, 8, or 9).
2. As a bounding and conservative approach (this step does not require the characterization of ventilation/openings), use the 15 MJ/m^2 threshold to capture the potential damage of non-cable fire PRA targets within the ZOI. This includes electrical enclosures, electrical enclosures with cable endpoints, or other equipment identified in Section F.1. For this additional equipment damage, do not postulate sustained ignition.
3. For further refinements of the results obtained in Step 2, the analyst can review the equipment-related targets and determine if the venting contained within the ZOI is considered as limited ventilation or open ventilation. The venting's location relative to the HEAF ignition source can be also considered in this step (i.e., whether it is in the line of sight of the HEAF ignition source). If considering vent location, each vent in the enclosure should be evaluated. The enclosure should be modeled assuming the vent configuration with the potential to allow the most damage (if multiple vents are within the line of sight).
    a. "Limited ventilation" refers to equipment that is closed (no vents) or that has vents with louvers or filters. Enclosures with vents that are not in the line of sight of the HEAF are considered limited ventilation.
    b. "Open ventilation" refers to equipment with vents exposed (including open-punched vents, expanded-metal vents, or non-enclosed equipment) and in the line of sight of the HEAF. These openings may allow the ingress of heat/particles from the HEAF.
4. The fragility thresholds for limited ventilation and open ventilation for equipment defined in Section F.1 are as follows:

- Limited ventilation:
    - Electrical failure/damage for electrical equipment within steel enclosures is 30 MJ/m^2.
    - Electrical failure/damage for electrical equipment within aluminum enclosures is 15 MJ/m^2.
    - No sustained ignition is assumed, concurrent with or after the HEAF.
- Open ventilation:
    - Electrical failure/damage for electrical equipment within any metal enclosures is 15 MJ/m^2.
    - No sustained ignition is assumed, concurrent with or after the HEAF.

G
EXAMPLES

Six examples demonstrate aspects of the methodology in different scenarios.

G.1 Example 1: NUREG/CR-6850 Medium-Voltage Switchgear

The example from Appendix M of NUREG/CR-6850 [1] is assessed using the methodology in NUREG/CR-6850 and the updated methodology presented in this report. The information provided in the example includes the following:

- The source is a MV switchgear.
- There are two targets in a stack of three cable trays above the cabinet.
  - The first target is the first tray located 3 ft (0.9 m) above the cabinet.
  - The second target is in the third tray.

Additional information is necessary to apply the revised methodology, defined for this example as follows:

- The switchgear is located in Zone 1 (see Section 3.1).
  - A split fraction of 0.86 is used to apportion the Bin 16.b generic fire ignition frequency for Zone 1 switchgear (see Section 5.2.2.3).
- There are six Zone 1 switchgear banks, including the bank in which the HEAF is postulated.
- The normal supply for the switchgear is the UAT.
  - The FCT is 1.5 s.
- The secondary supply for the switchgear is the SAT.
  - The FCT is 1 s.
- There is a generator circuit breaker.
- The targets are subject to TP damage criteria.
- Vertical sections are separated by two steel barriers (i.e., double wall construction).
- The target cable tray stack runs above both the normal and secondary supply vertical sections (see Figure G-1).

G.1.1 NUREG/CR-6850 Methodology

When following NUREG/CR-6850, Appendix M, the first target tray is assumed to ignite concurrently with the arcing fault because it is located within the 5 ft (1.5 m) vertical energetic ZOI. The second tray in the stack (not a PRA target) does not immediately ignite because the first tray blocks the line of sight of the energetic HEAF. (The second tray ignites 4 minutes after the first tray and third tray in the stack [the second target in this example] ignites and is assumed damaged 3 min later [7 min post-HEAF]).

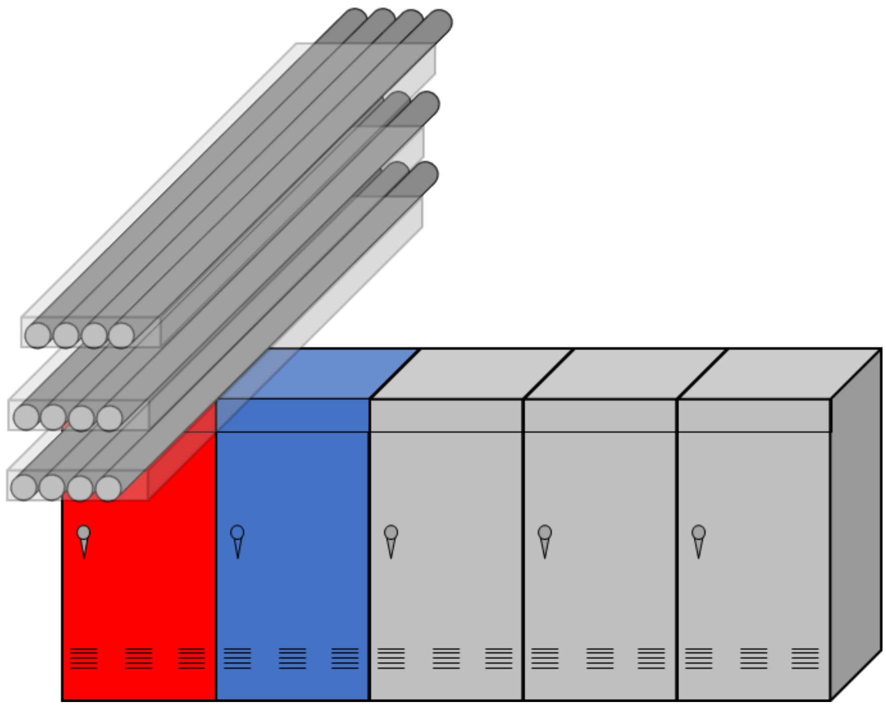

Figure G-1
Example 1: Switchgear bank, normal supply in red, secondary supply in blue

The frequency for the scenario that damages the first target is determined as the following:

$$(\lambda_{16.b}) \cdot W_{is}$$

Where the ignition source weighting factor, W_{is}, is the number of vertical sections included in the scenario divided by the number of MV switchgear vertical sections at the plant.

The first target tray is damaged by the energetic of the HEAF, and no non-suppression probability (NSP) can be credited. An NSP can be applied for each end state considering the second tray, the third tray, and any additional targets beyond the third tray in the stack. Each of these end states has a conditional probability of occurrence. The conditional probability of each end state must sum to 1.0. Assume the NSPs are determined following the approach in NUREG/CR-6850. Table G-1 summarizes the scenario values. The cumulative suppression probability P_s is calculated as 1 minus the NSP. The conditional probability of end state 1, 0, is the probability that suppression occurs at 0 min and damage is limited to the ignition source only. During the subsequent interval, after 0 min but before 4 min (end state 2), the probability of suppression is the cumulative probability of suppression at 4 min minus the cumulative probability of suppression at 0 min, 0.08 - 0.0 = 0.08. Therefore, there is an 8% likelihood that damage is limited to the second tray above the ignition source. A similar calculation applies to the third tray, (0.15 - 0.08) = 0.07. The final interval receives the remaining probability, 1 - (0.07 + 0.08) = 0.85.

There is an 85% chance of the full consequences occurring. The remaining 15% of the probability is apportioned between the second and third end states. Recall, no probability is associated with suppression of the first target, which is immediately damaged in the energetic.

Table G-1
Example 1: Conditional non-suppression probabilities

End state	Elapsed time after fire ignition (minutes)	Estimated non-suppression probability, *NSP*	Cumulative suppression probability, $P_s = 1 - NSP$	Formula for the conditional probability of the scenario	Conditional probability of the scenario
Damage limited to tray 1	0	1	0	$P_s(0)$	0
Damage limited to tray 2	4	0.92	0.08	$P_s(4) - P_s(0)$	0.08
Damage limited to tray 3	7	0.85	0.15	$P_s(7) - P_s(4)$	0.07
Further targets (15 min)	>7	0.68		*Remaining probability*	0.85

G.1.2 Screening Approach for MV Switchgear

Following the screening approach in Section 8.4, the ZOI for a UAT (normal supply) with an FCT of 1.5 s bounds the ZOI for the secondary supply (SAT with an FCT of 1 s). The energetic of the HEAF ZOI for the UAT with an FCT of 1.5 s is 3.5 ft (1.1 m) for TP targets (see Table 8-2). The first target (cable tray) located 3 ft (91 cm) above the switchgear is within the energetic of the HEAF ZOI. This tray is damaged but does not ignite.

The ensuing fire immediately reaches a peak HRR of 170 kW (from Section 6.5). The first cable tray is damaged by the flame ZOI, and bulk ignition of the tray occurs within 1 min [46]. The second target (the third cable tray in the stack) is damaged and ignited at 8 min (1 + 4 + 3).

A UAT fed event with a FCT of 1.5 seconds has an arc energy of 200 MJ. From Table 6-1, the energy required for fire spread to an adjacent vertical section is 233 MJ for double walled construction. For this scenario, fire spread to an adjacent vertical section is not postulated.

As discussed in Section 5.2.2.3, 86% of the generic fire ignition frequency for MV switchgear is apportioned to the switchgear in Zone 1. The ignition source weighting factor is determined using the Zone 1 population of switchgear (one out of six). The frequency for the scenario is as follows:

$$(\lambda_{16.b} \cdot 0.86) \cdot W_{is} = (1.98\text{E-}03 \cdot 0.86) \cdot \left(\frac{1}{6}\right) = 2.84\text{E-}04$$

G.1.3 Zone 1 Configuration-Specific ZOI for MV Switchgear

Section 8.5 describes more detailed modeling (if the screening methodology requires additional realistic or detailed modeling). Figure 8-6 (shown below as Figure G-2) indicates multiple scenarios can be developed (depending on the level of granularity needed). The ignition frequency for each scenario is apportioned between the normal supply vertical section, the secondary supply vertical section, and the load sections, as shown in Figure G-2 (also Figure 8-5
).

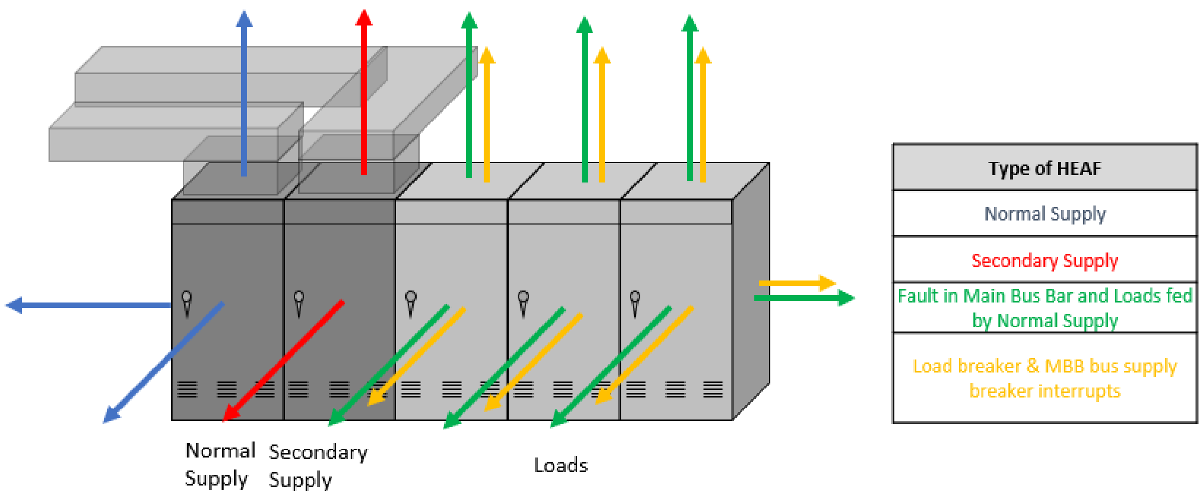

Figure G-2
Zone 1 MV switchgear configuration-specific ZOIs

For this example, the resulting scenario frequencies are calculated as follows:

- Normal (primary) supply:

$$GCB \cdot (\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.57 = 3.5\text{E-05} \cdot (2.84\text{E-04}) \cdot 0.57 = 5.66\text{E-09}$$

  - From Section 5.3.1, plants with a GCB can modify the frequency by 3.5E-05 for end states where the GCB can interrupt the fault (Zone 1 supply).
  - If there were no GCB, the scenario frequency would be:

$$(2.84\text{E-04}) \cdot 0.57 = 1.62\text{E-04}.$$

- Secondary supply:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.28 = (2.84\text{E-04}) \cdot 0.28 = 7.95\text{E-05}$$

- Loads, fault in load breaker or MBB fed via stuck normal supply breaker:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.15 \cdot 0.09 = (2.84\text{E-04}) \cdot 0.01 = 3.83\text{E-06}$$

- Loads, fault in MBB with Zone 1 bus supply breaker interrupting:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.15 \cdot 0.91 = (2.84\text{E-04}) \cdot 0.14 = 3.87\text{E-05}$$

Next, the ZOIs associated with these scenarios are selected to determine if the target trays are impacted by the energetic of the HEAF.

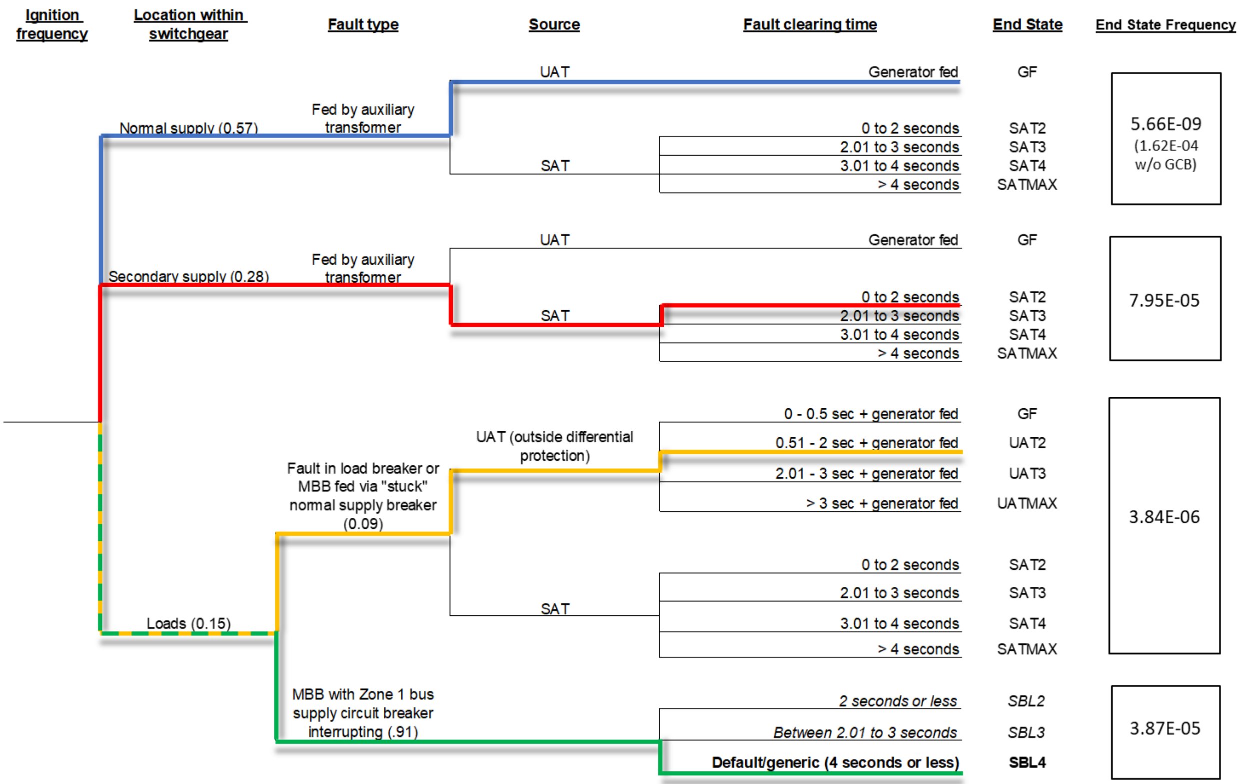

Figure G-3
Example 1: Zone 1 configuration-specific HEAF event tree

Table 8-3 lists the configuration-specific energetic ZOIs for targets subject to 15 MJ/m^2 fragilities (including TP cables). For the normal supply, the UAT, the end state is GF, generator-fed (because differential protection is assumed to be reliable in the Zone 1 supply). The generator-fed energetic ZOI is 1.5 ft (46 cm) vertically. The lowest target (first cable tray) is outside the energetic ZOI at an elevation of 3 ft (91 cm). However, the first cable tray is within the flame region for the post-HEAF ensuing fire. The first cable tray ignites within 1 min, with propagation to the third cable tray at 8 min (1 + 4 + 3).

For the secondary supply (SAT), an FCT of 1 s results in a vertical energetic ZOI of 1 ft (30 cm) (SAT2). The lowest target (first cable tray) is outside the energetic ZOI at 3 ft (91 cm). The first cable tray is within the flame region for the ensuing fire. The ensuing fire growth in the secondary supply section is identical to the primary supply (first tray within 1 min and the third tray at 8 min).

For the load vertical sections, the targets are located outside the energetic ZOI (UAT2 and SBL4). Note, while the load sections may have a horizontal component to their ZOI, this impact is limited to the horizontal direction below the top plane of the cabinet section (see Figure 8-2).

As discussed in Section 6.5.1, arc energies less than 233 MJ do not need to postulate fire spread to adjacent vertical sections for double wall configurations. Since all of the end states are under 233 MJ no fire spread to adjacent vertical sections is postulated.

G.1.4 Impact of ERFBS

The example is repeated assuming the lowest tray is protected by an ERFBS or fire wrap. Recall from the sections above, the first cable tray is located 3 ft above the switchgear. The bullets below discuss the treatment of ERFBS:

- NUREG/CR-6850, Appendix M: The first tray is within the vertical ZOI (5 ft).
    - The ERFBS treatment in NUREG/CR-6850 assumes that if the cable tray is protected, it is assumed damaged but not ignited.
    - For the post-HEAF ensuing fire, per NUREG/CR-6850 cables protected by an ERFBS are assumed damaged but not ignited by the arcing event. However, as the cables are – and by extension the ERFBS – considered damaged, the ERFBS no longer provides protection to the trays from the ensuing fire which ignites and eventually propagates to the third tray in the cable tray stack.
- Screening: The first tray is within the vertical energetic ZOI (3.5 ft).
    - As summarized in RIL 2022-01 [15] Section 6.2, the ERFBS is neither damaged nor ignited. Therefore, the first cable tray is protected from damage and ignition by the ERFBS consistent with its fire resistance rating. No PRA targets are damaged (the ensuing fire does not reach the second cable tray and therefore the fire does not propagate to any of the trays located above the cabinet).
- Zone 1 configuration-specific: The first tray is outside the vertical energetic ZOI of 1.5 ft for the normal supply vertical section and 1 ft for the secondary supply vertical section.
    - As summarized in RIL 2022-01 [15] Section 6.2, the ERFBS is neither damaged nor ignited. Therefore, the first cable tray is protected from damage and ignition by the ERFBS consistent with its fire resistance rating. No PRA targets are damaged (the ensuing fire does not reach the second cable tray and therefore the fire does not propagate to any of the trays located above the cabinet).

G.1.5 NUREG/CR-6850 Example Summary

Table G-2 compares the differences in the results for the various methods in Example 1.

Table G-2
Summary of NUREG/CR-6850 comparison example

Example Case	Results and Discussion
NUREG/CR-6850	First target: Within energetic ZOI. Damaged and ignited at time 0. Second target: Outside the energetic HEAF ZOI. Ensuing fire propagates to this tray in 7 min.
Screening Approach	First target: Within energetic ZOI. Damaged at time 0 but does not ignite. The tray is subject to direct flame impingement from the ensuing fire and ignites within 1 min. Second target: Outside the energetic ZOI. Ensuing fire propagates to this tray in 8 min. Double wall construction limits the propagation of fire to adjacent vertical sections.
Zone 1 Configuration Specific	First target: For end state GF (normal supply) and SAT2 (secondary supply), the first target is outside the energetic ZOI, but within the flame region of the ensuing fire. The first tray ignites within 1 minute. For end states UAT2 and SBL4 (loads) the first target is undamaged as it is outside the energetic and ensuing fire ZOIs. Second target: Outside the energetic ZOI. Ensuing fire propagates to this tray in 8 min. Even though first target tray is outside the HEAF energetic ZOI following the Zone 1 configuration-specific ZOI, the impact of the ensuing fire results in the target trays being damaged and igniting in a time similar to NUREG/CR-6850 and screening methods. Double wall construction limits the propagation of fire to adjacent vertical sections.
NUREG/CR-6850 (with ERFBS)	First target: Within energetic ZOI. The cable tray and ERFBS are damaged at time 0 but the tray does not ignite per the guidance in NUREG/CR-6850. The tray is subject to direct flame impingement from the ensuing fire and since the ERFBS is damaged by the HEAF, the tray is ignited within 1 min. Second target: Outside the energetic ZOI. Ensuing fire propagates to this tray in 8 min.
Screening (with ERFBS)	First target: Within energetic ZOI but not damaged and not ignited (protected by ERFBS). Target is not damaged and does not ignite due to the continued protection of the undamaged ERFBS consistent with its fire resistance rating. Second target: Outside the energetic ZOI. Target is not damaged because the fire does not propagate from the lowest tray.
Zone 1 Configuration Specific (with ERFBS)	First target: Outside the energetic ZOI for UAT2 and SBL4. The target is within the HEAF ZOI for end states GF and SAT2, however the event does not impair the ERFBS, which protects the first tray from damage and ignition. Second target: Outside the energetic ZOI. Not damaged because the fire does not propagate from the lowest tray.

G.2 Example 2: Zone 2 MV Switchgear

In this example, scenarios for a MV switchgear located in Zone 2 are developed. The following are defined:

- The MV switchgear is located in Zone 2 (see Section 3.1)
- There are seven switchgear banks in Zone 2
    - A split fraction of 0.14 is used to apportion the Bin 16.b generic fire ignition frequency for the Zone 2 switchgear (see Section 5.2.2.3)
- The normal supply for the switchgear is the UAT
    - The FCT is 2.8 s
- The secondary supply for the switchgear is the SAT
    - The FCT is 4.5 s (taken from example in Section 6.4.1)
- The upstream Zone 1 switchgear supply breaker FCT is 0.76 s (taken from the example in Section 6.4.2)
- The targets are subject to TS damage criteria
- Vertical sections are separated by a single steel barrier (single wall construction)
- There are three targets (see Figure G-4)
    - Conduit A is located 3 ft from the normal supply breaker vertical section
    - Conduit B is located 3 ft behind the secondary supply breaker vertical section
    - Conduit C is located 3 ft from the side of the end load vertical section

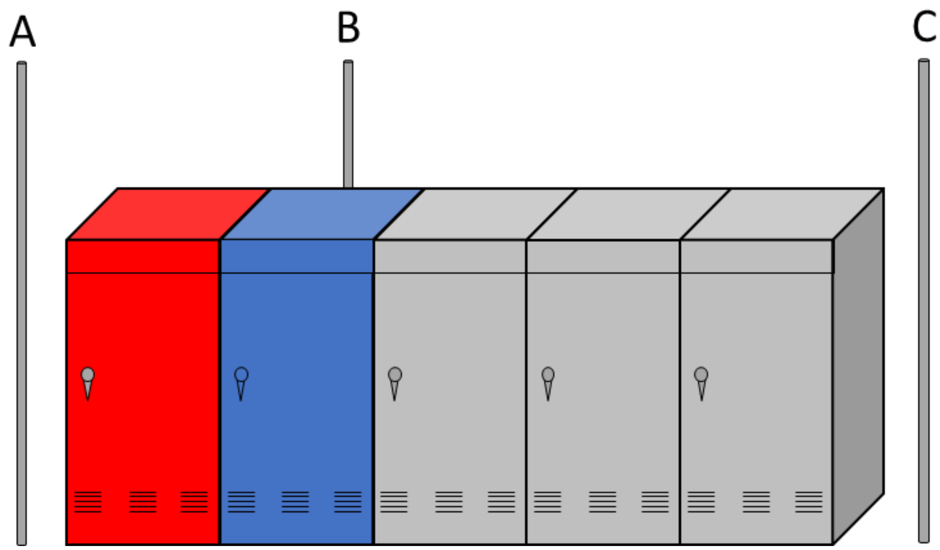

Figure G-4
Example 2: switchgear bank (normal supply in red; secondary supply in blue; conduits A, B, and C)

G.2.1 NUREG/CR-6850 Methodology

The horizontal ZOI for a HEAF is 3 ft from the front or rear panel doors. Therefore, conduits A and C are outside the HEAF ZOI. Conduit B is within 3 ft of the rear panel door ZOI and is damaged by the energetic HEAF ZOI. For the ensuing fire, the target conduits likely remain outside the ensuing fire ZOI involving multiple ignited vertical sections (the ZOI ultimately depends on the selected radiative fraction, fire diameter, and so on).

G.2.2 Screening Approach

Following the screening approach in Section 8.4, the energetic of the HEAF ZOI for the UAT (normal supply) with an FCT of 2.8 s is 3 ft (see Table 8-2) for 30 MJ/m^2 target fragility). In screening, all three target conduits are within the energetic ZOI.

As discussed in Section 5.2.2, 14% of the generic fire ignition frequency for MV switchgear is apportioned to the total population of switchgear in Zone 2. The ignition source weighting factor is determined using the switchgear in Zone 2 (one out of seven). The ignition frequency for the scenario is as follows:

$$(\lambda_{16.b} \cdot 0.14) \cdot W_{is} = (1.98\text{E-}03 \cdot 0.14) \cdot \left(\frac{1}{7}\right) = 3.96\text{E-}05$$

G.2.3 Zone 2, Refinement Level 1

In refinement level 1 (Section 8.6.1), two scenarios are developed (see Figure G-5). The ignition frequency for each scenario is split between a HEAF fed by the auxiliary transformer and the SBL fault, as shown in Figure G-5-5 (also Figure 8-8).

Examples

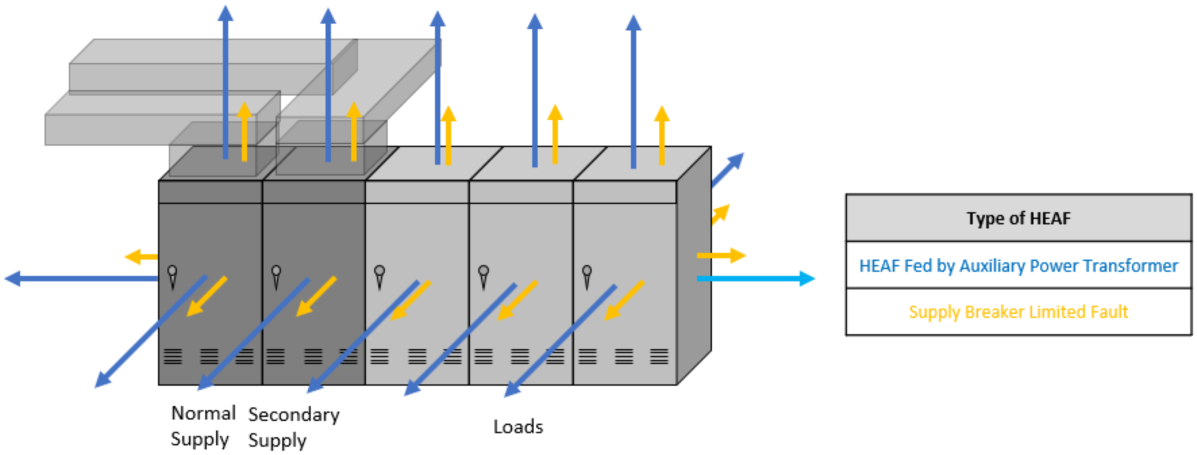

Figure G-5
Zone 2 MV switchgear refinement level 1 ZOIs

The resulting scenario frequencies are calculated as follows:

- Fault in load breaker or MBB with the bus supply breaker interrupting (SBL2):

$$(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot 0.94 = (3.96\text{E-}05) \cdot 0.94 = 3.72\text{E-}05$$

- Fault in normal or secondary supply with upstream breaker failure (UAT3):

$$(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot 0.06 = (3.96\text{E-}05) \cdot 0.06 = 2.38\text{E-}06$$

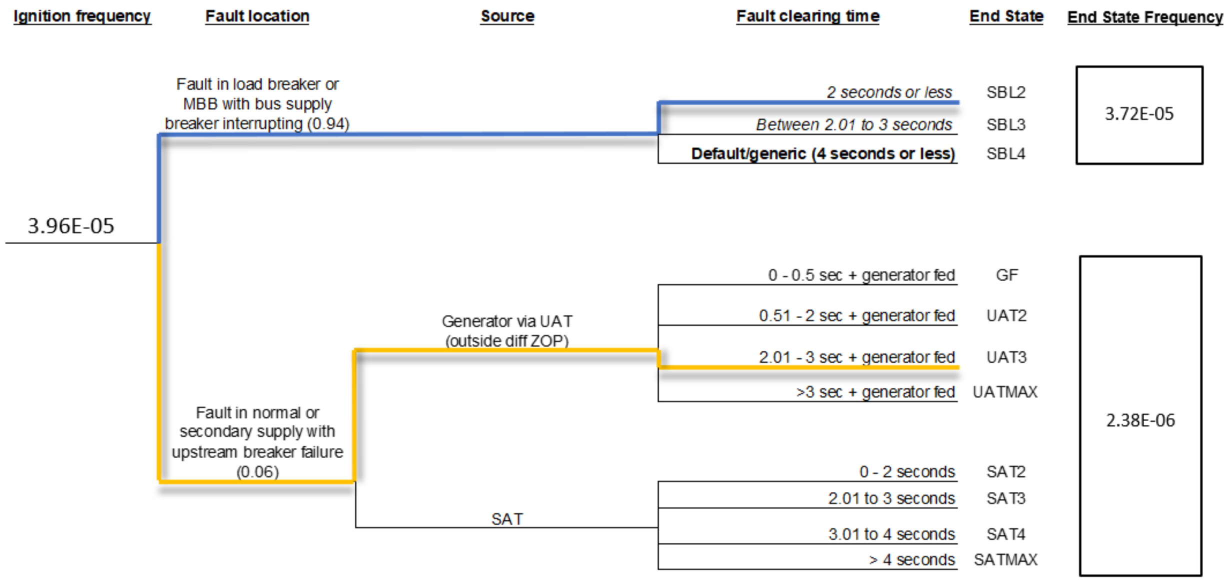

Figure G-6
Example 2, Zone 2 refinement level 1 HEAF event tree

Table 8-6 lists the 30 MJ/m^2 fragilities (including thermoset jacketed cables). For end state SBL2, the ZOI is 1 ft in the back direction and 0.5 ft in the side (left/right). Therefore, the target conduits, located 3 ft from the switchgear, are outside the energetic ZOI. A 170 kW post -HEAF ensuing fire is postulated. There is no cabinet to cabinet fire propagation for end state SBL2 as it is below the threshold for propagation (energy is 68 MJ from Table 8-6). Depending on the specific parameters selected (radiative fraction, fire diameter, and so on) the target conduits likely remain outside the ensuing fire ZOI for the single ignited switchgear vertical sections.

A fault in either normal or secondary supply with upstream breaker failure for this switchgear results in a ZOI of 2.5 ft to the side and 3 ft in the back direction (end state UAT3). Only conduit B is within the energetic ZOI. With an arc energy of 233 MJ (UAT3, Table 8-6), fire propagation to adjacent vertical sections is postulated along with the ensuing fire described in Section 6.5. Depending on the specific parameters selected (radiative fraction, fire diameter, and so on) the target conduits likely remain outside the ensuing fire ZOI of two or three ignited switchgear vertical sections.

G.2.4 Zone 2, Refinement Level 2

In refinement level 2 (Section 8.6.2), the scenario ignition frequency can be further analyzed. Figure 8-12 (shown below as Figure G-7) shows six scenarios developed. The ignition frequency for each scenario is divided into multiple end states as shown in Figure G-8).

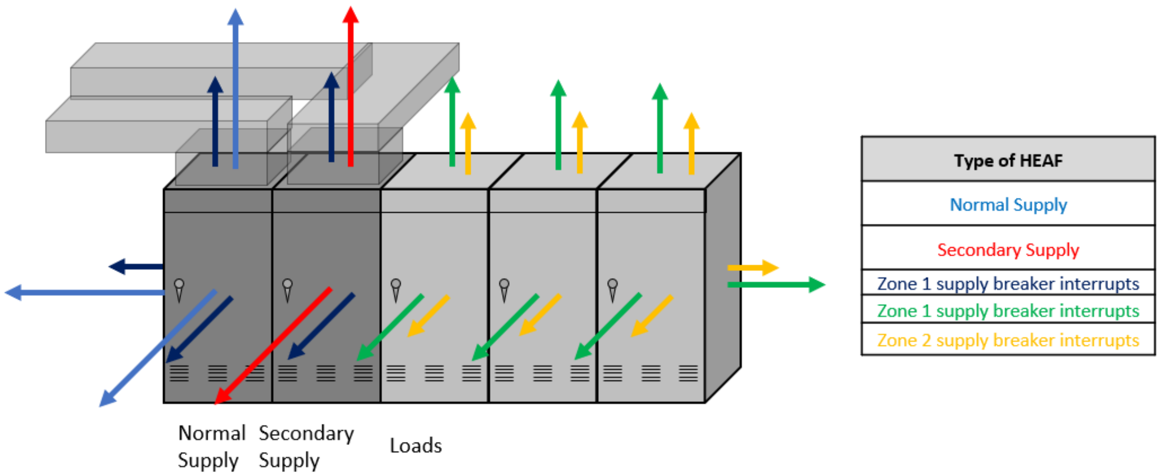

Figure G-7
Zone 2 MV switchgear refinement level 2 ZOIs

The resulting scenario frequencies are calculated as follows:

- Normal (primary) supply:

  $(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.54 \cdot 0.05) = (3.96\text{E-}05) \cdot 0.03 = 1.07\text{E-}06$

- Zone 1 SBL (normal supply):

  $(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.54 \cdot 0.95) = (3.96\text{E-}05) \cdot 0.51 = 2.03\text{E-}05$

- Secondary supply:

  $(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.32 \cdot 0.05) = (3.96\text{E-}05) \cdot 0.02 = 6.34\text{E-}07$

- Zone 1 SBL (secondary supply):

  $(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.32 \cdot 0.95) = (3.96\text{E-}05) \cdot 0.3 = 1.20\text{E-}05$

- Loads, Zone 1 SBL:

  $(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.14 \cdot 0.05) = (3.96\text{E-}05) \cdot 0.01 = 2.77\text{E-}07$

- Loads, Zone 2 SBL:

  $(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.14 \cdot 0.95) = (3.96\text{E-}05) \cdot 0.13 = 5.27\text{E-}06$

Table 8-6 lists the energetic ZOIs for the 30 MJ/m^2 fragility (including TS cables). The end states along with the energetic ZOIs (in the direction of the target conduits) for each scenario are the following:

- Normal (primary) supply: end state UAT3: 2.5 ft to the side (left/right), conduit A is outside the HEAF ZOI
- Zone 1 SBL (normal supply): end state SBL2 (refinement based on Zone 1 switchgear bus supply breaker operating in 0.76 seconds): 0.5 ft to the side (left/right), conduit A is outside the HEAF ZOI
- Secondary supply: end state SATMAX: 2.5 ft to the rear, conduit B is outside the HEAF ZOI
- Zone 1 SBL (secondary supply): end state SBL2: 1 ft to the rear, conduit B is outside the HEAF ZOI
- Loads, Zone 1 SBL: end state SBL2: 0.5 ft to the side (left/right), conduit C is outside the HEAF ZOI
- Loads, Zone 2 SBL: end state SBL2: 0.5 ft to the side (left/right), conduit C is outside the HEAF ZOI

The arc energy for end state UAT3 (233 MJ) on the normal supply/load and SATMAX (169 MJ) on the secondary supply exceeds 101 MJ, and the scenario progression must consider fire propagation to adjacent vertical sections. The remaining end states do not have sufficient energy and the HRR is limited to 170 kW (for the ignition source, excluding secondary combustible propagation). For the ensuing fire, the target conduits likely remain outside the ensuing fire ZOI involving one, two, or three ignited vertical sections (the ZOI ultimately depends on the selected radiative fraction, fire diameter, and so on).

Examples

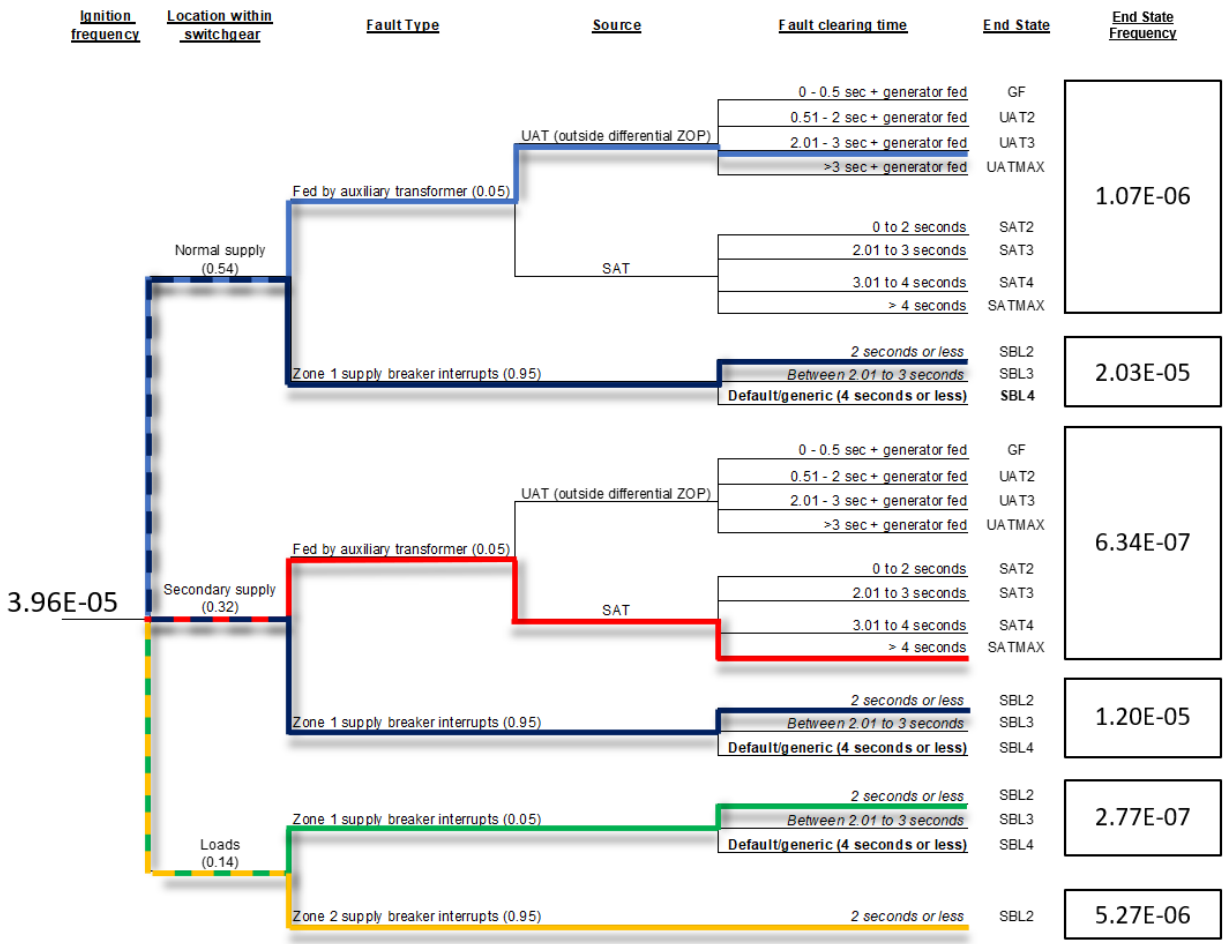

Figure G-8
Example 2: zone 2 refinement level 2 HEAF event tree

G.2.5 Example 2 Summary

Table G-3 compares the differences in the results for Example 2.

Table G-3
Summary of horizontal target comparison cases

Example Case	Results and Discussion
NUREG/CR-6850	Conduit A, located to the side of the switchgear, is outside the HEAF ZOI and is not damaged. Conduit B is located behind the switchgear at a distance of 3 ft. It is within the HEAF ZOI and is damaged by the energetic. Conduit C, located to the side of the switchgear, is outside the HEAF ZOI and is not damaged. The ensuing fire involves multiple vertical sections. At a horizontal distance of 3 ft the conduits are likely outside the post-HEAF ensuing fire ZOI.
Screening	Conduit A is located to the side of the switchgear at a distance of 3 ft. It is within the energetic ZOI and is damaged. Conduit B is located behind the switchgear at a distance of 3 ft. It is within the energetic ZOI and is damaged. Conduit C, located to the side of the switchgear at a distance of 3 ft, is within the energetic ZOI and is damaged. The ensuing fire may involve two to three vertical sections. At a distance of 3 ft the conduits are likely outside the post-HEAF ensuing fire horizontal ZOI.
Refinement level 1	Only conduit B is within the energetic ZOI, with a scenario frequency of 2.38E-06. The normal or secondary supply with upstream breaker failure scenario has an arc energy sufficient to propagate fire to adjacent vertical sections. At a distance of 3 ft the conduits are likely outside the post-HEAF ensuing fire horizontal ZOI.
Refinement level 2	All targets are outside the energetic HEAF ZOI. The arc energy for the generator-fed scenario on the normal supply section has an arc energy sufficient to propagate fire to adjacent vertical sections. At a distance of 3 ft the conduits are likely outside the post-HEAF ensuing fire horizontal ZOI.

G.3 Example 3: Multiple Supplies

G.3.1 MV Switchgear

In this example, the MV switchgear bank has three supplies. This example shows how to apportion the scenario frequencies for a switchgear with three supplies (see Figure G-9). The following information is provided for the MV switchgear:

- The switchgear is in Zone 1
- There are four Zone 1 switchgear (banks)
- The normal supply for the switchgear is the UAT (there is no generator circuit breaker)
    - The FCT is 3.5 s
- There are two off-site power sources, each supporting a different SAT

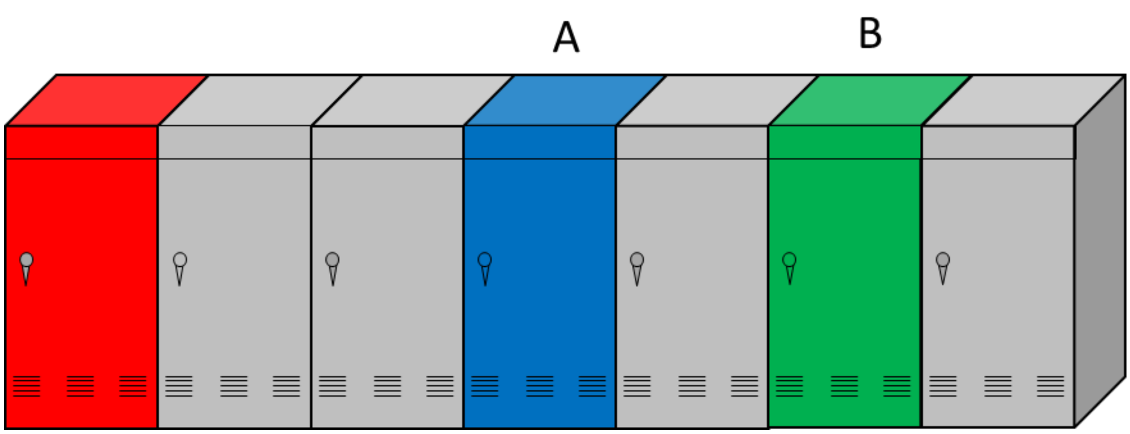

Figure G-9
Example 3: switchgear bank (normal supply in red, A secondary supply in blue, B secondary supply in green)

The Zone 1 configuration-specific scenario frequencies are the following:

- Normal (primary) supply:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.57 = \left(1.98\text{E-03} \cdot 0.86 \cdot \left(\frac{1}{4}\right)\right) \cdot 0.57 = 2.43\text{E-04}$$

- Secondary supply A:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.28/2 = \left(1.98\text{E-03} \cdot 0.86 \cdot \left(\frac{1}{4}\right)\right) \cdot 0.28/2 = 5.96\text{E-05}$$

- Secondary supply B:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.28/2 = \left(1.98\text{E-03} \cdot 0.86 \cdot \left(\frac{1}{4}\right)\right) \cdot 0.28/2 = 5.96\text{E-05}$$

- Fault in loads fed via stuck normal supply:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.01 = \left(1.98\text{E-03} \cdot 0.86 \cdot \left(\frac{1}{4}\right)\right) \cdot 0.01 = 4.26\text{E-06}$$

- SBL fault in loads:

$$(\lambda_{16.b} \cdot 0.86 \cdot W_{is}) \cdot 0.14 = \left(1.98\text{E-03} \cdot 0.86 \cdot \left(\frac{1}{4}\right)\right) \cdot 0.14 = 5.96\text{E-05}$$

For the two secondary supplies, the frequency is apportioned equally between the two secondary supply sections. The development of the scenario (energetic ZOIs plus ensuing fire) continues as shown in the previous examples.

G.3.2 Load Center

In this example, the scenario frequencies for two load centers connected by a cross-tie are examined to determine the frequency of 16.a HEAFs for the ignition source in Figure G-10. The following information is provided:

- The sources are two load centers, LC-1 and LC-2.
  - LC-1 consists of sections A, B, and C. There is a supply breaker in section A.
  - LC-2 consists of sections E, F, and G. There is a supply breaker in section E.
  - Section D is a cross-tie connecting the two load centers that is administratively open during normal operation.
- There are a total of eight load center supply breakers in the plant.

Examples

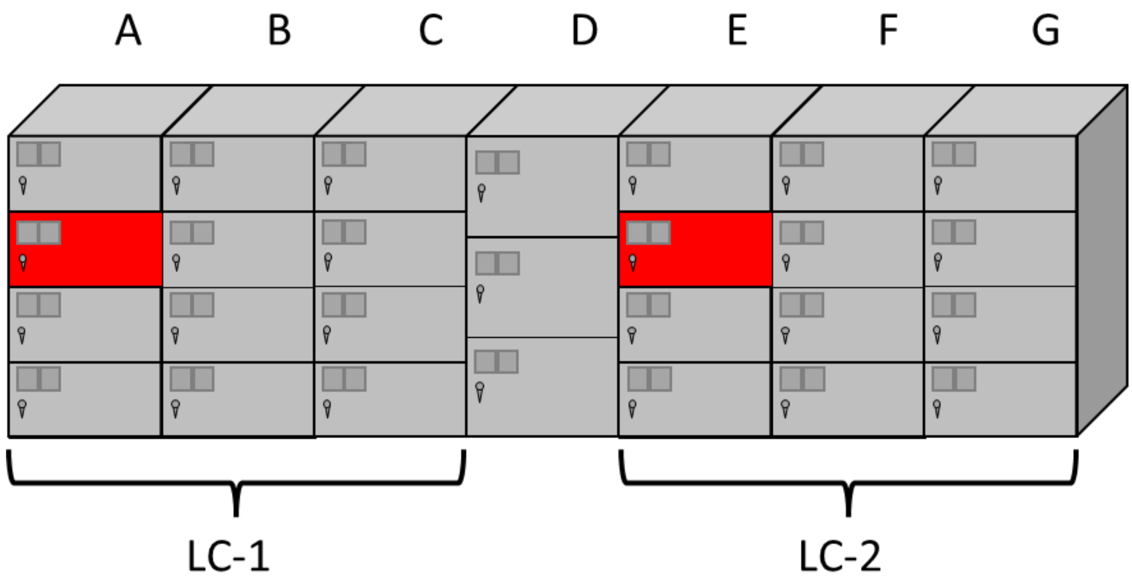

Figure G-10
Example 3: load centers LC-1 and LC-2 (supply breakers in red)

- LC-1 supply breaker in section A: $(\lambda_{16.a} \cdot W_{is}) = \left(5.32\text{E-}04 \cdot (1/8)\right) = 6.65\text{E-}05$

- LC-2 supply breaker in section E: $(\lambda_{16.a} \cdot W_{is}) = \left(5.32\text{E-}04 \cdot (1/8)\right) = 6.65\text{E-}05$

Either load center could be supplied by the other through the cross-tie in section D. The cross-tie in section D is not counted as a HEAF source because it is normally open and does not function as a supply during normal operations. LC-1 and LC-2 each have a count of one (single supply breaker) for Bin 16.a.

G.4 Example 4: Fire Spread to Adjacent Cabinets

In this example, a scenario is developed to illustrate modeling fire spread to adjacent cabinets from Section 6.5.1. Specifically, this example focuses on a HEAF in the ‘B’ secondary supply vertical section and the impact of an ensuing fire on the conduit located above the ‘D’ vertical section. This example uses the results from Example 2 (Appendix G.2), a MV switchgear with the following configuration:

- The MV switchgear is located in Zone 2 (see Section 3.1).
- The normal supply for the switchgear is the UAT.
  - The FCT is 2.8 s.
- The secondary supply for the switchgear is the SAT.
  - The FCT is 4.5 s (taken from example in Section 6.4.1).
- The upstream Zone 1 switchgear supply breaker FCT is 0.76 s (taken from the example in Section 6.4.2).
- The targets are subject to TS damage criteria.
- Vertical sections are separated by a single steel barrier (i.e., single wall construction).
- There is a target conduit located directly above the ‘D’ load section, approximately 0.3 m (1 ft.) from the edge of section ‘C’ (see Figure G-11). Note that this is a different target orientation than considered in Example 2.

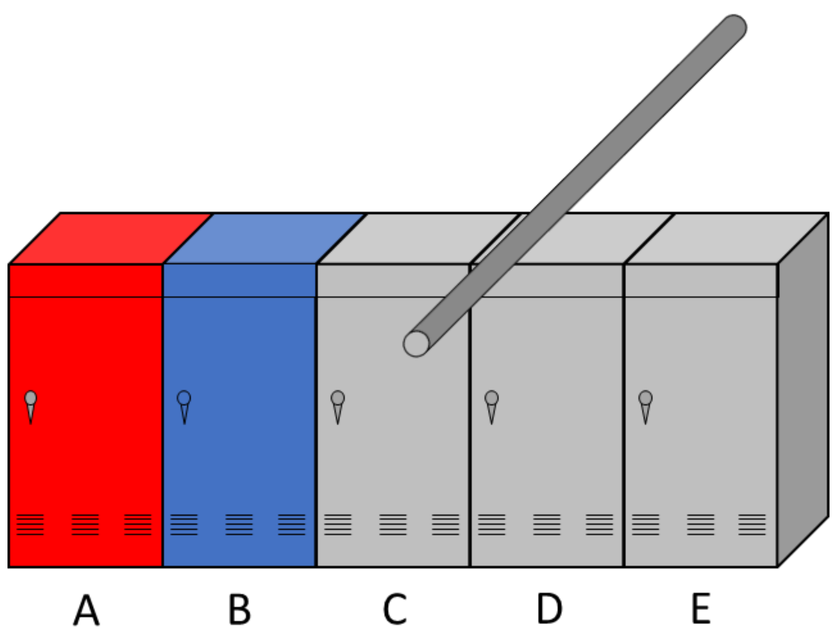

Figure G-11
Example 4: switchgear bank (normal supply in red; secondary supply in blue)

G.4.1 Zone 2, Refinement Level 1

Application of the first refinement level for a Zone 2 MV switchgear results in two end state ZOIs – HEAF fed by auxiliary power transformer (UAT3) and a supply breaker limited fault (SBL2), each ZOI applied across the entire switchgear bank. The target conduit located above vertical section ‘D’ is damaged in the energetic phase by both ZOIs.

G.4.2 Zone 2, Refinement Level 2

Six end states are analyzed as part of Example 2 (see Section G.2.4). The end states are summarized as:

- Normal supply/fed by auxiliary transformer: UAT3 (233 MJ)
- Normal supply/Zone 1 SBL: SBL2 (68 MJ)
- **Secondary supply/fed by auxiliary transformer: SATMAX (169 MJ)**
- **Secondary supply/Zone 1 SBL: SBL2 (68 MJ)**
- Loads/Zone 1 SBL: SBL2 (68 MJ)
- Loads/Zone 2 SBL: SBL2 (68 MJ)

This example will focus on the ‘B’ secondary supply vertical section (bolded in the bulleted list) and the potential impact on the target conduit above the ‘D’ vertical section. The frequencies for vertical section ‘B’ (from Section G.2.4) are:

- Secondary supply:

  $$(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.32 \cdot 0.05) = (3.96\text{E-}05) \cdot 0.02 = 6.34\text{E-}07$$

- Zone 1 SBL (secondary supply):

  $$(\lambda_{16.b} \cdot 0.14 \cdot W_{is}) \cdot (0.32 \cdot 0.95) = (3.96\text{E-}05) \cdot 0.3 = 1.20\text{E-}05$$

For SBL2 (with an arc energy of 68 MJ), an ensuing fire in vertical section ‘B’ is postulated. At this arc energy no fire propagation to the adjacent vertical sections is necessary. The target conduit above vertical section ‘D’ is not impacted in SBL2.

For SATMAX (with an arc energy of 169 MJ), an ensuing fire in vertical section ‘B’ is postulated as well as fire spread to the adjacent vertical sections ‘A’ and ‘C’ (as the arc energy is greater than 101 MJ for single wall construction). The fire spread event tree in Figure G-12 is used to determine the scenarios and the resulting HRRs.

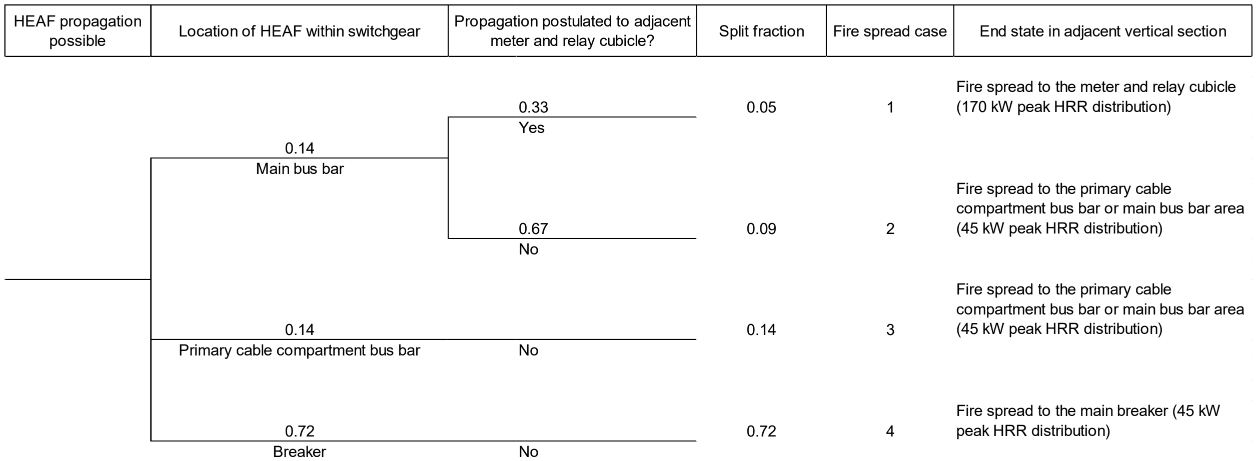

Figure G-12
Generic fire spread event tree

To determine if the target conduit is within the ZOI in vertical section ‘B’ for each fire spread case, the individual vertical section HRR and the location of the fire in the adjacent panel is considered. As discussed in Section 6.5.1.5, for fire spread case 1 the adjacent vertical section (vertical sections ‘A’ and ‘C’) each have a peak 98th percentile HRR of 170 kW. The fire base is located 0.3 m (1 ft.) below the top of the cabinet. With the target conduit located a foot away from the edge of vertical section ‘C,’ a 170 kW fire is capable of damaging the conduit.

Fire spread cases 2 and 3 result in a HRR representative of a medium volume enclosure with a very low fuel load. When fire spreads to vertical section ‘C’, the 98th percentile HRR is 45 kW and the fire is located 0.3 m (1 ft.) below the top of the cabinet. Using the adjusted solid flame model in NUREG-2178, Volume 2, this fire size is not capable of damaging the target conduit located above vertical section ‘D’ (a foot from the edge of the vertical section ‘C’).

Fire spread case 4 has a HRR similar to cases 2 and 3, but the fire base in vertical section ‘C’ is located at the middle height of the cabinet. The fire is not capable of damaging the target conduit located above vertical section ‘D.’

Note, in a complete scenario analysis, the impact of fire propagation in the other vertical sections must be considered.

Using the results from Example 2 (Section G.2.4), the vertical section ‘B’ secondary supply/fed by auxiliary transformer frequencies for each of the fire spread cases are shown in Figure G-4. For HGL analysis, Table G-4 also displays the total recommended HRR values for each fire spread case (taken from Table 6-4) from the Monte Carlo sampling trials.

Table G-4
Zone 2 refinement level 2 scenario frequency and HRR

Fire spread case	Scenario frequency for secondary supply section 'B' of Figure G-11	Total HRR 98th percentile
1	$6.34E\text{-}07 \cdot 0.05 = 3.17E\text{-}08$	360
2	$6.34E\text{-}07 \cdot 0.09 = 5.71E\text{-}08$	228
3	$6.34E\text{-}07 \cdot 0.14 = 8.88E\text{-}08$	228
4	$6.34E\text{-}07 \cdot 0.72 = 4.56E\text{-}07$	228

G.4.3 Double Wall Construction Impact

If it is determined that the vertical sections are separated by two steel barriers (double wall construction), the arc energy required to propagate to an adjacent section is greater than 202 MJ.

For the UAT3 end state (normal supply fed by auxiliary transformer) the arc energy of 233 MJ is greater than 202 MJ. Fire propagation to adjacent sections should be postulated. The results for refinement level 1 unchanged from Section G.4.1.

For SATMAX, when applying refinement level 2, the arc energy of 169 MJ is less than 202 MJ and fire propagation is not postulated.

G.4.3 Example 4 Summary

Table G-5 compares the differences in the results for Example 4.

Table G-5
Summary of fire propagation example

Example Case	Results and Discussion
Refinement level 1	The target conduit is damaged by end states UAT3 and SBL2 during the energetic phase.
Refinement level 2	For a HEAF in the ‘B’ vertical section, the SBL2 end state (68 MJ) does not lead to fire propagation to adjacent sections and does not impact the target conduit located above vertical section ‘D.’ The SATMAX (169 MJ) end state has sufficient energy to propagate fire to the adjacent ‘C’ vertical section. Fire spread case 1 damages the conduit over vertical section ‘D’. For spread cases 2, 3, and 4 the conduit over vertical section ‘D’ is undamaged.
Double wall construction	No change in the conclusions for refinement level 1. At refinement level 2, for SATMAX, fire propagation is not postulated. Since there is no propagation to vertical section ‘C’ the target above vertical section ‘D’ is undamaged.

G.5 Example 5: Target Equipment Fragility

In this example, the scenarios from the refinement level 2 case in Example 2 (Section G.2.4) are used to determine if a PRA target (switchgear) is within the energetic HEAF ZOI. From Section G.2.4, the end states for this example are the following:

- Normal supply/fed by auxiliary transformer: UAT3 (233 MJ)
- Normal supply/Zone 1 SBL: SBL2 (68 MJ)
- Secondary supply/fed by auxiliary transformer: SATMAX (169 MJ)
- Secondary supply/Zone 1 SBL: SBL2 (68 MJ)
- Loads/Zone 1 SBL: SBL2 (68 MJ)
- Loads/Zone 2 SBL: SBL2 (68 MJ)

Additional information for this example includes the following:

- A switchgear (PRA target) is located 4 ft behind the HEAF source (switchgear).
- The switchgear has open parquet vents (similar to Figure Figure F-6F-6) in the line of sight of the HEAF.

Using Table 8-5, as the open ventilation result in failure criteria of 15 MJ/m^2, the back energetic dimensions and target switchgear damage is characterized as follows:

- Normal supply/fed by auxiliary transformer: UAT3 = 4 ft back direction (switchgear within energetic and damaged)
- Normal supply/Zone 1 SBL: SBL2 = 2 ft back direction (switchgear outside the energetic ZOI)
- Secondary supply/fed by auxiliary transformer: SATMAX = 3.5 ft back direction (switchgear outside the energetic ZOI)
- Secondary supply/Zone 1 SBL: SBL2 = 2 ft back direction (switchgear outside the energetic ZOI)
- Loads/Zone 1 SBL: SBL2 = 2 ft back direction (switchgear outside the energetic ZOI)
- Loads/Zone 2 SBL: SBL2 = 2 ft back direction (switchgear outside the energetic ZOI)

G.6 Example 6: Non-Segregated Bus Ducts

For this NSBD example, the following inputs are used:

- The source is a run of NSBD located in Zone BD1 between two MV switchgear as shown in Figure **G-13**
- There are 50 total transition points in Bin 16.1-2
- This section of bus duct is powered from the SAT with an FCT of 1.6 s
- The bus duct has an aluminum enclosure with a width of 3 ft and a height of 2 ft
- The targets are subject to TP damage criteria
- A target cable tray above the bus duct at transition point A, approximately 2 ft above the duct enclosure.
    - There are no covers on the tray.

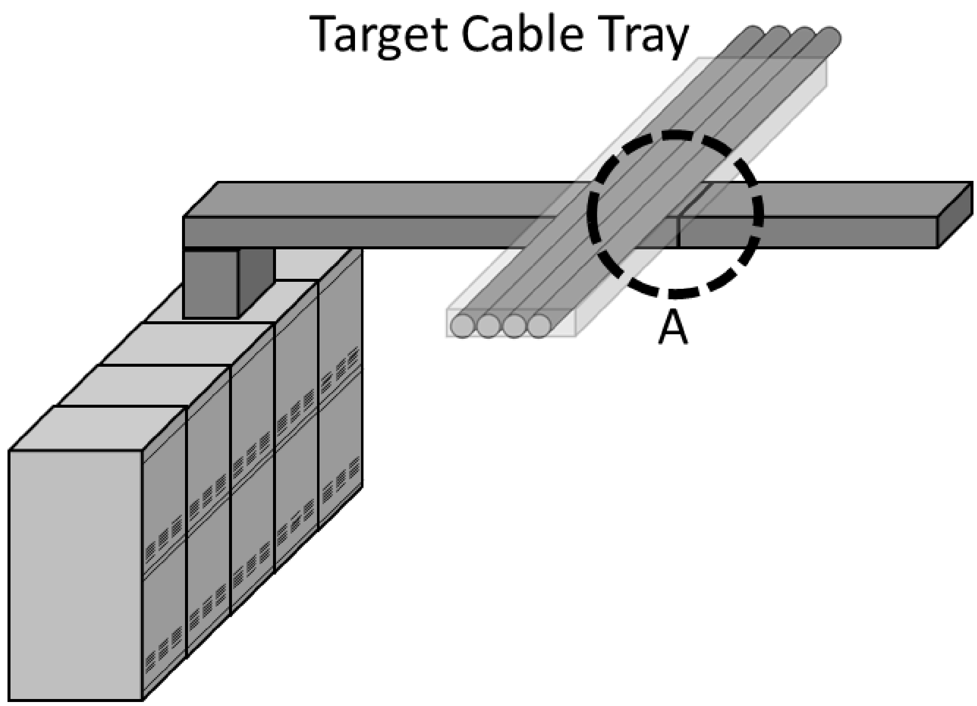

Figure G-13
Example 6: NSBD with known transition points (not to scale)

G.6.1 Supplement 1 to NUREG/CR-6850

According to NUREG/CR-6850, Supplement 1, neither the target cable tray nor the electrical cabinet are within the ZOI of a bus duct HEAF along the bus duct length or within the circular cone below the bus duct. The bus duct HEAF has a ZOI along the length of bus duct 1.5 ft from the fault point. Assuming the fault is located at the center of the bus duct cross-sectional area, the ZOI only reaches 0.5 ft above the top of the bus duct housing (as shown in Figure G-14). Therefore, the tray located 2 ft from the bus duct is outside the ZOI.

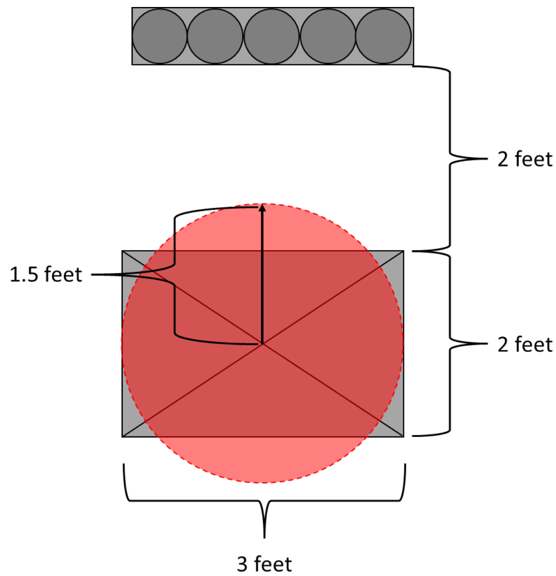

Figure G-14
Example 6: NSBD ZOI (red) as analyzed per Supplement 1 to NUREG/CR-6850 with target cable tray

G.6.2 BD1 HEAF, Known Transition Points

Per Section 9.2.4, up to two scenarios can be developed for bus ducts in Zone BD1. These scenarios capture the potential outcomes of the following:

- A HEAF fed directly from the power transformer (5% of scenario frequency)
- SBL HEAF (95% of scenario frequency)

The resulting scenario frequencies for this transition point is as follows:

- Power transformer:

$$(\lambda_{16.1-2} \cdot W_{is})\ 0.05 = \left(8.98\text{E-}04 \cdot (1/50)\right) \cdot 0.05 = 8.98\text{E-}07$$

- SBL:

$$(\lambda_{16.1-2} \cdot W_{is})\ 0.95 = \left(8.98\text{E-}04 \cdot (1/50)\right) \cdot 0.95 = 1.71\text{E-}05$$

The analyst may select the bounding scenario without using the 5/95 split fraction.

With a SAT FCT of 1.6 s, the ZOIs are developed using BDSAT2 (for the power transformer) and BDSBL4 (for SBL) end states as shown in Figure G-15.

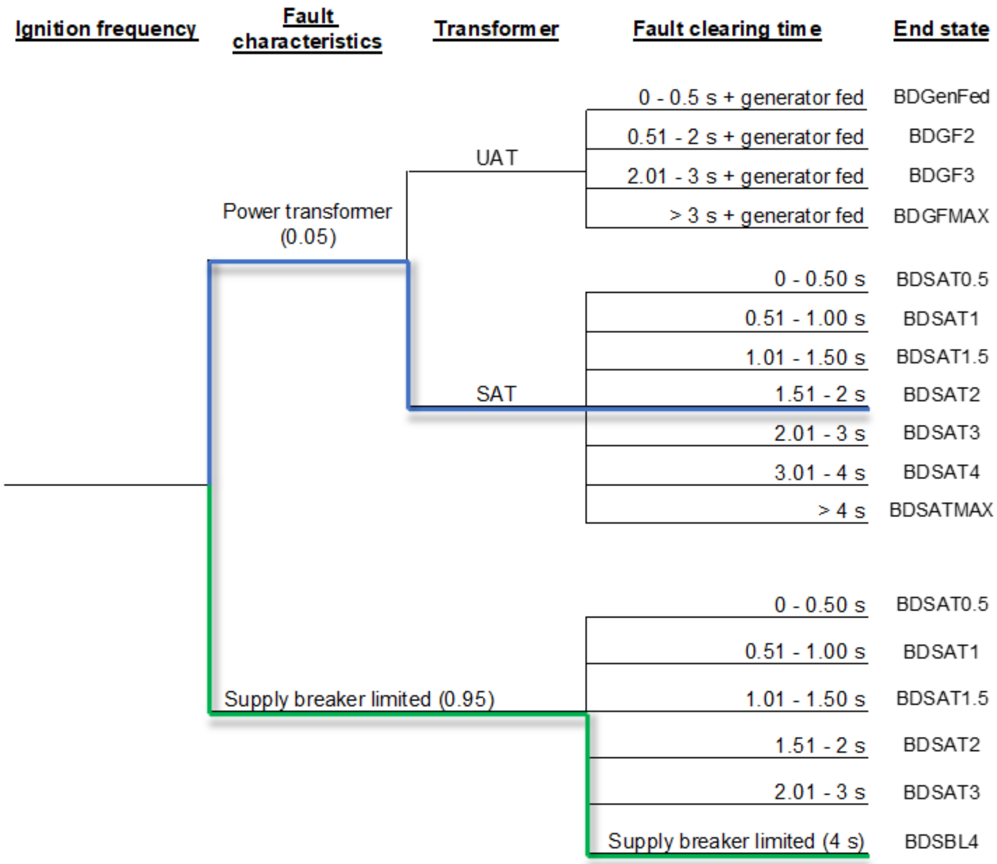

Figure G-15
Zone BD1 HEAF event tree

For transition point A, the target cable tray is located 2 ft above the bus duct. Per Table 9-2, the ZOIs for the two scenarios (assuming an aluminum enclosure and 15 MJ/m^2 target fragility) are as follows:

- Power transformer: 1.5 ft (end state BDSAT2)
- SBL: 3 ft (end state BDSBL4)

For BDSAT2, the cable tray is not within the energetic ZOI along the bus duct or the waterfall component below the bus duct (see Figure **G-16**). For BDSBL4, the cable tray is within the energetic ZOI. If more detail is necessary, the analyst may elect to determine the FCT of the Zone 1 MV switchgear bus supply circuit breaker. To be selectively coordinated with the upstream transformer protection, the Zone 1 bus supply circuit breaker should interrupt before the TOC protection for the auxiliary power transformer.

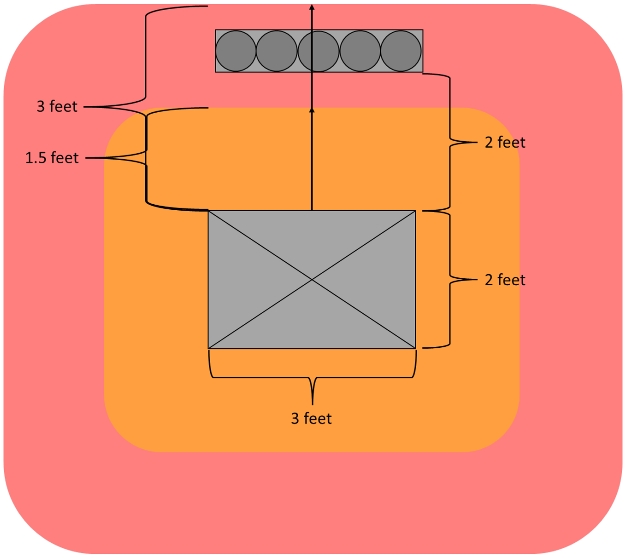

Figure G-16
NSBD end state BDSAT2 energetic along the bus duct ZOI (orange); BDSBL4 energetic along the bus duct (red) with respect to the cable tray

G.6.3 BD1 HEAF, Unknown Transition Points

Consider the same example, but this time the transition points are not known. The total length of bus duct in Bin 16.1-2 is 600 ft (linear foot approach). Figure G-17 develops scenario A for the cable tray and scenario B for the electrical cabinet.

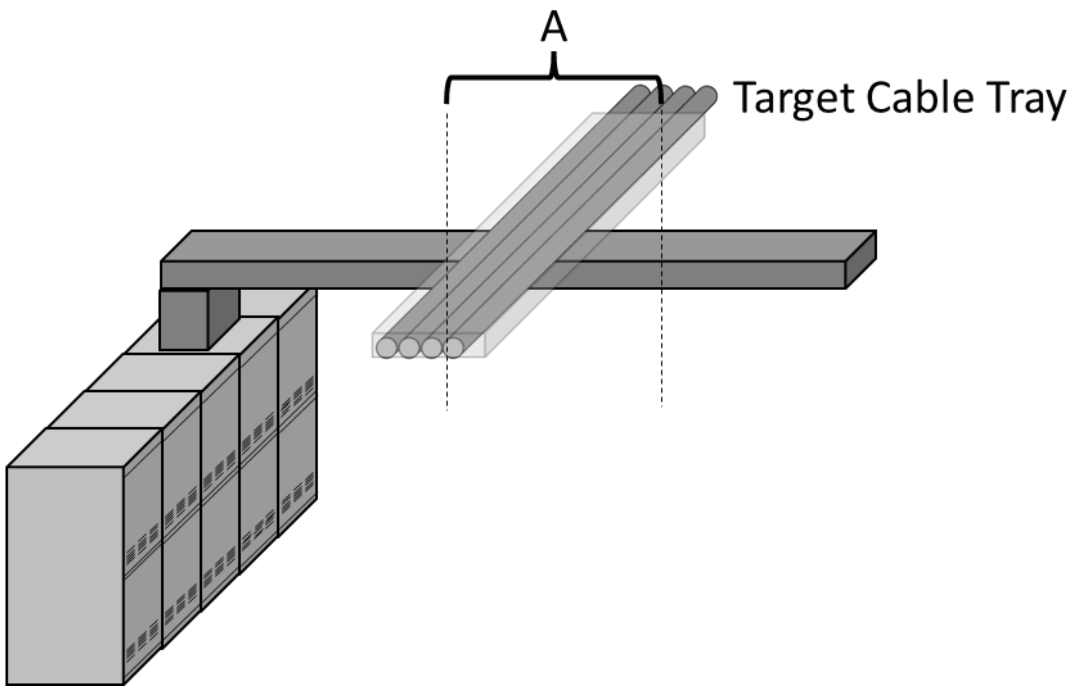

Figure G-17
Example 6 NSBD with unknown transition points (not to scale)

When the linear foot approach is used (see Section 5.2.3.2), a minimum of 12 ft should be assumed. The frequency for scenario A is determined using the same apportioning as the example above. The ignition source weighting factor is calculated as 12 ft out of 600 ft for Bin 16.1-2. The resulting frequencies for scenario A are as follows:

- Power transformer:

  $(\lambda_{16.1-2} \cdot W_{is})\ 0.05 \rightarrow \left(8.98\text{E-}04 \cdot (12/600)\right) \cdot 0.05 = 8.98\text{E-}07$

- SBL:

  $(\lambda_{16.1-2} \cdot W_{is})\ 0.95 \rightarrow \left(8.98\text{E-}04 \cdot (12/600)\right) \cdot 0.95 = 1.71\text{E-}05$

Note that the example is purposely developed to ensure that the number of NSBD transition points and linear feet are equivalent and result in the same apportioned frequencies. The goal is to highlight the different approaches for calculating the ignition source weighting factor, not to suggest a preferred approach. The frequencies can, and usually will, be different for the two approaches. Therefore, the analyst may desire to explore both approaches and select the method that minimizes the scenario frequency.

NRC FORM 335 (12-2010) NRCMD 3.7 — U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG-2262
2. TITLE AND SUBTITLE High Energy Arcing Fault Frequency and Consequence Modeling	3. DATE REPORT PUBLISHED MONTH: April — YEAR: 2023 4. FIN OR GRANT NUMBER
5. AUTHOR(S) N. Melly (NRC) A. Lindeman, M. Randelovic (EPRI)	6. TYPE OF REPORT Technical 7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

US NRC
Office of Nuclear Regulatory
Research Division of Risk Analysis
Washington, DC 20555-0001

Electric Power Research
Institute 3420 Hillview Avenue
Palo Alto, CA 94304-1338

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Same as above

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

High-energy arcing faults (HEAFs) are one type of hazard modeled in fire probabilistic risk assessments. This report combines previous HEAF-related research and provides methods and data to more realistically calculate plant risk due to HEAFs. Ignition frequency and non-suppression estimates are updated. The zone of influence (ZOI) selection is greatly expanded. Using computational fluid dynamics software Fire Dynamics Simulator (FDS) results, the working group reviewed and grouped the ZOI estimates from the simulation effort to determine consensus ZOIs for the three equipment classes, with varying levels of detail commensurate with potential risk significance. In general, the ZOIs for non-segregated bus ducts are larger, except for fault-clearing times of 2 s or less on the station auxiliary transformer (feed from off-site). The load center supply breaker ZOIs are smaller than the ZOI recommended in NUREG/CR-6850.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)	
Arcing fault, fire events, fire ignition frequency, fire probabilistic risk assessment (Fire PRA) High-energy arcing fault (HEAF)	13. AVAILABILITY STATEMENT unlimited 14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified 15. NUMBER OF PAGES 16. PRICE

NUREG-2262
EPRI 3002025942

High Energy Arcing Fault Frequency and Consequence Modeling

April 2023