Computational Study of Parameters Affecting Electric Cabinet Fire Heat Release Rate

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ABSTRACT

Electrical cabinet fires occur frequently in commercial and industrial facilities. The severity of these fire events varies widely, making it difficult to estimate the fire growth and size with certainty. The purpose of this study is to identify the significant parameters that affect electrical cabinet fires, which is quantified as the heat release rate (HRR), and properly categorize. With this knowledge, optimal parameter-response relationships can be developed to predict the electrical cabinet fire behavior.

Statistical analysis conducted in this study on historical fire incident data revealed that the fires in Nuclear Power Plants (NPP) were primarily associated with electrical cabinets. The database used in this research was an electronic version of the publicly available Updated Fire Event Database developed by Electric Power Research Institute including 2,111 fire events. 540 of these events were labelled as being challenging fires with 74.2% of these challenging fire events being due to eleven selected fire types. Electrical cabinets were found to represent a majority (40.7%) of all the challenging fire events.

Although historically conducted electrical cabinet fire experiments sought to explore the influence of parameters on HRR, the parameters were not systematically varied to statistically quantify which parameters were most important/relevant. Research in this study used statistical analysis on a series simulation results on electrical cabinet fires from the computational fluid dynamics code Fire Dynamic Simulator (FDS). Simulation matrices were developed and evaluated using fractional factorial Design of Experiments (DOE) to screen the importance of different parameters on the electric cabinet HRR. Based on statistical analysis of the results, the combustible material surface area was found to be the most significant parameter followed by cabinet volume, combustible configuration, burning duration and combustible material heat release rate per unit area. Material ignition temperature was found to not be statistically significant.

The last phase of this research assessed the robustness of the electrical cabinet parameters on the predicted HRR with more detailed simulations. Two investigations were undertaken. To identify the nonlinear effects of parameters on the electrical cabinet fire HRR, a Response Surface Methodology (RSM) based Central Composite Design (CCD) was used to create a simulation matrix that would allow statistical analysis of important parameters as well as their effects on the fire heat release rate while keeping the combustible configuration inside the cabinet constant. To explore the effect of combustible configuration and ignition source location, a series of simulations were conducted varying these parameters while keeping all other variables constant. The analysis revealed that all variables had a statistically significant impact on peak HRR. For the average HRR, both ventilation area into the cabinet and the ignition source HRR were found to be statistically insignificant. For both output variables, the cabinet volume, material heat release rate per unit area, and material surface area were found to be the most significant parameters. Combustible configuration and ignition source location were also found to be statistically significant.

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GENERAL AUDIENCE ABSTRACT

Electrical cabinet fires are a major concern for industries, commercial electric plants, telecommunication buildings, and nuclear power plant (NPP) facilities. These cabinets typically represent a metallic enclosure of varying sizes. Additionally, several different electronic components of heterogenous composition and configuration are included within this cabinet. The fires within the cabinet can propagate to several other nearby components, which can result in large fires that are difficult to suppress. Thus, it becomes necessary to understand the fire behavior of electrical cabinet and the factors influencing the fire propagation. Having a better knowledge of the factors influencing the electrical cabinet fires will enable facilities to have better fire resilience and further prevent multiple components and structures being damaged by these fires.

Statistical analysis of historic fire events validated that the most frequent challenging fires in NPP involve electrical cabinets. A detailed study was conducted to investigate what parameters most significantly affect the size of the electrical cabinet fire, which is quantified as the heat release rate (HRR). The parameters in the study included cabinet volume, ventilation area, combustible fuel detail (ignition temperature, heat release rate per unit area (HRRPUA), burning duration), fuel configuration inside the cabinet, and size of the ignition source. In order to determine which of these factors significantly impacted the electrical cabinet HRR, a computational fluid dynamics code Fire Dynamic Simulator (FDS) was used to predict the fire growth electrical cabinet fires. After employing a rigorous statistical analysis on the FDS results, the combustible material surface area was found to be the most significant parameter followed by cabinet volume, combustible configuration, burning duration and combustible material HRRPUA.

The last phase of the research sought to explore the significance of the parameters while developing a nonlinear expression to predict the fire HRR based on cabinet parameters. Given the wide range of electrical cabinet parameters, especially combustible configuration, two studies were conducted where the configuration was fixed or varying with respect to other parameters. For fixed combustible configuration, simulations were conducted with FDS systematically varying the other parameters so their importance could be ranked. Simulations were also performed with all parameters fixed expect the combustible configuration and ignition source location. The analysis revealed that all variables had a statistically significant impact on peak HRR. For the average HRR, both ventilation area into the cabinet and the ignition source HRR were found to be statistically insignificant. For both output variables, the cabinet volume, material heat release rate per unit area, and material surface area were found to be the most significant parameters. Combustible configuration and ignition source location were also found to be statistically significant.

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Finally, I would like to extend my unending gratitude to my family.

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1. INTRODUCTION

1.1 Background

Nuclear Power Plant – Probabilistic Risk Assessments (NPP-PRAs) use experimental data and simulations to support quantifying the risk associated with different fire events. One of the contributors in the uncertainty of PRA is the uncertainty in the experimental data. Experimental data used in PRA can be several decades old and taken before more modern measurement techniques were available. The overarching focus of this project was to identify experiments that need to be conducted to reduce the uncertainty in the data used in PRA. In general, this involves identifying what fire scenarios need to be considered for NPP, what parameters most significantly affect the fire behavior in these scenarios and compare these results with the currently available experimental data to determine what new experiments need to be performed. The focus of the research described in this thesis is on identifying which fire scenarios need to be considered for NPP and developing a framework to assess the important parameters that affect the fire development.

A statistical analysis was conducted in this study on the publicly available NPP Fire Event Database (FEDB) to determine the most frequent challenging fire scenarios. These data have been cataloged for Light Water Reactors (LWR) based in USA. Based on this analysis, electrical or electronic cabinets are responsible for a majority (40%) of these frequent challenging fires [1]. As a result, the primary focus of this research was developing a generalized framework to determine the parameters that most significantly affect the fire behavior and applying this to electrical cabinet fires.

There are many variables that may affect the fire behavior of electrical cabinets making it difficult to experimentally quantify the relative impact of different parameters on the fire. Until recently, only a few electrical cabinet factors have been experimentally explored and statistically analyzed in order to assess their individual and combined effect on fire Heat Release Rate (HRR). Experiments included different size cabinets with varying ventilation area and combustible load. In addition, combustibles are typically placed centrally or along sidewalls to determine its influence on fire behavior. Despite these efforts, the influence of combustible fuel details has not been thoroughly explored on cabinet HRR.

1.2 Research Objectives

The overall objective of this research is to identify the fire scenarios to focus on for reducing PRA uncertainty and develop a generalized framework for identifying parameters that impact the fire behavior. This framework was demonstrated on electrical cabinet fires since they are they were found to be the most frequent fires in NPP. The specific objectives of the research included:

1. Statistical analysis of historic fires to identify the most frequent and challenging fire scenarios using historic fire data from nuclear power plants (NPP) in the United States,
2. Statistical screening of parameters that may have an impact on electrical cabinet fire HRR, and
3. Detailed statistical analysis to rank parameter importance (main as well as interactions) on electrical cabinet HRR.

The first objective of this research investigated the most frequent fire scenarios using an electronic version of the publicly available Updated Fire Event Database developed by Electric Power Research Institute. For this purpose, fire scenarios were categorized according to their type, cause, and level of severity. The most frequent fires which were deemed challenging according to this study were classified primarily according to the fire type.

The second objective of the research was to employ a statistical screening based on design of experiment (DOE) to identify the parameters that affect the electrical cabinet HRR. The parameters investigated included volume, ventilation area, combustible surface area, heat release rate per unit area (HRRPUA), burning duration, ignition temperature, combustible configuration, and ignition source HRR. The main effect and interaction effect of the independent parameters on the electrical cabinet output response was tested using ANOVA and Student's t-statistics following fractional factorial design of experiment structure.

The final objective was to extend the study conducted in the preceding section by utilizing a more detailed DOE to support a nonlinear statistical analysis using input parameters that represent electrical cabinet that may be found in NPP. Through this statistical analysis, the main and interaction effects of the electrical cabinet parameters on HRR could be quantified and their relative importance ranked. Two investigations were carried out. The first part used Central Composite Design (CCD) based on Response Surface Methodology (RSM) to investigate the impact of electrical cabinet characteristics on heat release rate while keeping the combustible configuration constant. In contrast, a number of alternative combustible configurations were examined in terms of HRR versus time while all other factors remained constant. The results were combined to provide a overall impact of different parameters on electrical cabinet HRR.

1.3 Organization

This thesis is organized as a series of articles with each article being a chapter. The chapters included in the thesis include the following:

Chapter 2 contains the paper "Analysis of Historic Fires to Determine Most Frequent Challenging Events"

Chapter 3 contains the paper "Statistical Analysis Approach to Determine the Significant Parameters that Affect the Electrical Cabinet HRR

Chapter 4 contains: "Assessing Parameter Importance on Electrical Cabinet Fire Heat Release Rate".

2. ANALYSIS OF HISTORIC FIRES TO DETERMINE MOST FREQUENT CHALLENGING EVENTS

This chapter was published in the Progress in Nuclear Energy journal. The database pertaining to Nuclear Power Plant fires was developed by Saeed Alhadhrami and Jun Wang of University of Wisconsin-Madison. Additionally, Elvan Sahin of Virginia Tech supported in identifying the fire scenario details from the database.

Abstract

The fire probabilistic risk assessment framework for nuclear power plants relies on experimental data to determine expected fire behaviour or to validate models to predict fire conditions in the plant. To support reducing the uncertainty in this experimental data, a research effort was conducted to identify the most frequent and challenging fire scenarios using historic fire data from nuclear power plants in the United States. To support this effort, an electronic version of the publicly available Updated Fire Event Database developed by Electric Power Research Institute was produced resulting in data on 2,111 fire events, 540 events were labelled as being challenging fires with 74.2 % of these challenging fire events being due to eleven selected fire types. Of these fire types, electrical and electronic equipment, transient combustibles, and liquid fires were the most frequent of the challenging fires. The fire scenario specifics were characterized for each of the eleven selected types and then related to existing fire experiments.

Keywords: Nuclear Power Plant - Probabilistic Risk Assessment, Fire Event Database, Fire Scenarios, Fire Severity Classification, Data Analysis, Uncertainty quantification.

1. Introduction

A Fire Probabilistic Risk Assessment (PRA) in a Nuclear Power Plant (NPP) is used to assess the overall fire safety of the plant based on conditions identified through a field survey. In this field survey, potential fire scenarios inside of a NPP are identified and generally characterized through the knowledge of the location, fuel loads, and type of combustible materials. To quantify the risk associated with these different fire scenarios, it is common to use experimental data and computational models to predict what conditions could develop from the fire and cause potential damage [2, 3]. To reduce the uncertainty in fire PRA, the quality of the existing experimental data needs to be evaluated. The first step in this is describing the most frequent and challenging fire scenarios in sufficient detail such that they can be related to existing experimental data. This research was conducted to identify the details of the frequent challenging fires through statistical analysis of historic fire events and perform analysis to provide fire scenario descriptions sufficient to relate these fire events to experimental data.

In the framework of NPP PRAs to mitigate potential fire events, early attempts to statistically quantify fire incident information across NPPs typically employed database acquisition and analysis focusing only on a single fire attribute. Two independent studies conducted statistical assessments only on electrical induced fire records giving insight into the distribution of components involved during fire incidents. Keski-Rahkonen et al. investigated only the electrically induced Finland-based NPP fire records and the International Atomic Energy Agency (IAEA) and Organization of Economic Cooperation and Development / Nuclear Energy Agency Advanced Incident Reporting Systems (OECD/NEA AIRS) database to establish the most typical electrical ignition mechanism [4]. It was observed that the most prevalent cause for electrical ignition was defective cables leading to short circuits and ground shorts as well as loose connections leading to overheating. The authors also examined the Sandia National Laboratories (SNL) Fire Event Database catalogued from 1965 to 1989 to quantify the failed components in electrical fires. Their findings indicate that cable, wiring, or bus contributed to 21% of the overall failed components in the fire scenarios [5]. The statistical assessment of the OECD Fire Data Project [6] advocates that most fires inside NPP buildings originated from electrical equipment, with cable insulation materials being the most common fire load. Several studies have also conducted quantitative and qualitative analysis on individual NPP systems to better characterize the events to support PRA for nuclear installations [7-11].

The studies described in the previous paragraph only investigate the attributes of one type fire event (e.g., electrical components) that may occur in NPP installations. NPP rooms harbor different components that may give rise to a broad spectrum of fire events. The attributes of all of these different fire events must be considered in a PRA; therefore, the details of these other fire events need to be determined to support identifying the required experimental data to predict the behaviour of these events. Specifically, the most frequent challenging fires need to be identified since they pose a significant threat to NPP safety and sufficient data needs to be available on these fires to reduce the uncertainty of the fire PRA.

Frequency of fire events has been the focus of some studies available in the literature. Fire occurrences are typically measured in frequency by characterizing the locations and equipment involved during the fire event. This information is further used to evaluate the risk associated with certain fires [12]. Together with different fire event attributes, it becomes necessary to consider a database that provides information on fire event detail, such as location, components involved, and causal factors. This information in the database provides a better route to understand NPP fire scenarios and further support PRAs. For instance, Shalabi et al. investigated the OECD Fire Database to foster qualitative insights for the cause of fire incidents and leverage this information to Canada deuterium uranium (CANDU) NPP PRAs. The study explored the information encapsulated in OECD by analysing plant characteristics, compartment-specific conditions, potential fire sources, and safety targets. Fire events were measured as frequency by percentage, and the findings showed that most of the fire events occurred in the Turbine Building. Furthermore, the cause of ignition was mainly electrical [13]. The study looked at each aspect of the fire event individually rather than the details of specific types of fire events. For example, it is not possible to tell the details of the electrical fire event but just that they are the most frequent. The details of the most frequent challenging fire events are needed to relate them to experimental data.

Studies have used database information to identify risk-significant fire events in NPP using a fire severity classification. The NUREG 2169 and NUREG/CR-6850 report fire severity level classification allowing for identifying fire occurrences that are challenging [14, 15]. Several studies have used fire database information against this fire severity criteria to identify challenging fire scenarios. For instance, Nagata et al. used the Central Research Institute of Electric Power Industry (CRIEPI) database to determine the fire event distribution in PRA among Japanese industries [16]. A four-step process was exercised to analyse the distribution. The process involved data acquisition, categorization, classification, and fire ignition frequency quantification. Using the database, the fire event records were screened against the fire severity classification criteria per NUREG-2169 [15]. Furthermore, the data were categorized following updated fire scenario definition that encapsulates fire ignition sources like dryers, electric motors, pumps, air compressors, and location details that include plant-wide, turbine building, transformer area. It was determined that more than 70% of the fire events were attributed to transients, electrical cabinets, and pumps, and these fire events were identified to be significant risk contributors to Japanese NPPs. However, the specifics of these fire events were not sufficiently detailed to relate them to fire experiment data. Kang et al. quantified significant oil fire scenarios from Essential Service Water System (ESWS) records after qualifying location and ignition source regarding fire severity level defined in NUREG/ CR-6850 [14]. However, risk significance for all potential events in a NPP was not explored. Another study evaluated fire events recorded for a process room in Loviisa NPP to quantify significant risk contributors per ignition source and location information of the fire event following severity classification defined in NUREG-2169. This study only looked at risk significant events in a specific NPP location and not throughout the entire NPP.

The studies mentioned above used statistical assessment of historical databases conceived prior to many of the advanced reporting techniques employed for recording fire events. The fire event characteristic used to develop Fire PRA models may be subject to significant uncertainty. As a result, the most recent version of the database should be used since it provides more event details to reduce uncertainty. It is also necessary to consider a database flexible enough to support multiple aspects of fire event details that best represent fire scenarios and further map the data to configure fire experiments. For several decades, EPRI has collected fire event data for nuclear power installations in the USA and developed generic fire ignition models [17-21]. Following this, EPRI has continued to look into different methods of collecting NPP fire records in order to improve data quality. The updated FEDB includes expanded and improved data fields, coding consistency, incident detail, and reference data to better support fire PRA [22, 23]. The EPRI FEDB also includes the fire severity classification defined in NUREG-2169 [15]. This allows for determination of fire events details sufficient to relate to fire experiments for the most frequent and challenging fires, which has not previously been reported in the literature.

The focus of this paper is to conduct statistical analysis on the updated EPRI-FEDB from 1990 through 2014 to identify the most frequent challenging fires and attributes that best characterize the fire scenario details. For NPPs operating in the United States, the updated FEDB developed by EPRI incorporation with the United States Nuclear Regulatory Commission (USNRC) under a document of understanding [24] is the most comprehensive and consolidated source of fire incident information. The FEDB's unabridged version includes confidential information given by nuclear power station owners and operators and access to the whole database is restricted. Additionally, the non-proprietary version in [22, 23] provides only a high-level tally of the fire event types. This research used the non-proprietary FEDB information and digitized it to perform a thorough statistical analysis. The data derived through the electronic version was further parsed to identify and retrieve fire event attributes that best describe the fire scenario details. These events were qualified against the fire severity classification following to quantify the most frequent and challenging fire event details. Finally, the fire scenarios in NPPs are related to existing fire experimental tests commonly used in modeling validation.

2. Methods

This section provides an overview of the approach used to obtain data specific attributes on fire incidents that have occurred in NPPs from 1990 through 2014 and to characterize fire scenarios accordingly. In addition, this section describes the use of Fire Severity Classification to understand which fires are the most challenging since these fires will likely most contribute to the NPP risk. Using the most challenging fire events, the process used to determine the fire scenario details with the FEDB is described.

2.1 Database

The FEDB was developed by EPRI in cooperation with USNRC and is the primary source of operational fire event data used in PRAs of NPP fire incidents. EPRI updated its FEDB for the period of 1990-2014 [22, 23]. This included fire events from 84 NPPs across the USA resulting in 2,116 events within the database. For this research, the non-proprietary information provided in Appendices C to G in the report was utilized here to conduct quantitative and qualitative analysis to determine the most frequent and challenging fire scenarios. The contents within these appendices are described in *Table 1*. Each of the summary reports in the FEDB was digitized to conduct quantitative as well as qualitative analysis. The data specifics pertaining to each report were entered manually and stored in an Excel spreadsheet for analysis.

Table 1. A description of the appendices in the FEDB used to create the searchable database for this research [22].

Appendices	**Description**
Appendix C – FEDB Fire Summary Report	The FEDB Fire Summary Report provides a brief description of the probable fire event. Fields of interest in this summary report mainly include plant location, system, component, and component group.
Appendix D – FEDB Fire Attribute Report	A high standard evaluation of the probable fire event is provided with FEDB Fire Attribute Report. The report provides information about Fire Cause, Fire Type, and Combustibles involved. In addition, smoke effects, collateral damage, and temperature effects are also reported.
Appendix E – FEDB Fire Severity Evaluation Report	The report enlists fire incidents that the fire severity determination algorithm has automatically determined.
Appendix F – Fire Timeline Report	The FEDB Fire Timeline Report provides timing information from the time of ignition to the time of response and extinction. This report also specifies if the length of the fire was known in minutes, approximated, or unknown. The report also discusses detection and suppression techniques.
Appendix G – Plant Response Report	The FEDB Plant Response Report provides a high-level summary of the plant state prior and after the potential fire event. Fields of interest include mode prior/after, power level prior/after and emergency action level.

The digitized FEDB generated from summary reports consists of 60 unique attributes characterizing the fire events that occurred in NPP from 1990 through 2014. Attributes like Fire ID, Event Date, Disposition, and Review Status are shared across all the summary reports and were used to correlate them across different appendices. Information about plant location, system, component group, combustibles involved is some of the other attributes that provide a high-level assessment of the fire scenario details for each event. The data also provides the plant state before and after a fire event, the suppression method applied, and the emergency action taken during that particular fire incident. This research focused on a subset of the attributes that were used to define the fire scenario. The FEDB contains several other attributes that highlight other aspects of the fire event, but these were not considered in this research effort.

Given multiple attributes archived in the FEDB, the fire event's unique features provide knowledge of a large number of fire scenarios. This research primarily focused on the most frequent, challenging fires identified through statistical analysis of the FEDB events. The majority of the fire scenario details can be described through the following data types: Building, Fire Type, Fire Cause, Combustible Types and Forms, and Component Group. Building is where the fire was located while fire cause provides information on how the fire was initiated. Primary Combustible Group – Types and Forms, describes the fuel and configuration involved in the fire. In addition, Component Group refers to the general type of the component (e.g., electric motor, pumps, and generators) where the fire was initially ignited. These details provide the most frequent, challenging fire scenario details, which are cases that should likely contribute most to the NPP risk and, therefore, should be considered in a Fire PRA in detail. Having an accurate understanding of how these fires behave through experiments and modeling is needed to reduce the uncertainty of the Fire PRA.

2.2 Data Analysis

The digitized fire events data in the Excel spreadsheets were imported for analysis using Python 3. The data derived from the summary reports were cleaned of any irregularities by manual examination as well as using several Python tools and libraries. Python 3 was then used to manipulate the data, conduct statistical analysis, and plot the information.

2.2.1 Identifying Challenging Fires

In order to obtain the most frequent, challenging fire scenarios through the FEDB, it was necessary to study the Fire Severity Classification as specified by NUREG/CR-6850 and EPRI [14, 22]. The Fire Severity Classification data provides information on whether the components and combustibles resulted in a fire that was easily suppressed or resulted in a challenging fire that was difficult to control and suppress. The updated FEDB uses a five tired classification for fire incidents. These classifications are shown in *Table 2* along with a high-level description of the Fire Severity Classification defined by EPRI.

Table 2. Fire Severity Classification defined by EPRI.

Fire Severity Classification	**Description**
Challenging (CH)	Challenging Fires are occurrences which have observable and significant environmental repercussions, irrespective of the source of the fire
Potentially Challenging (PC)	Potentially Challenging Fires are occurrences that were not classified as CH but may have progressed to that status.
Not Challenging (NC)	Not Challenging Fires do not cause, or cause, any neighboring items or components, to be harmed or to ignite for any length of time regardless of the location, but may be automatically identified by fire detection
Undetermined (NC – PC)	Fires are considered NC, but the insufficient information makes it difficult to categorize it as a Potentially Challenging Fires
Undetermined (PC – CH)	Fires are considered PC, but the insufficient information makes it difficult to categorize it as a Challenging Fires

To determine the most frequent and challenging fire scenarios, the five levels of classification were combined into three levels of fire severity classification: (i) Challenging (CH), Potentially Challenging (PC), and Undetermined (PC – CH) were grouped as challenging fire events (ii) Not Challenging (NC) and Undetermined (NC – PC) were grouped as not challenging fire events, and (iii) the remaining fire events that were not classified were considered as Not Evaluated.

2.2.2 Determination of Fire Details

The primary goal of the present research was to use the FEDB to quantify the details of the most frequent, challenging fires. This was done through analysis of the Primary Combustible Group – Types and Forms data. *Table 3* below illustrates the sub-categorization of Primary Combustible Groups according to its Types and Forms. The dark green shaded cells represent the area of interest to determine the fire scenario details. Though some of the other blocks provide more granular detail about the fire scenario, the green shaded area provides the required information to determine the fire scenario detail for future comparison with experiments conducted on similar fires. Statistical analysis was performed using this information from the FEDB to quantify and rank the challenging/potentially challenging fires. The following section seeks to give a brief description of a typical fire experimental framework for Primary Combustible Group induced fires.

Table 3. Primary Combustible Groups and their Types and Forms.

Primary Combustible Group	**Types**	**Forms**
Liquid	Lube Oil or grease, Fuel oil, Transformer oil, cleaning solvent or paints, Others	Pressurized Spray, Leak- oil-soaked insulation, Spill confined by curbs, Contained within reservoirs, Contained within component, Unconfined liquid spill, Confined liquid spill, Other
Insulation	Thermoplastic, Thermoset, Mixed, Others	Multiple bundles, Cable tray stack, Multiple cables not in a tray or bundle, Stored unused cables, Single unbundle, Single cable tray, Single cable, Unknown, Other
In-Situ	Other electrical or electronic equipment, Thermal insulation material, Interior finish, Other	No form specified
Transient	Cellulosic materials including wood, paper or other solid transients, Temporary electrical wiring or equipment, Plastic Sheets, Temporary thermal insulation materials, Trash (i.e., solid refuse collected for disposal), Other (specify)	No form specified
Gas	Hydrogen, other	Pressurized in container, Jet from a pressurized source, Ambient pressure, within a compartment, Ambient pressure, within a component, others

3. Results

This section presents the statistical analysis results based on data from the EPRI – FEDB summary reports. Following the removal of any abnormalities in the dataset, statistical analysis was conducted to determine the most frequent, challenging fire scenarios. The distribution of fire events was assessed across various buildings, component groups, and combustible groups.

3.1. Fire Event Database Overview

This section contains some of the findings obtained from the statistical analysis on the FEDB. Overall, EPRI – FEDB was collected for three different ranges of periods 1990-99, 2000-09, and 2010-14. It is divided into three unique data sets, each with its own set of data sources, quality, and completeness. The updated database for three different periods was summarised in two EPRI reports, this distribution required the data to be merged before processing the data and conducting statistical analysis.

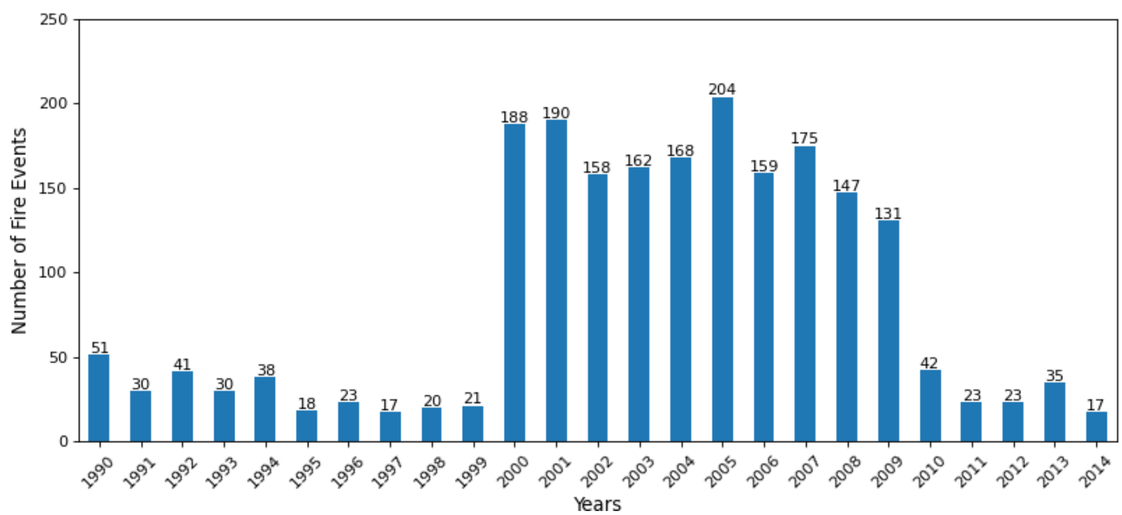


Figure 1. Number of Fire Events from 1990 - 2014

The updated FEDB for the period from 1990-2009 is reported solely for the 84 plants that have completed the whole data gathering protocol and plant examination for fire incidents. The database was later appended with additional fire events reported from 2010-14. For the period 1990-99, fire event data were obtained from multiple sources, the significant event details were conceived from License Event Reports (LERS), Nuclear Electric Insurers, Limited (NEIL), Equipment Performance Information Exchange Systems (EPIES), Emergency Notifications (EN's) and Plant Reports. For 2000-09, the data was primarily based on fire incident data directly collected from Nuclear Power Plant records, together with LERS and EN's. Over the 2010-14 period, data was collected and stored in the ICES database by the Institute of Nuclear Power Operations (INPO) [22, 23]. *Figure 1* above shows the number of Fire Events reported each year from 1990 to 2014, and as illustrated in *Table 4* EPRI has cataloged Fire Events and Total Reactor Years for three different periods.

Table 4. Sources, Number of Fire Events, and Total Reactor Years

	Period		
	1990-99	**2000-09**	**2010-14**
Data Sources	LERs, ENs, NEIL, NPRDs, Plant Reports	LERs, ENs, Plant Reports	INPO
Fire Events	198	1497	421
Reactor Years	1081	850	425

Figure 2. represents fire events from 1990 – 2014 for the most severe fires. The orange line represents fire events that were labeled as Challenging. The blue line represents fire events that are regarded as severe, which are a combination of Challenging (CH), Potentially Challenging (PC), and Undetermined (PC-CH). The data are normalized relative to the Counts per Reactor Year. The Updated FEDB CH, PC, and U (PC-CH) as seen through the blue line have a discontinuity between 1999 to 2000, but the Updated FEDB CH Fire Event reports overall remain similar for each year. According to Ref. [15], more common but less severe Potentially Challenging (PC) fire events were not reported and are given less importance for the 1990-99 period. This is partly a consequence of the fire event data collection protocol used to update the fire event data for the 2000-09 period. The 2000-09 period is assumed to be more complete for the 84 plants that participated in the FEDB update when compared to the 1990-99 period. The report also indicates that there is the possibility of missing data for the 1990 – 99 period.

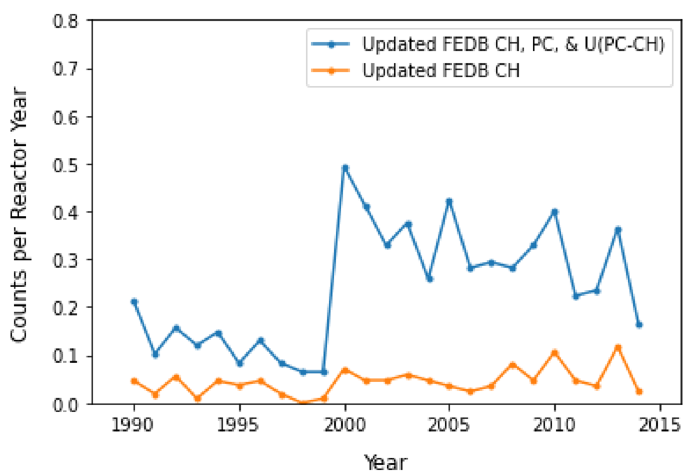


Figure 2. Counts per Reactor Year

Figure 3. below contains the percentage of fire events according to the revised fire severity classification. About 71.86% of the 2,111 Fire Events were classified as Not Challenging (NC + Undetermined (NC – PC)) Events. About 25.58% were classified as Challenging (Challenging + Potentially Challenging + Undetermined (PC – CH)), and at least 2.56% of the Fire Events were Not Evaluated or Not Labelled. The following sections show how the fire events, when qualified against the revised fire severity classification, are distributed across the Building, Component Groups, and Primary Combustible Groups.

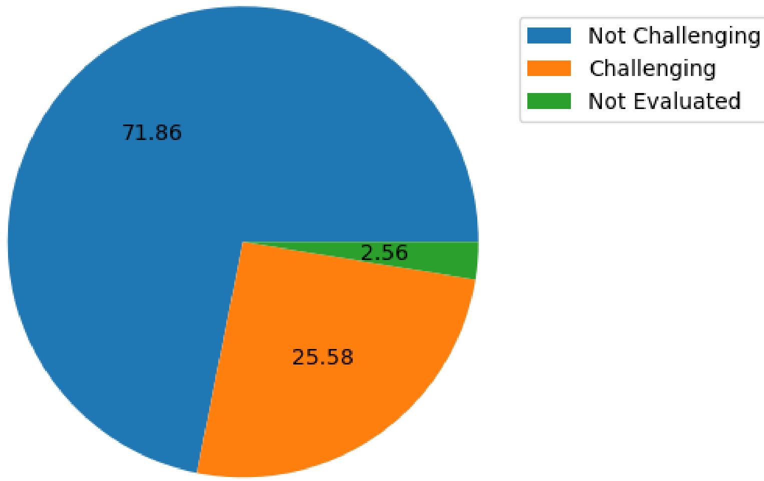


Figure 3. Distribution of Fire Events according to revised Fire Severity Classification

3.1.1. Building

Building specifies the location where in the NPP the fire started. The percentage of fire events distributed according to the building in which it was initially located is illustrated in *Figure 4*. The Other category was 27.66 % of the fire reports; however, no specific details were provided about these events in the database. For the known locations, the majority of the fire events occurred in the Turbine Building (20.84 % of the 2,111 fire events) followed by Containment (PWR), Diesel Generator Building, Auxiliary Building which corresponded to 6.49%, 5.31%, and 4.64% of the total fire events, respectively.

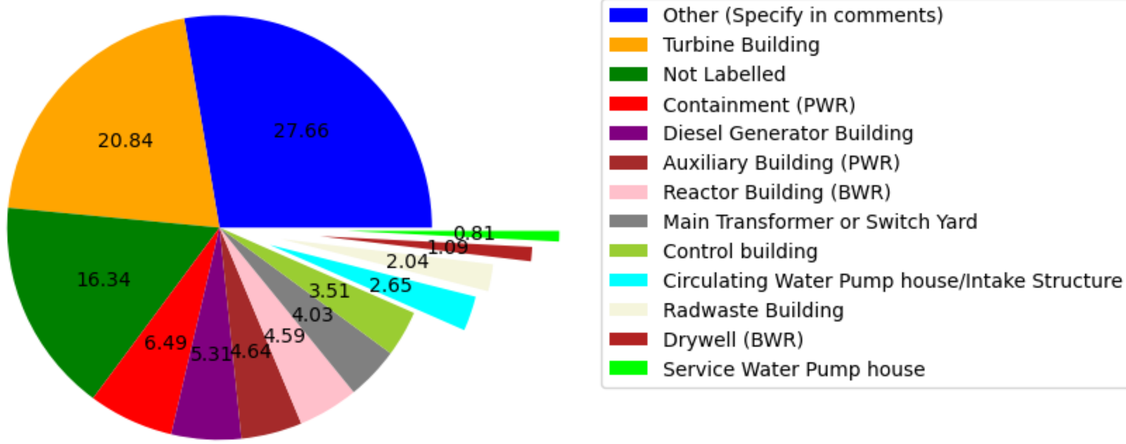


Figure 4. Distribution of Fire Events according to Building in which fire was initially located.

3.1.2 Component Group

Component Group specifies the type of equipment/object where the fire was located. *Figure 5* contains the percentage of fire events distributed according to the Component Group. The most frequent component involved was Electrical Panel at 14.07% with Pumps being the next most frequent at 8.01%. Electrical Motor, Generator, and Transformers contributed 5.78, 5.31, and 5.3 %, respectively, to the overall number of fire events.

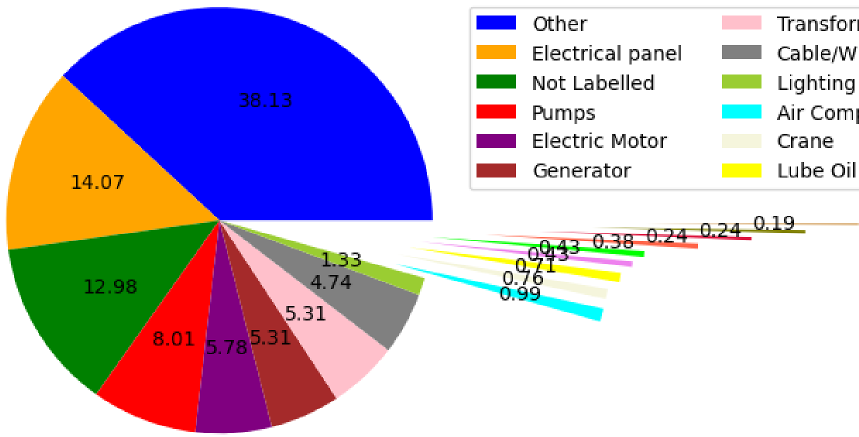


Figure 5. Distribution of fire events according to the Component Groups.

3.1.3. Fire Cause

Fire Cause is the ignition mechanism that initiated the fire. The distribution of fire events according to the Fire Cause is illustrated in *Figure 6*. A majority of the fire events occurred as a result of Electric failure resulting in overheating materials (29.70%), followed by Hot work (cutting/ welding/ grinding, etc.) representing 23.16% of the events and Overheated material causing 14.50% of events.

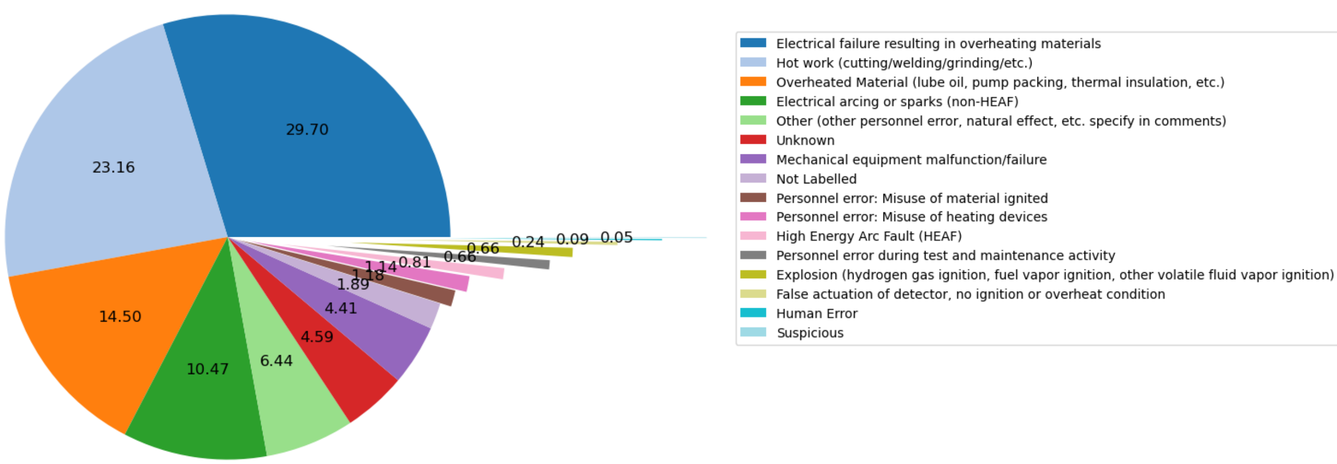


Figure 6. Distribution of fire events according to the Fire Cause

3.1.4. Primary Combustible Group

The percentage of fire events sorted by Primary Combustible Group is provided in *Figure 7*. Primary Combustible Group is a high-level descriptor for the type of fuel involved in the fire. The most frequent Primary Combustible Group was In-Situ (e.g., inside of electrical cabinets, electronic boxes, equipment, etc.) which accounted for 43.4% of the fires. The next most frequent was Transient materials (e.g., not permanent including trash, temporary cables, etc.) at 26.5% followed by Liquid at 9%.

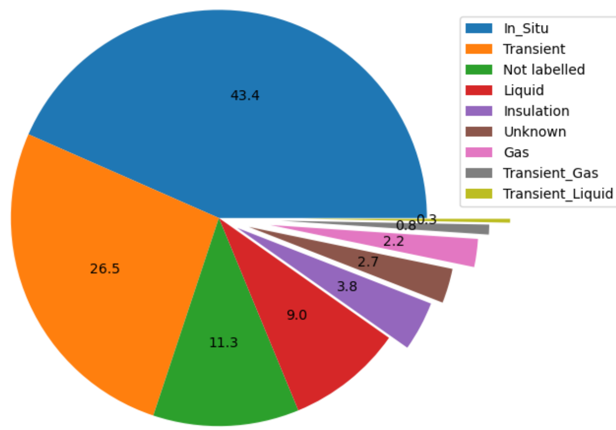


Figure 7. Fire Events caused by Primary Combustible Groups.

The results in *Figure 8* provide a breakdown of the fire events by fire severity classification level for each Primary Combustible Group. Note that the fire severity levels contained in the figure are based on combining some categories in the database as previously described. This research focused on the challenging fires since they resulted in the most severe conditions. In general, the combustible groups with more fire events also had a higher number of challenging fire events. The groups with the most challenging fire events were In-Situ, Transient, Liquid, and Insulation.

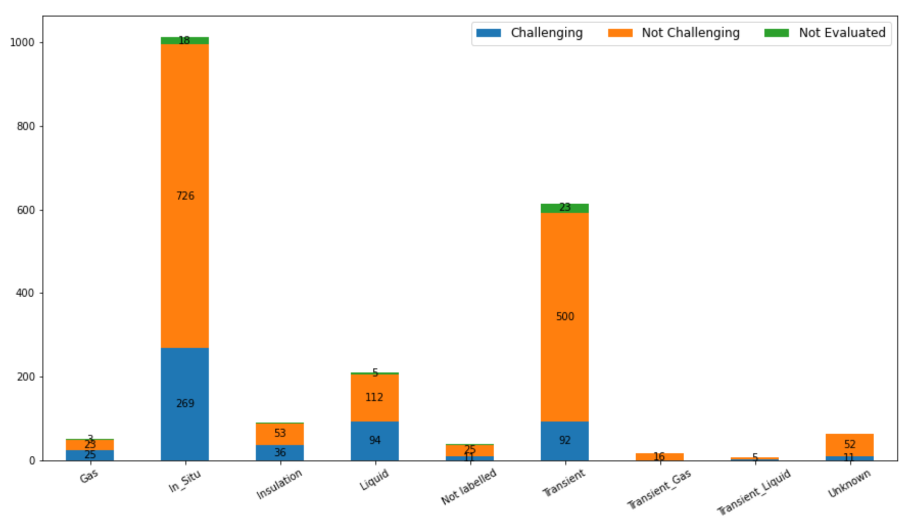


Figure 8. Distribution of Revised Fire Severity classification across Fire Events defined by Primary Combustible Group

3.2. Challenging Fire Events

The database contained a total of 540 fire events classified as Challenging Fire Events. This section presents a detailed assessment of the data to quantify the fire scenario details for these challenging fires. Specifically, the fire scenario for the top Primary Combustible Groups was identified including Building, Component Group, and Fire Cause, which describes how the fire was initiated.

The challenging fire events by Primary Combustible Group are shown in *Figure 9*. The most frequent group was In-Situ, which accounted for 49.81% of the events. Liquid and Transient groups each had approximately 17% of the events while Insulation contributed 6.67% of the events. In the following section, each primary combustible group is further described to provide a more detailed description of the source fire.

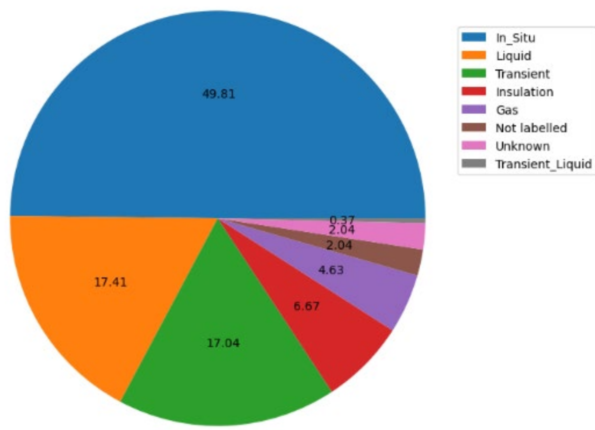
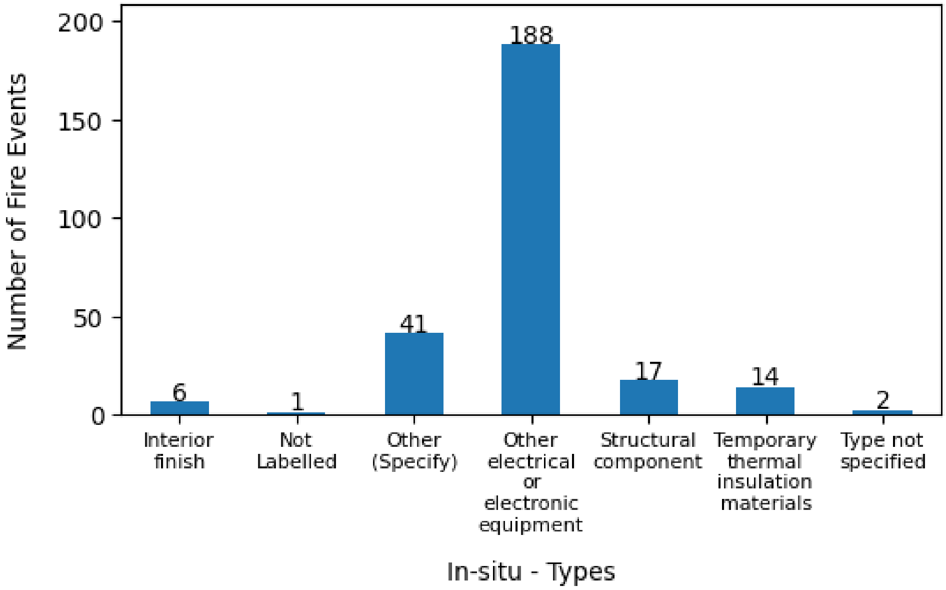


Figure 9. Challenging Combustible Groups

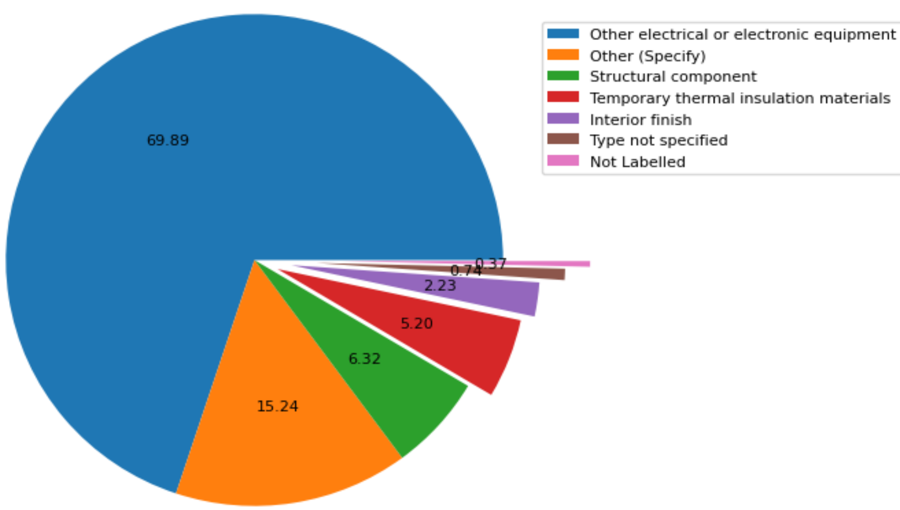
3.2.1. Challenging Fire Event Count

Each Primary Combustible Group was sub-categorized in the database by a more detailed description. The count and percentage of these more detailed descriptions are provided to support determining the most frequent, challenging fires and their scenario details.

The In-situ group contained 269 of the 540 fire events and these were subdivided into the categories shown in *Figure 10.* The 'Other electrical and electronic equipment' category had the highest contribution while 'Structural component' and 'Temporary insulation' were the categories with the next most frequent events. These three categories accounted for 219 or 81% of the In-Situ challenging fire events.



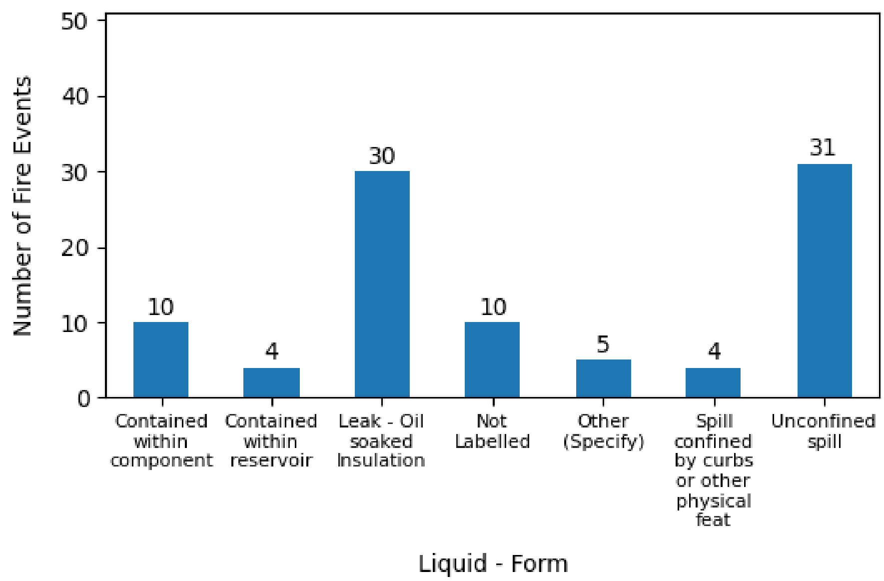
a. Fire Event Count for In-situ Types.



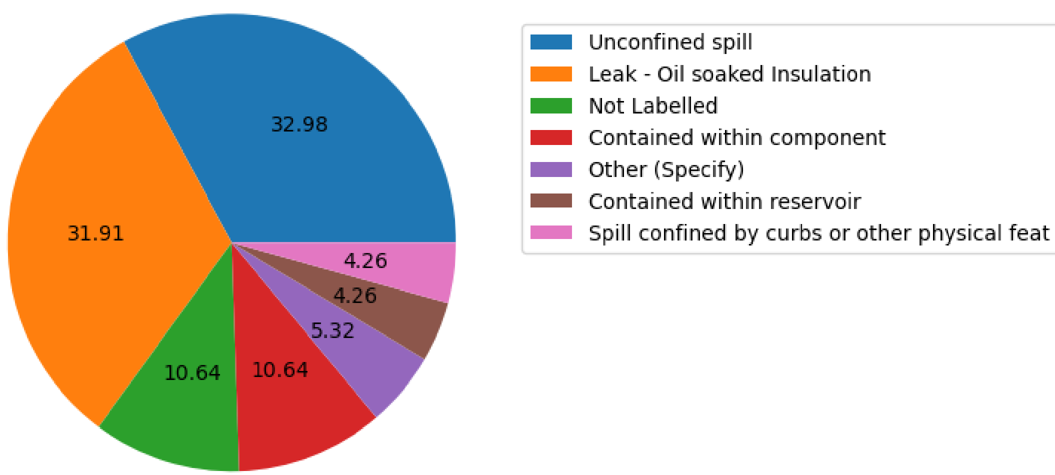
b. Fire Event percentage distribution for In-situ Types.

Figure 10. a) Fire Events count and b) Fire Event distribution of In-Situ Type for Challenging Fire Events

For the Liquid group, the top types of fires were ‘Leak – oil-soaked insulation’, ‘Unconfined Spill’, and ‘Contained within Component’ as seen in *Figure 11*. These accounted for approximately 76% of the Liquid group fire events.



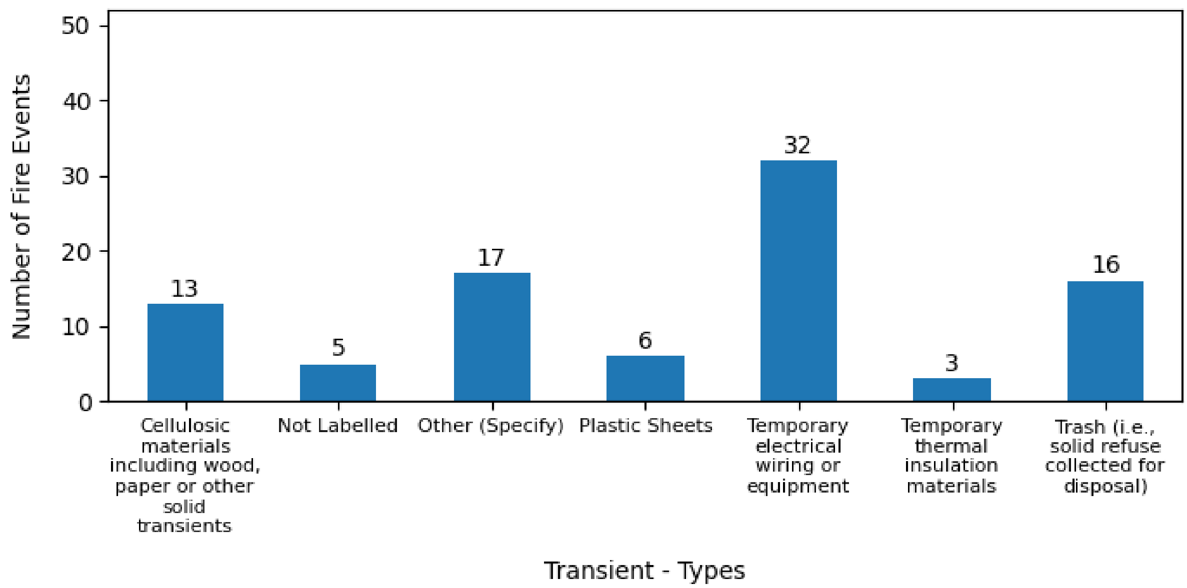
a. Fire Event Count for Liquid Form.



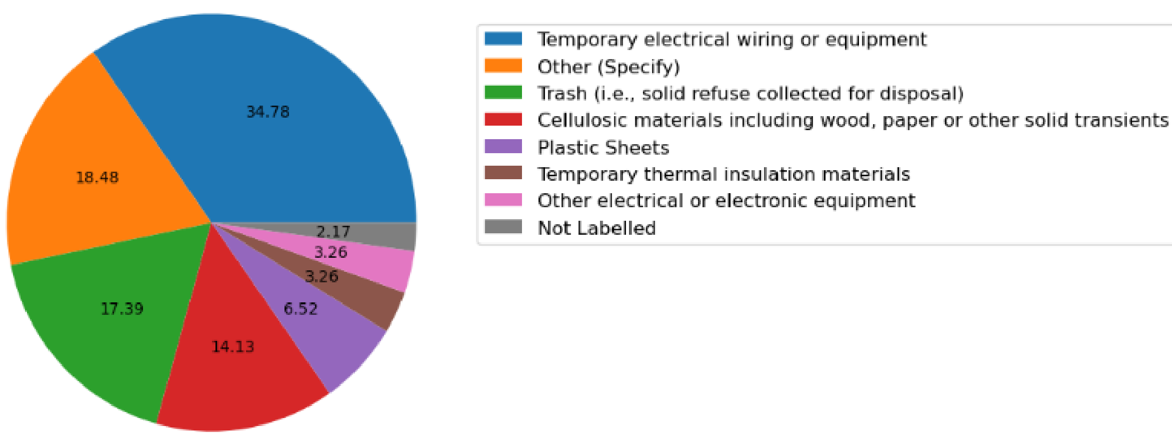
b. Fire Event percentage distribution for Liquid Form

Figure 11. a) Fire Events count and b) Fire Event distribution of Liquid Form for Challenging Fire Events

In the Transient group events, the results in *Figure 12* show that 'Temporary electrical wiring or equipment' contributed the most with 32 events. Moreover, 'Trash', and 'Cellulosic materials including wood, paper, or other solid transients' also had a major contribution. These three categories represented approximately 66% of the Transient fire events.



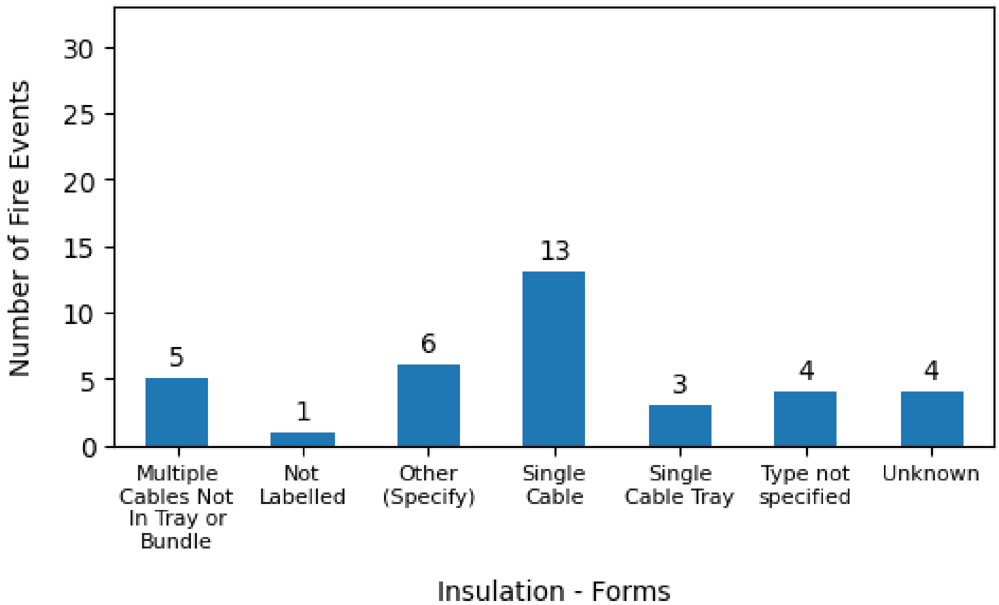
a. Fire Event Count for Transient Types.



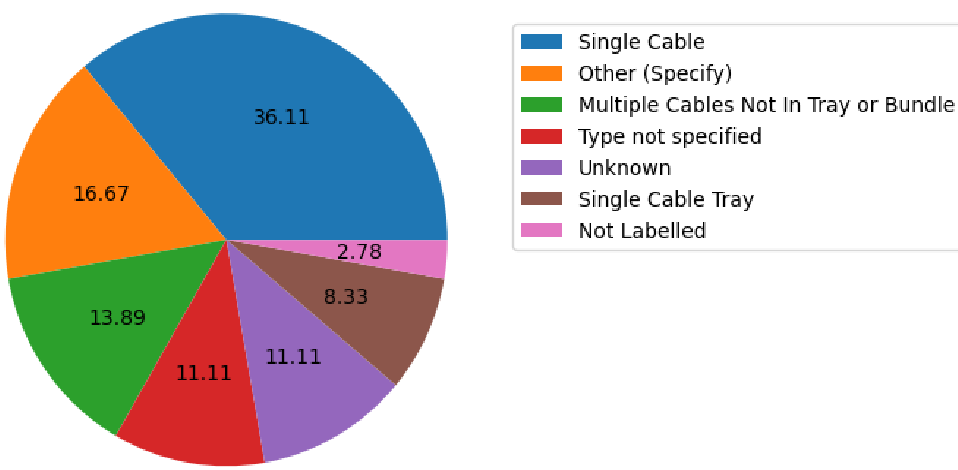
b. Fire Event percentage distribution for Transient Types.

Figure 12. a) Fire Events count and b) Fire Event distribution of Transient Types for Challenging Fire Events

The Insulation group challenging fires, which correspond to cable fires, was found to be mostly due to 'Single Cable' and 'Multiple Cables not in a Tray or Bundle', see in *Figure 13.* These two subcategories accounted for 50% of the Insulation fires.



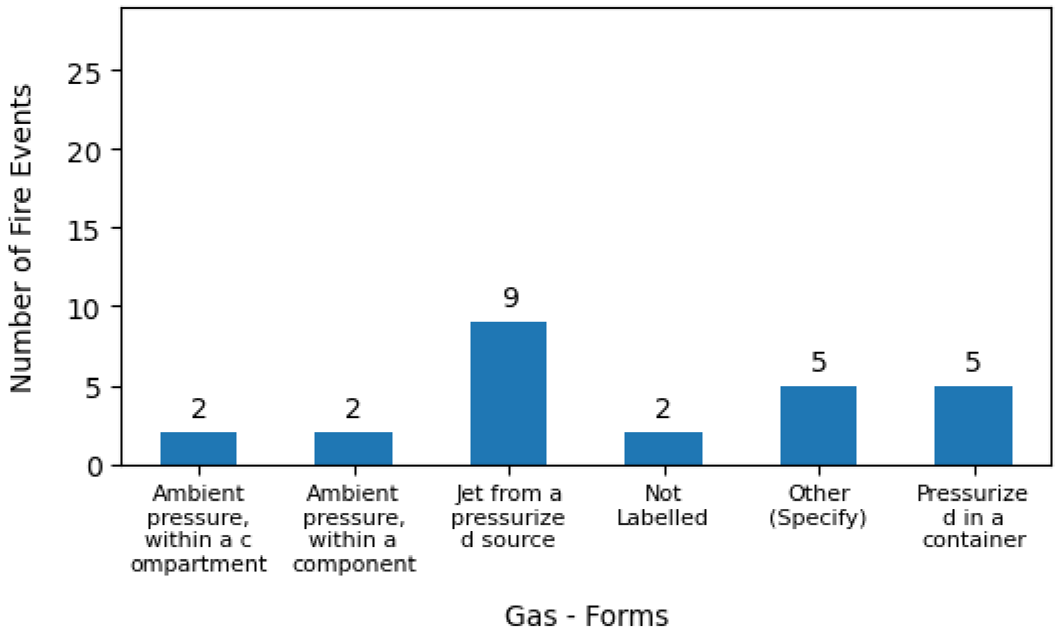
a. Fire Event Count for Insulation Forms.



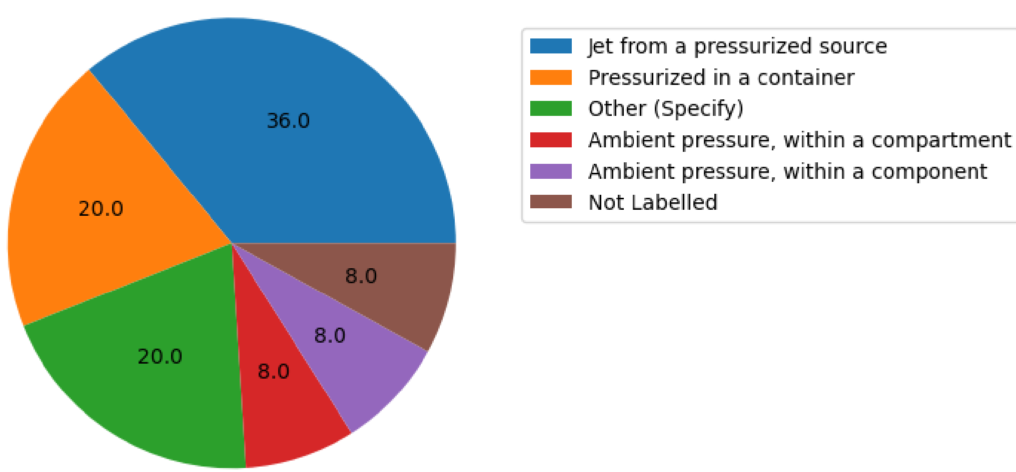
b. Fire Event percentage distribution for Insulation Forms.

Figure 13. a) Fire Events count and b) Fire Event distribution of Insulation Form for Challenging Fire Events

The results for the Gas group are shown in *Figure 14*. Based on this data, the 'Jet from a pressurized source' contributed the most events with 9 followed by 'Pressurized in a container' with 5 events. These two cases represented 56% of the challenging fire events.



a. Fire Event Count for Gas Forms.



b. Fire Event percentage distribution for Gas Forms.

Figure 14. a) Fire Events count and b) Fire Event distribution of Gas Form for Challenging Fire Events

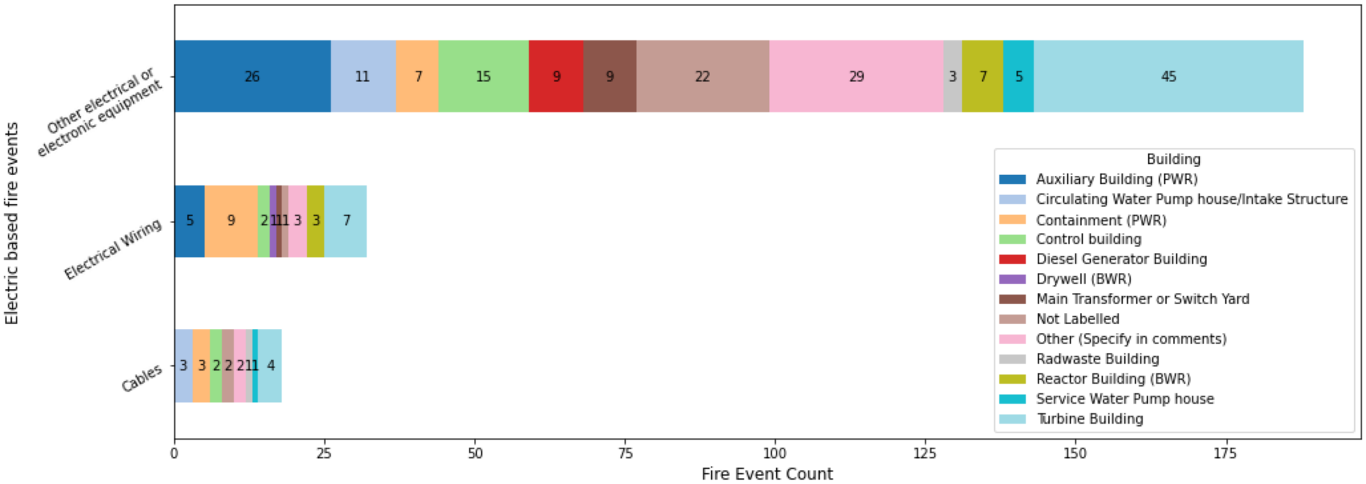
3.2.2. Fire Scenario Details

Fire scenarios can mostly be defined through the categories Buildings, Component Group, Combustible Group, and Fire Cause. Buildings and Component Group where the fire is located while Combustible Group describes what is burning and Fire Cause indicates how the fire was initiated. In this section, the fire scenario details for the challenging fires are explored through further analysis of the database. This was only done for the Combustible Groups that were responsible for the most frequent fire events identified in the previous section.

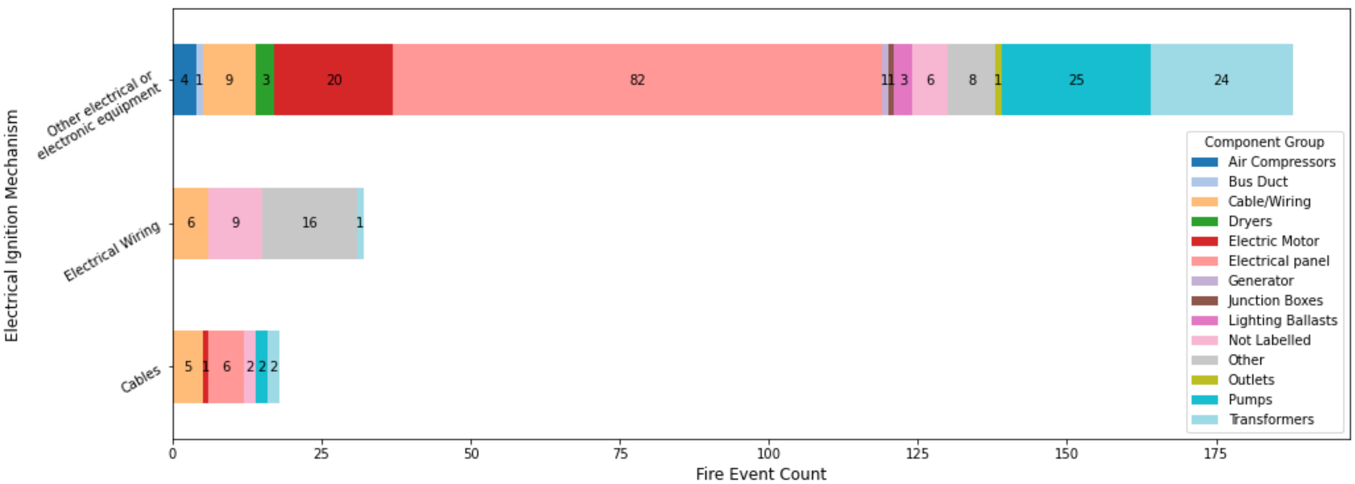
The details of electrical-based fire scenarios are provided in *Figure 15.* Other electrical equipment and electronic components (in-situ group), single cables and multiple cables not in a tray or bundle (insulation group), and temporary electrical wiring (transient group) are included in this electrical-based fire scenarios. This data found that most of these fire events occurred in the Turbine, Auxiliary, Control, and Containment (PWR) buildings. These fire events typically occurred in Cable/Wiring, Electric Motors, Pumps, and Transformers. Electric Failure resulting in overheating materials was the major Cause of Fire associated with these events.

Additional fire scenario details for the Trash and Cellulosic Materials (both in the Transient group) are provided *Figure 16*. These fires typically occurred in the Turbine and Containment (PWR) buildings. Since these are transient fires, there were typically no components associated with these fires. Hot Work (Cutting/ Welding/ Grinding, etc.) was the fire cause that generally initiated these events.

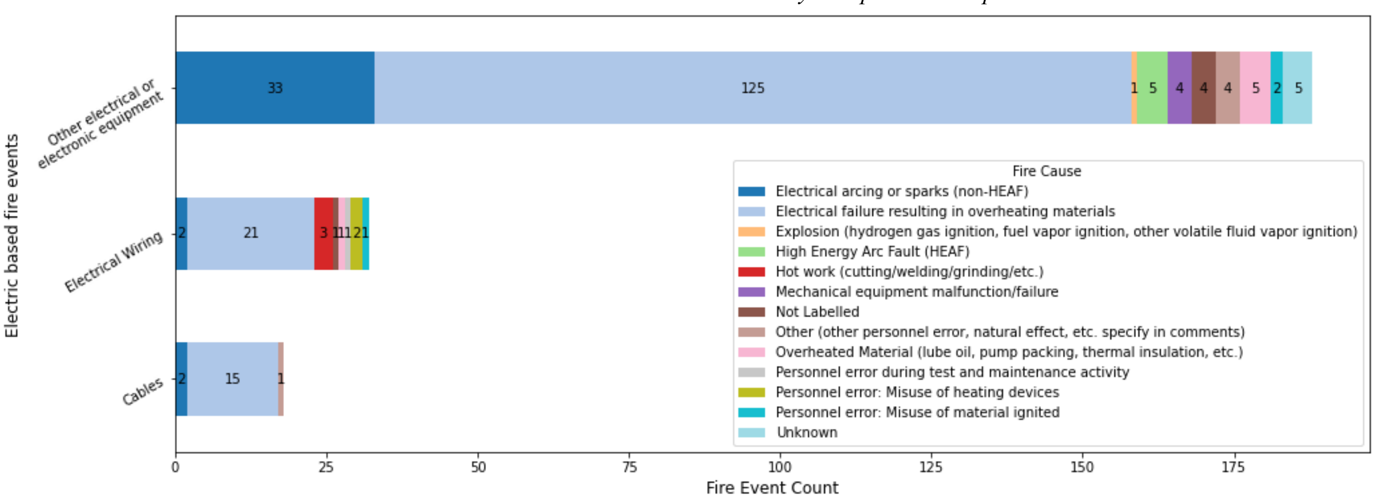
The details for Liquid and Gas forms are provided in *Figure 17.* For Unconfined Spills, the Turbine and Main Transformer/Switch Yard buildings were where the majority of fires occurred. These typically involved Transformers, Pumps and Electrical Panels. Electric arcing or sparks (non-HEAF), Electric failure resulting in overheating materials, and Overheated materials (lube oil, pump packing, thermal insulation, etc.) were the major causes of fire. Leak – Oil-Soaked Insulation fires commonly occurred in Turbine, Diesel Generator, and Containment (PWR) buildings and mostly involved Generators and Pumps. The major cause of ignition was Overheated materials (lube oil, pump packing, thermal insulation, etc.). For Pressurized Gas Sources, these events were mostly in the Turbine building involving Generators with Explosion (hydrogen gas ignition, fuel vapor ignition, other volatile fluid vapor ignition) and Mechanical equipment malfunction/ failure being the major Fire Causes.



a. Fire Event Count in accordance with Building

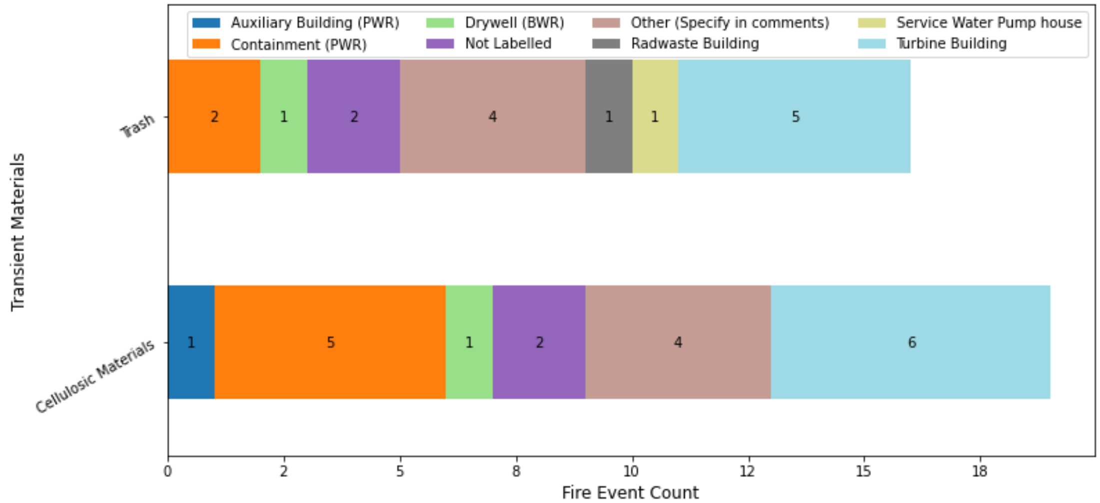


b. Fire Event Count by Component Group

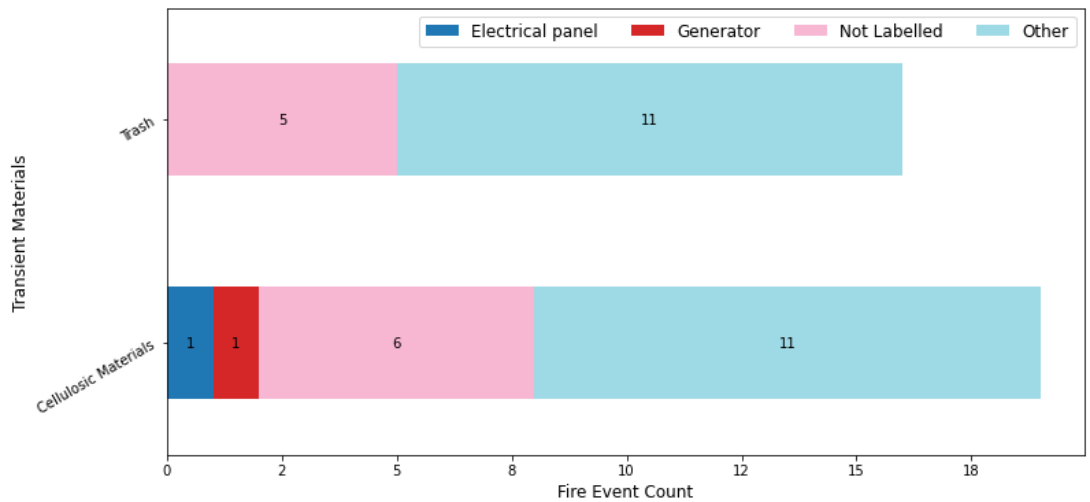


c. Fire Event Count by Fire Cause.

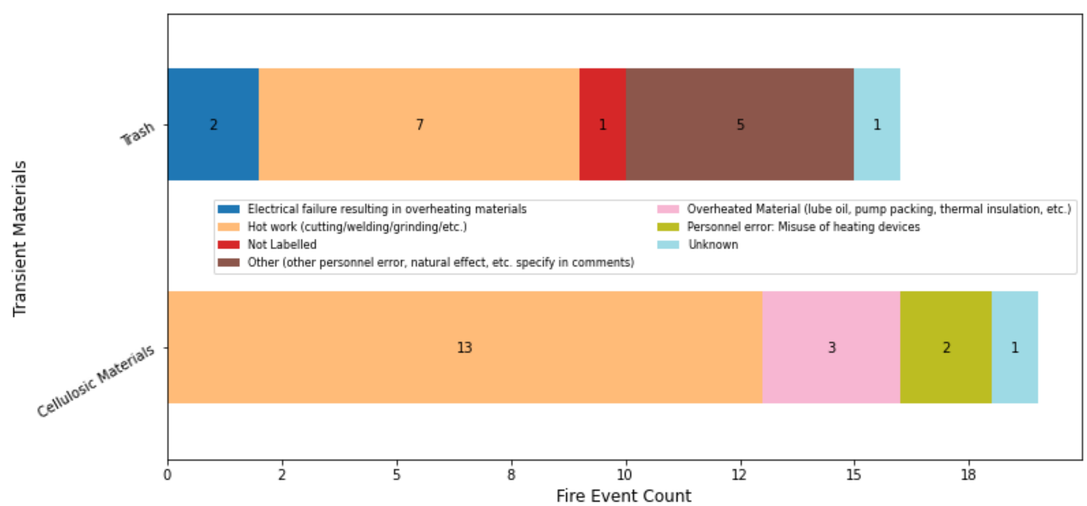
Figure 15. Fire Event Count are represented for Electric-based fire events according to a) Buildings, b) Component Group, and c) Fire Cause.



a. Fire Event Count in accordance with Building

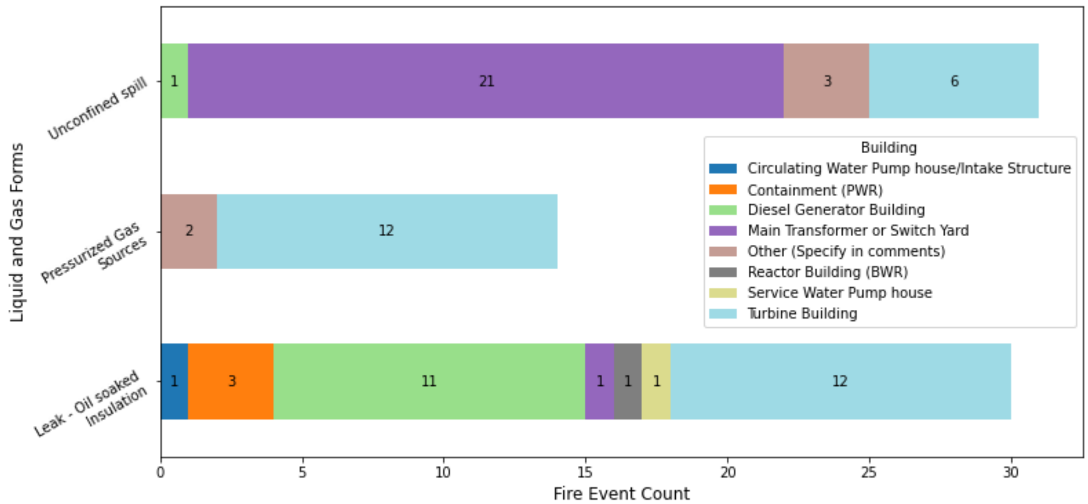


b. Fire Event Count by Component Group.

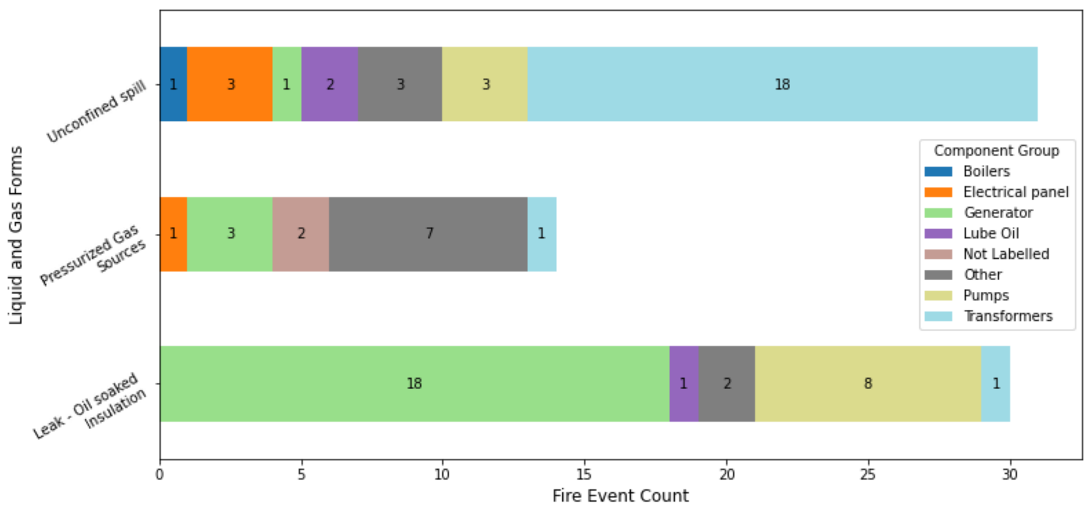


c.. Fire Event Count by Fire Cause.

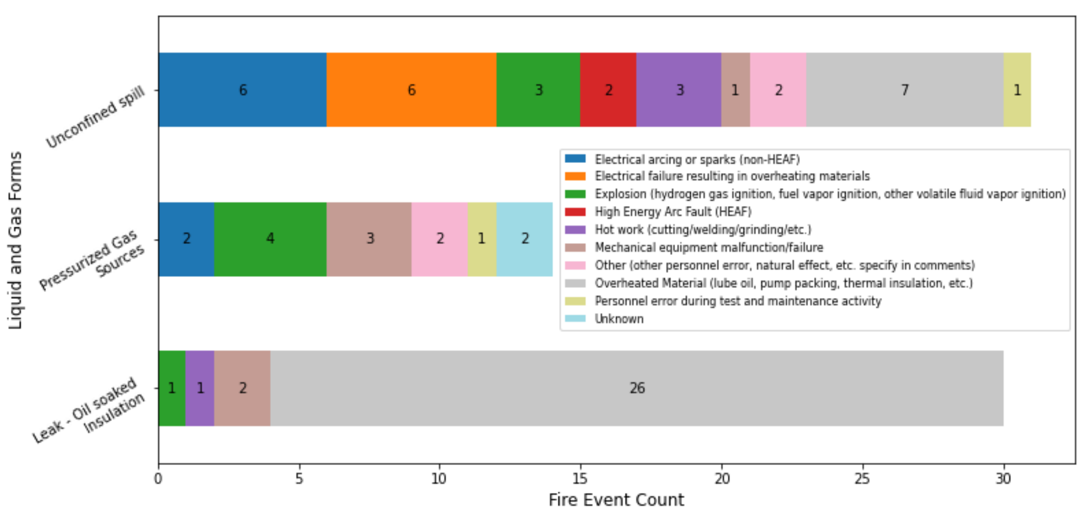
Figure 16. Fire Event Count are represented for Transient Materials according to a) Buildings, b) Component Group, and c) Fire Cause.



a. Fire Event Count in accordance with Building



b. Fire Event Count by Component Group



c. Fire Event Count by Fire Cause.

Figure 17. Fire Event Count are represented for Liquid and Gas forms according to a) Buildings, b) Component Group, and c) Fire Cause.

4. Discussion

According to the modified fire severity criteria, 540 fire events were classified as challenging (challenging/ potentially challenging). Based on the results in the previous section, *Table 5* represents the most frequent and challenging fires in NPP. The eleven types of fires in this table represent 74.2% of all challenging fires. The fire events are primarily identified and characterized through Primary Combustible Group – Types and Forms. Half of the challenging fire events in EPRI-FEDB are in the electrical and electronic equipment group, while transient and liquid fires contribute significantly to the number of events. The components typically involved in the challenging fire are electrical panel and pumps. The findings are comparable to the conclusions reached after examining the CREIPI database in [16], where for more than seventy percent of the fire events, significant risk contributors were identified to involve components classified as transients, electrical cabinets, and pumps in Japanese NPPs. The study in Ref. [16] only enlists the components involved and does not provide sufficient information on combustibles needed to relate the events to fire experiments.

Table 5. Most frequent, challenging fire scenarios.

Primary Combustible Groups	Types/ Forms	Counts	Counts per Reactor Year (×100)	Percentage of Challenging Fire Scenario
In-Situ	Other Electrical and Electronic equipment	188	7.98	34.8
Transient	Temporary electrical wiring and equipment	32	1.36	5.9
Liquid	Unconfined Spill	31	1.32	5.7
Liquid	Leak – Oil-soaked insulation	30	1.27	5.6
Insulation	Single Cable, Single Cable Trays and Multiple Cable not in a Tray or Bundle	21	0.89	3.9
Liquid	Confined spill	19	0.8	3.5
Transient	Cellulosic Material including Wood Transient or other solid materials + Plastic Sheets	19	0.81	3.5
In-Situ	Structural Component	17	0.72	3.1
Transient	Trash	16	0.68	3.0
In-Situ	Temporary Thermal Insulation Materials	14	0.59	2.6
Gas	Pressurized in a container and Jet from a pressurized source	14	0.59	2.6
Total		401	17.01	74.2

The details of the most frequent challenging fire events were grouped and related to the types of fire experiments that could be used to quantify their burning behavior (e.g. heat release rate, flame height, gas temperature above fire, etc.). The results of this are provided in *Table 6*. The table also provides the most common buildings, components involved, and fire cause. Additionally, these fire events primarily occurred in the Turbine Building with the major cause of the fires being overheating materials or electrical failure. The finding that most events occur in the Turbine Building is consistent with the analysis of the OECD database in Ref. [13], though details of the fire events were not provided. Fire experiment data are broadly used directly in

PRA or used to validate models for PRA of NPPs. A description of the frequent challenging fire events and how they relate to previously performed fire experiments [25-35] is provided below.

Table 6. Fire Scenario occurrences in fire experiment.

Primary Combustible Group - Types/ Forms	Fire Experiment	Building	Component Group	Fire Cause
Other Electrical and Electronic equipment and Temporary electrical wiring and equipment	Electrical Cabinet	Turbine Building, Auxiliary Building, Main Transformer or Switch Yard	Transformers, Pumps	Electric Failure resulting in overheating materials, Electrical arcing or sparks (non-HEAF), Personal error
Confined and Unconfined Spills	Liquid fuel fires (pools, spills)	Main Transformer or Switch Yard, Turbine Building	Transformers, Pumps	Overheated Material (lube oil, pump packing, thermal insulation, etc.), Electrical arc or sparks (non-HEAF), Electrical failure resulting in overheating materials
Leak – Oil-soaked insulation	Oil soaked materials	Turbine Building, Diesel Generator Building, Containment (PWR)	Generator, Pumps, Transformers	Overheated Material (lube oil, pump packing, thermal insulation, etc.), Mechanical equipment malfunction/failure, Explosion (hydrogen gas ignition, fuel vapor ignition, other volatile fluid vapor ignition)
Cellulosic Material including Wood Transient or other solid materials + Plastic Sheets	Wood pallets / Combustible linings	Turbine Building, Containment (PWR), Auxiliary Building	Electrical Panel, Generator	Hot work (Cutting/ welding/ grinding, etc.), Overheated Material (lube oil, pump packing, thermal insulation, etc.), Personnel error: Misuse of heating devices
Trash	Mixed Trash (paper, plastics)	Turbine Building, Containment (PWR), Other	Other, Not Labelled	Hot work (Cutting/ welding/ grinding, etc.), Other (other personnel error, natural effect, etc. specify in comments), Electric Failure resulting in overheating materials
Single Cable, Single Cable Trays, and Multiple Cable not in a Tray or Bundle	Cables (single, multiple, trays)	Turbine Building, Circulating Water Pump House/ Intake Structure, Containment (PWR)	Electrical Panel, Cable/ Wiring, Pumps	Electric Failure resulting in overheating materials, Electric arcing or sparks (non - HEAF), Other (other personnel error, natural effect, etc. specify in comments)
Pressurized in a container and Jet from a pressurized source	Flammable Gas Jets	Turbine Building	Generator, Electrical Panel	Explosion (hydrogen gas ignition, fuel vapor ignition, other volatile fluid vapor ignition), Mechanical equipment malfunction/failure, Electrical arcing or sparks (non-HEAF)

The most frequent of the challenging fires is electrical related equipment. Other electrical and electronic equipment of the in-situ combustible group and temporary electrical wiring and equipment of transient groups were grouped because they both depict the materials placed inside an enclosure. These enclosures contain combustible materials and electrical circuits with power flowing through them, which can overheat or fail, resulting in a significant hazard event in an NPP. To quantify the fire behavior of these fire events, electrical cabinet fire experiments have been conducted previously [27, 36]. The electrical cabinet experiments typically evaluate the effect of burning behavior of combustibles inside the cabinet (circuit breakers, terminal blocks, power rails, relay circuits, switchboards, wiring, cables, etc.), ventilation into the cabinet, and cabinet size on the fire conditions [27, 36].

Unconfined and confined spill forms represent the most common types of liquid fuel fires that can occur. Unconfined spills are liquid fuel spills that occur on a surface without anything to control how large the fuel surface area can be (e.g., a flat floor). Conversely, confined spills have curbing or dykes around where a spill may be expected to control how large the fuel spill surface area will become. Since the surface area of the liquid is related to the heat release rate of the fire, the curbing or dykes are used to limit the heat release rate of the fire. These liquid fires are typical in areas where spills may be expected such as transformers, pumps, etc. Previous fire experiments have been conducted on both spill fires and confined spills. Spill fire experiments have typically been conducted over different types of flat surfaces and have explored the effects of spill volume and continuous spill flow rate scenarios, both of which could occur in an NPP [37]. Confined spill burning behavior has also been explored through pool fire experiments in pans, where the burning behavior is dependent on pool diameter and the fuel-burning characteristics [38]. Confined spill burning rates are typically higher than unconfined rates in part due to unconfined spills being thin (on the order of 1.0 mm) resulting in more heat losses to the floor [37].

Oil-soaked materials involve oil that has collected onto a surface over time and then ignited either due to self-heating or other ignition sources (e.g., sparks, elevated temperatures, etc.). These fire events represent a more challenging fire than just the material since the oil in the material tends to enhance how easily it is ignited and the overall heat release rate of the material. Fire experiments on the burning behavior of oil-soaked materials are not common in the literature and need to be further studied.

The most common transient type fires are pallets/combustible linings as well as trash. Pallets can be wood or plastic-based, and fire experiments have explored the impact of the stacking height and material on the burning behavior [39]. Combustible linings are combustibles that are attached to walls or ceilings and can present a significant hazard due to flames being able to spread over their surfaces. These have been widely studied for different experimental configurations (walls, corners, ceilings, inside rooms, etc.) with the behavior significantly affected by the ignition and burning behavior of the material. Trash fires are fires that contain paper-based products and plastics in a container or bag. Fire experiments have explored the effects of the ratios of paper and plastic, mass of trash, and bag/container type [39].

Fires involving cables represent a significant hazard in NPP due to the amount of power cables through the plants as well as the impact of cable failure on plant operation. Cables can be found throughout an NPP in different configurations such as single cables, single cable trays, multiple cables not in a tray or bundle, and multiple cable trays. This is different from an electrical cabinet fire in that these cables are typically in the open and not located inside an enclosure. Experiments have been conducted on all of these different types of cable configurations where the overall heat release rate, flame spread rate across cables, and ignition of items adjacent to burning cables have been measured [25, 37]. However, the burning behavior of cables is complex due to the effects of metal conductors, different combustibles through the thickness, spacing between cables, loading in trays, etc., making it difficult to accurately quantify the burning behavior.

The last type of fire is a flammable gas jet from a container or pressurized source. Based on the databased results, this is either hydrogen or hydrocarbon fuel. Fire experiments have been performed to explore the burning behavior of flammable gas jets including the effects of leak hole size and gas pressure on the heat release rate and flame length [40].

Future studies need to provide a detail review of the fire experiments provided above to highlight what experimental parameters have been explored as well as variables that have not been sufficiently investigated. In addition, analysis needs to be conducted to determine which variables have the largest impact on the burning behavior to ensure sufficient data has been collected.

5. Conclusion

This research produced an electronic version of the publicly available data in the EPRI-FEDB to identify the most frequent and challenging fire event details. From a database of 2,111 fire events, approximately 25% (540 events) of fire events were labelled as challenging using our simplified classification. Of these challenging fire events, eleven types of fires represented the majority (74.2%) of challenging fires. The fire scenario details found by this analysis, such as location, components, and ignition mechanism, yielded similar results from previous studies [5, 13, 16]. However, the fire event attributes considered during this present study captured the plant-event characteristics more thoroughly by examining the combustibles involved together with components and nature of ignition during each fire event. The paper further leveraged this information to develop an association with fire experimental tests.

For electric-based fire events (which consisted of other electrical and electronic equipment, temporary electrical wiring, and cables), most of the fire events occurred in the Turbine Building and typically involved electrical panel, pumps, and transformer component group. The fire cause for many of these events was reported as electrical failure resulting in overheating materials. Electrical cabinet-related fires where combustible components are inside an enclosure represented the largest group of all challenging fires (40.7%). Cable fires, where the cables are not inside an enclosure but in open as single cables or routed in trays, were also a significant contributor to the number of challenging fires (3.9%).

Transient fires, including pallets, combustible linings, and trash, typically occurred in the Turbine Building and Containment (PWR) Building. The components typically involved in these fires included electrical panels and generator components, and the fire cause was mainly caused by hot work (cutting/ welding/ grinding, etc.). These types of fires were responsible for 6.5% of the challenging fires.

Fires related to liquid and gaseous fuels included unconfined/confined spill fires, leak oil-soaked materials, and pressurized gaseous fuel fires. Unconfined and confined spill fires were primarily found in the Main Transformer or Switch Yard Building primarily caused by overheated material (lube oil, pump packing, thermal insulation, etc.), electrical arcing or sparks (non-HEAF), electrical failure resulting in overheating materials. The unconfined/confined spill fires accounted for 9.2% of the challenging fire events. Leak oil-soaked insulation occurred mostly in the Diesel Generator Building and involved the generator component group. The fire cause was typically due to overheated material (lube oil, pump packing, thermal insulation, etc.). Leak oil-soaked insulation was responsible for 5.6% of challenging fires. Pressurized gaseous fuel fires occurred mostly in Turbine Buildings and were reported as an explosion (hydrogen gas ignition, fuel vapor ignition, other volatile fluid vapor ignition) ignited by mechanical equipment malfunction/failure, electrical arcing, or sparks (non-HEAF). These fires accounted for 2.6% of the challenging fires and are not commonly investigated in experimental facilities and laboratories.

The challenging fire events identified through the statistical analysis of the EPRI-FEDB were then related to fire experiment types that could be used to quantify the fire behavior of these events. The overarching goal of the research is to reduce the uncertainty in PRA through improving the experimental data used for these risk assessments. The results from this data analysis will be used to focus literature review of the experimental data to determine whether sufficient and accurate data exists for the most frequent and challenging fires. This will be used to inform future experiments that can reduce the Fire PRA uncertainty.

3. STATISTICAL ANALYSIS TO DETERMINE SIGNIFICANT PARAMETERS THAT AFFECT THE HEAT RELEASE RATE OF ELECTRICAL CABINETS

Abstract

Fires inside electrical cabinets are a major concern for nuclear power plant facilities representing fire in switchgears, control panels, main control boards, distribution panels, etc. The growth of these fires and the heat release rate of the fire may be dependent on several variables including cabinet size, ventilation, combustible properties, fuel configuration, etc. To date, this has been primarily studied through experiments concentrated on limited factors, and all parameters have not been systematically altered to determine which are the most significant. Thus, there is a need to assess all the relevant electrical cabinet features and statistically establish the most significant parameters that affect the HRR of the electrical cabinet. This research uses simulations to predict the heat release rate of cabinet fires with the simulation input matrix developed through design of experiments to allow for statistical analysis of results. The statistical analysis conducted on results from a series of simulations helps rank the importance of different variables on the cabinet fire heat release rate. Based on statistical analysis of the results, the combustible material surface area was found to be the most significant parameter followed by cabinet volume, combustible configuration, burning duration and combustible material heat release rate per unit area.

1. Introduction

The fires which are of electrical origin are a major concern for industries, commercial electric plants, telecommunication buildings, and nuclear power plant (NPP) facilities. They represent fires in switchgears, control panels, main control boards, distribution panels, etc. [41]. Based on statistical analysis conducted on 2,111 fire events cataloged in Electric Power Research Institute Updated Fire Event Database (EPRI-FEDB) in [42], about 540 fire events were labelled as challenging. Moreover, fires initiated within an electrical cabinet represented a majority (40.7%) of all challenging fire events.

An electrical cabinet is a metal enclosure that houses combustible electronic components and has natural or mechanical ventilation. The impact of several parameters of the electrical cabinet and their interaction on the overall fire heat release rate (HRR) is not fully understood. Previous experiments have sought to explore electrical cabinet fires by examining the HRR and thermal conditions inside the cabinet. Experiments primarily employed cabinets of defined sizes and ventilation condition. Two studies conducted by VTT and Sandia National Laboratory used full-scale electrical cabinet fire testing by incorporating cabinets of specific dimensions and varied fire loads [43, 44]. Based on measurements in the tests, the influence of the tested parameters on HRR was evaluated.

One of the earliest experiments conducted by VTT on electrical cabinet fires employed cabinets of defined size and varied the fuel loads composed of cables, circuit boards, circuit board rails and connectors and wiring [44]. The cabinets were equipped with a fuel load of 54.8, 27.2, 81.7 and 81.2 kg during four different experiments. For each of the four experiments the electrical cabinet had a consistent volume of 0.78 m^3 with ventilation areas of 0.047 m^2 and 0.0792 m^2 on the lower and top portions of the cabinet, respectively. The results showed that the fire behavior is affected by the cabinet dimension, fuel load, and placement of combustibles inside the cabinet.

Another study conducted 25 electric cabinet fire experiments under a hood calorimeter and measured the effect of different parameters on target values including peak HRR, steady state HRR, and the time to reach flashover conditions inside the cabinet [4]. During the experimental series, the percentage volume filled by fuels such as PMMA, PVC, and PE was adjusted while the total mass occupied by the fuels remained constant at 10 kg. The ventilation areas varied between 0.025 – 0.10 m^2. The study found that the ventilation area was the most influential parameter on the HRR, while the effect on flashover conditions was attributed to several parameters [27].

Though previous research studies have analyzed one or two factors through experiments, the parameters were not systematically varied to statistically quantify which parameters were most important/relevant. The aim of this paper is to use results from a series of computational fluid dynamics (CFD) simulations to determine the statistically relevant parameters that affect the HRR of electrical cabinets. Electrical cabinets were modeled using the CFD software Fire Dynamic Simulator (FDS). The simulation matrix of varying input parameters was generated using design of experiments so that statistical analysis could be conducted using FDS results to determine the significant parameters that influence the HRR. In this study, the impact of eight different electrical cabinet parameters on the peak and average HRR was considered. A partial factorial design was used to reduce the number of simulations required to provide an initial assessment on the importance of different variables prior to conducting more computationally intensive studies (e.g., central composite design and Monte Carlo analysis) that will provide distributions on the expected HRR for electrical cabinets.

2. Methodology

The purpose of this study is to identify relevant electrical cabinet parameters that affect the HRR of the electrical cabinet. This section describes the methodology adopted in identifying the significant parameters that affect the heat release rate of the electrical cabinet.

2.1 Electrical Cabinet Features

Electrical cabinet parameters expected to impact the HRR include cabinet geometrical features (volume, ventilation area) and combustible material features (heat release rate per unit area (HRRPUA), burning duration, ignition temperature, combustible surface area, and combustible configuration). Additionally, the ignition source output is also explored in concert with these parameters. The following section describes the parameters that are a reasonable representation of electrical cabinets features in NPP facilities.

2.1.1. Geometrical Features

The electrical cabinet considered in this study is a steel structure with a thickness of 0.0028 m as shown in *Figure 18a. T*he cabinet width and depth are constant in all simulations at 0.5 m while the cabinet height had two different heights (1.0 m and 2.0 m) to vary the cabinet volume. In addition to keep the number of parameters to minimum, the volume of the cabinet was varied following only the height of the cabinet. The cabinet is provided with ventilation openings in upper and lower portion of the front door. The ventilation area levels were 0.01 m^2 and 0.02 m^2.

The impact of cabinet depth on the HRR was explored through a series of initial simulations investigated by changing the cabinet depth and keeping other parameters constant in the simulation. *Figure 18a* and *Figure 18* b depict the FDS simulation detail that was explored by changing the depth of the electrical cabinet from 0.25 m to 0.50 m (height of 1 m and 2 m) respectively. This enabled to keep the volume consistent and determine the effect of cabinet depth on the HRR.

a *b*

Figure 18. FDS Simulation detail a) Cabinet depth of 0.50 m b) Cabinet depth of 0.25 m

The heat release rate of the cabinet was determined to not be significantly affected by the cabinet depth. Decreasing the depth reduced the time required for the combustible to reach the ignition temperature. However, the average and peak HRR were consistent between the two simulations. Thus, in order to keep the parameters to a minimum, the depth was kept consistent throughout the simulations while the height was varied to change the cabinet volume.

2.1.2 Combustible Material Features

The materials associated with electrical cabinets typically include thermoplastic based materials: polymethyl methacrylate (PMMA), polyethylene (PE), polyvinyl chloride (PVC), epoxy, etc. This varied nature of the materials makes it challenging to simulate the electrical cabinet fire behavior. Amongst these materials PVC based cable insulation material is the most commonly used material in NPP facilities [45]. As shown in *Figure 19.a*, the combustible panel considered in this study was placed in a parallel configuration at a distance of 0.05 m or 0.15 m opposite the ventilation openings and the total surface area of the two plates was either 0.25 m^2 or 0.5 m^2. The combustible material HRRPUA and ignition time data were based on the flexible type of PVC taken from Ref. [46] and referred to as flexible PVCWC and PVCWC-FR. When tested in the ASTM E1354 cone calorimeter [47] at an exposure heat flux of 40 kW/m^2, the materials have an average HRRPUA of 150 and 75 kW/m^2 with a burning duration of 600 and 900 s, respectively. In order to define combustible material input burning rate during FDS simulations, the average HRRPUA is stylized over a burning duration of 600 and 900 s. A depiction of the stylized curves with a 600 s burning duration is provided in *Figure 19b.*

Ignition of materials in FDS was predicted when the surface temperature of the material exceeded the ignition temperature. For this, FDS requires the thermal properties of the material and an ignition temperature. Based on data in the ignition temperature was taken to be either 325°C or 400°C based on ignition temperature data provided in [39]. In this paper the values of thermal properties (specific heat, thermal conductivity) were determined by optimizing their values in FDS so that the predicted times to ignition from the model were within the experimental error of the measured ignition times [46] at exposure heat fluxes of 20, 40 and 70 kW/m^2 in a cone calorimeter. This was performed using an ignition temperature of 325°C. *Table 7* contains the thermal properties of the combustible materials determined through optimization. These thermal properties were used in all analyses of this study while the ignition temperature was varied to assess the impact of material ignitability on the overall HRR.

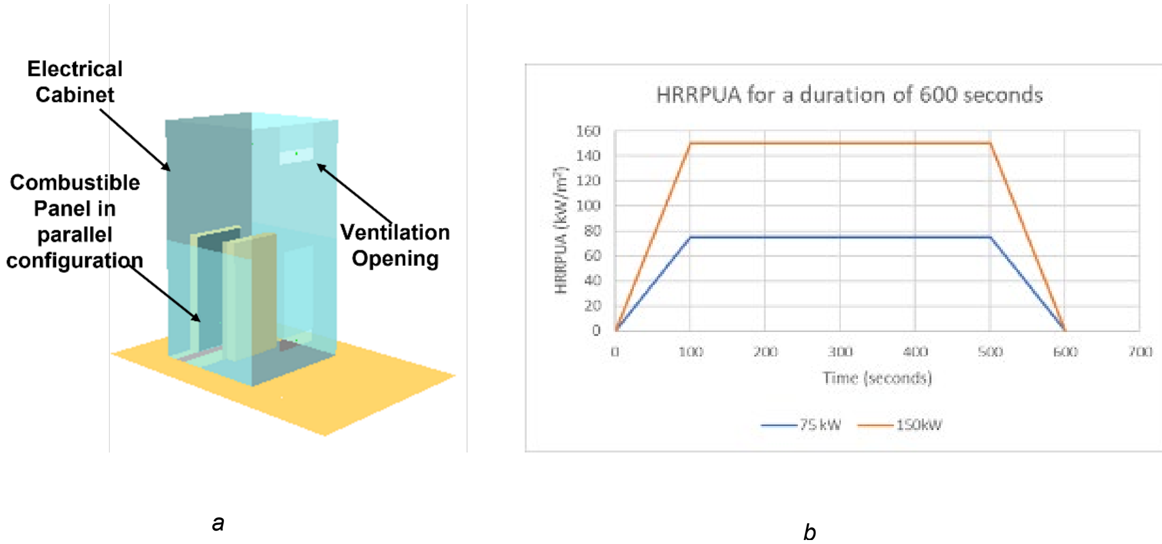


Figure 19. a) Electrical cabinet geometry and combustible panel, b) stylized HRRPUA for a burning duration of 600 seconds.

Table 7. Combustible material thermal properties

Combustible Material	Density (kg/m^3)	Thermal Conductivity (W/m K)	Specific Heat (J/ kg K)
PVCWC	1605	0.10	1.50

2.2. Fire Dynamic Simulator

Fire models based on CFD are frequently used in fire prevention engineering to predict complicated flow fields. In this paper, the CFD code Fire Dynamics Simulator (FDS) Version 6.7.7 was used to predict the fire-driven fluid flow as well as the smoke and heat transfer produced due to the fire. Additional information on FDS can be found in [48, 49]. Details on the FDS simulations performed in this study are provided below.

FDS is a CFD code to predict buoyancy driven fluid flow, species transport, and heat transfer due to fires. The FDS is a conceptual framework that describes the various components of a fire, including its turbulent combustion and the transport of thermal radiation. The FDS simulates features such as smoke transport, the thermal decomposition of materials, activation of fire detection system, the transport of water and liquid fuel droplets. These features encapsulate fire scenarios that occur both inside and outside of structures.

FDS utilizes a series of governing equations encompassing species mass concentration, conservation of mass, momentum, energy, and the ideal gas equation state. FDS uses Large Eddy Simulation (LES) to solve the governing equations by applying a low-pass filter to the transport equations of mass, momentum, and energy.

Initially an approximation to the equation of state is made by Equation 1 decomposing the pressure into a background component and a perturbation for low Mach number flows,

$$p(x,t) = \bar{p}_m(z,t) + \tilde{p}(x,t) \tag{1}$$

where x is the position in the domain, z is the height in the domain, t is time, p is the overall pressure field, $\tilde{p}(x,t)$ is the fluctuating hydrodynamic pressure, and $\bar{p}_m(z,t)$ is the background thermodynamic pressure.

Conservation of mass in its general form can be expressed by Equation 2,

$$\frac{\partial \rho}{\partial t} + \nabla \rho u = 0 \tag{2}$$

where ρ is the density and u is the velocity of the gas.

The DNS momentum Equation 3 in its conservative form is used for the i^{th} component of the velocity

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + f_{d,i} + \dot{m}_b''' u_{b,i} \tag{3}$$

where in the two-phase formulation $f_{d,i}$ represents the drag force due to unresolved Lagrangian particles. The bulk source term $\dot{m}_b''' u_{b,i}$ accounts for the effect of evaporation and pyrolysis. $\tau_{i,j}$ is the deviatoric stress tensor.

Conservation of energy equation 4 is implemented in accordance with sensible enthalpy h_s. Here The term $\dot{q}'''$ is the heat release rate per unit volume from a chemical reaction. The term $\dot{q}_b'''$ is the energy transferred to sub grid-scale droplets and particles, and $\dot{q}''$ is the net energy flux into a point

$$\frac{\partial(\rho h_s)}{dt} + \nabla.(\rho h_s u) = \frac{D\bar{p}}{Dt} + \dot{q}''' + \dot{q}_b''' - \nabla.\dot{q}'' \tag{4}$$

The equation of state in Equation 5 encapsulates the above governing equations.

$$\rho = \frac{\bar{p}W}{RT} \tag{5}$$

where W is the mixture molecular weight, R is the universal gas constant, and T is the temperature of the gas. Equations (1) – (5) are solved inside a rectilinear cell of grid size dx, dy and dz to predict the HRR information.

2.2.1 FDS Simulation Detail

2.2.1.1. Electrical Cabinet Features

Figure 20a below represents the FDS domain and linear propane ignition source implemented inside the cabinet. The FDS domain depth of 1.2 m and width of 0.8 m were kept consistent throughout all simulations performed in this study. The domain height was either 2.0 or 3.0 m and was defined in accordance with the height of the cabinet during the simulation. The grid cell size of the FDS domain was kept 0.025 m based on the convergence study results presented later in the paper. In order to represent the electrical ignition source, a linear propane ignition source 0.5 m wide and 0.05 m deep was placed on the cabinet floor at the bottom of the combustible panel. The ignition source generated a HRR of 15 kW and 45 kW. Additionally, the electrical cabinet was defined as a steel structure with a thickness of 0.0028 m.

Material ignition and burning were predicted in FDS using the IGNITION TEMPERATURE feature as well as the newly defined FDS feature CONE_HEAT_FLUX. The IGNITION TEMPEATURE feature predicts material ignition when the surface temperature exceeds a user defined ignition temperature for a material with the input thermal-physical properties. Once ignited, the combustible material heat release rate was predicted following the HRRPUA curve defined in *Figure 20b* and derived from cone calorimeter experiments in [7] working jointly with CONE_HEAT_FLUX, EXTERNAL_FLUX, and RAMP_Q features in FDS. For this curve, the equivalent reference heat flux at which the experiment is conducted is the total of heat flux emanating from the cone of the cone calorimeter and the heat flux from the flame excluding the convective losses based on the average of the ignition and steady state temperatures. The CONE HEAT FLUX feature in FDS helps in encapsulating the reference heat flux emanating from the cone and flame used in the cone-calorimeter experimental test. Furthermore, EXTERNAL HEAT FLUX is the heat flux imposed on the material during FDS simulation. HRRPUA and RAMP Q specify the burning rate at which the test data is shifted [48].

The burning rate data collected from cone calorimeter in Ref. [7] at 40 kW/m^2 heat flux for the PVCWC materials is used to extrapolate the burning phenomenon and ignition feedback of the material during the FDS simulation. For 40 kW/m^2 imposed cone heat flux a flame heat flux of 25 kW/m^2, is considered in this study. This resulted in a reference heat flux of 65 kW/m^2. Following this, experimental reference heat flux and the average Heat Release Rate Per Unit Area (HRRPUA) as shown in *Figure 20b* is feed forwarded to the FDS simulation. Additionally, the ignition temperatures of 325 ^{0}C and 400 ^{0}C works jointly with other parameters to control the burning rate whilst simulating the ignition phenomenon of the material.

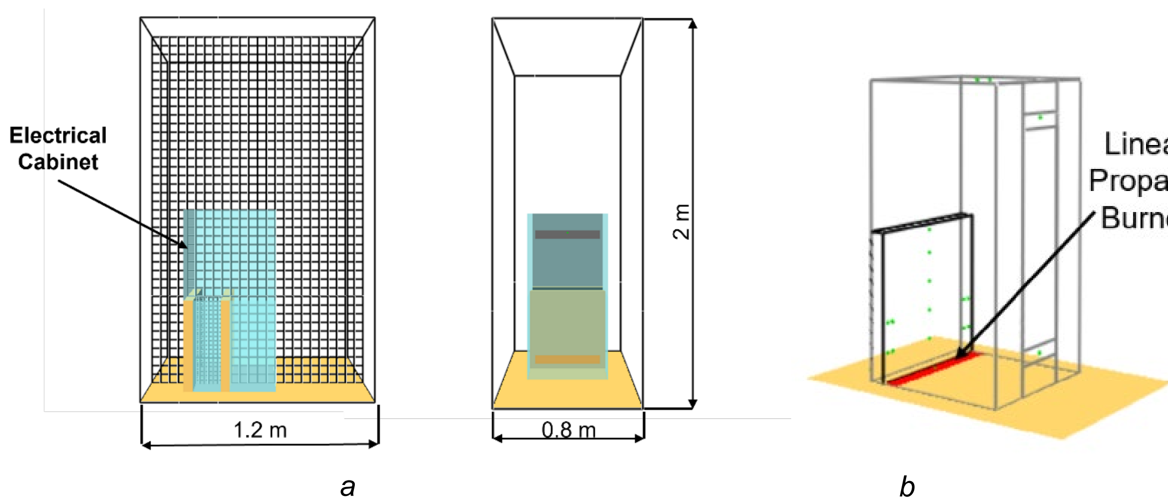


Figure 20. a. FDS domain geometry, b. Linear propane ignition source defined inside the cabinet

2.2.1.2. Monitoring Devices

Devices were mounted along the surface of the combustible material and at the ventilation opening to provide predicted the surface temperature, incident radiative heat flux, convective heat flux and total gauge heat flux with time. Devices were also placed along the ceiling of the cabinet to monitor the upper gas layer temperature. Additionally, the HRR was calculated for the entire domain using HRRPUV feature of the FDS algorithm.

2.2.1.3 Convergence Criteria

In order to determine appropriate spatial resolution that is computationally efficient to execute the simulation, a convergence analysis was conducted over the FDS domain by spatially discretizing it in 3 different grid sizes. The FDS simulations used a grid size based on the characteristic fire diameter,

$$D^* = \left(\frac{\dot{Q}}{p_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \tag{6}$$

where D^* is the characteristic fire diameter, $\dot{Q}$ is the expected heat release rate of the fire, ρ_∞ is the air density, c_p is the specific heat capacity of the air, and T_∞ is the ambient air temperature.

The FDS convergence study was evaluated with a grid cell size of 0.05 across the domain except between the combustible surfaces. Between the combustible surfaces around the ignition source, the grid size was resolved to 0.05, 0.025 and 0.01 m in the convergence study to better predict conditions in this high gradient region of burning. *Figure 21* contains images of the FDS domain with grid cell size of 0.025 m near the combustible surface and ignition source. The convergence was evaluated based on the average HRR was calculated between 10 percent to 90 percent of the total heat released, peak HRR, as well as the HRR versus time curve.

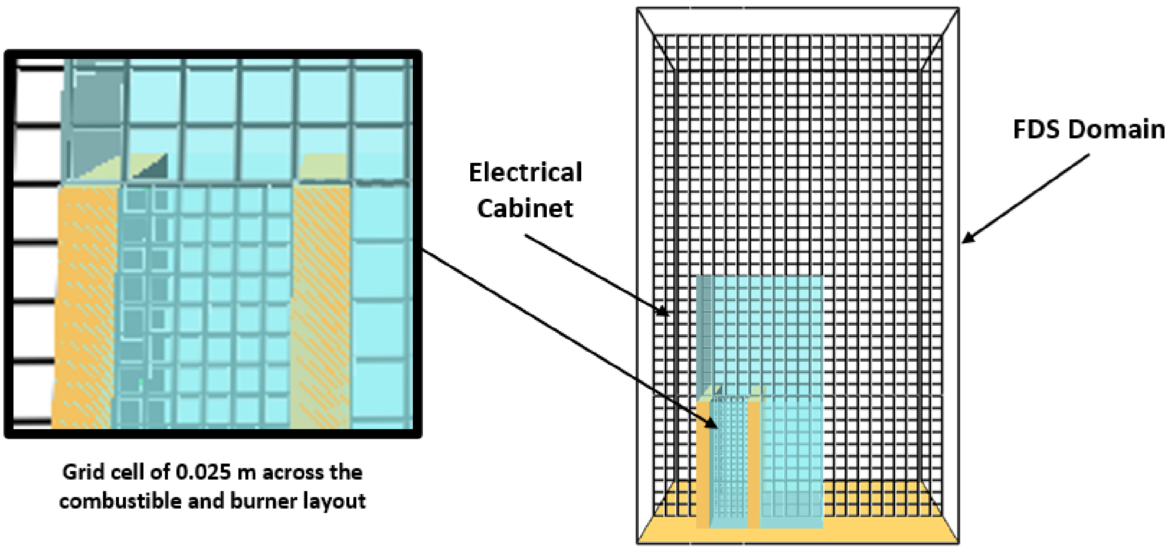


Figure 21. FDS domain simulation detail of grid cell size of 0.025 m between combustible panels and 0.05 m at all other locations.

2.3. Design of Experiments

In order to evaluate the effect of parameters on desired output response of HRR, it is necessary to strategically plan, analyze, and conduct simulations that vary multiple input factors and their important interactions that control the target values. This section describes the factorial design adopted and the parameter levels defined to conduct statistical analysis to determine the significant parameters.

2.3.1. Factorial Design and Analysis

This paper used 1/16th fractional factorial design analysis to determine the statistically significant electrical cabinet parameters that affect the HRR. The resolution of the selected fractional factorial design in this study was IV. Resolution IV is common to be utilized for application of factorial design in research studies exploring the importance of main variables. With this level of resolution, the main effects (main variables) and two-way effects (multiplication of two variables) are not aliased with each other, but some two-way effects may be aliased with other two-way effects. As a result, this analysis will provide which main effects (variables) are important but the two-way interactions shown to be important may be affected by other two-way interactions so their importance cannot be determined with complete confidence. The experimental structure that evaluates the electrical cabinet parameters including cabinet volume, ventilation area, combustible surface area, HRRPUA, burning duration, combustible configuration, ignition time, and ignition source output on the response HRR of the electrical cabinet.

The main effect can be defined as the effect on the HRR caused by one of the eight independent variables (e.g., increasing the combustible surface area increases the HRR), whereas two-way interaction can be defined as a relationship where the effects of one independent variable on the HRR depended on the level of another independent variable e.g., increasing the ventilation width times the ventilation height decreases the HRR)

The Analysis of Variance (ANOVA) is used to determine whether each main effect or interaction had a significant effect on the HRR. The impacts of each term are arranged from largest to smallest in the Pareto chart of standardized effects, with the red dashed line denoting the threshold for statistical significance. In the Pareto chart, the standardized effects are t-statistics used to test the null hypothesis that the term has no effect, with greater t-statistics correlating to lower p-values.

A parameter can be deemed significant or not by the t-statistics of the parameter. The t-statistic is the ratio of the departure of the estimated value of a parameter (difference between the means of the two levels (effect)) from its hypothesized value to its standard deviation. The difference between the mean of the two levels, represents the effect of the parameter on the output response.

$$t_{Value} = \frac{Effect}{S_E} \tag{7}$$

where, the standard deviation of the effect is given by

$$S_E = \frac{s}{\sqrt{n_f}} \tag{8}$$

where, s is the estimate of standard deviation calculated over all the n_f output response and is same for all the parameters.

The effect of a parameter on the output response is the difference between the means of the two levels. Dividing the effect with respect to standardized deviation gives the t-value. The statistical significance of each effect and interaction is judged by comparing its t-ratio, to the critical limit, denoted $t_{vp,\alpha}$ where v_p is the degree of freedom and $1-\alpha$ is the confidence level. Any t-value which is greater than the critical value will be considered statistically significant. At confidence level of 95% or significance of 0.05, the critical value of the parameter under consideration is obtained from the t-distribution table. Moreover, the significance of the effect can also be acknowledged by the p-value associated with the t-value. If the p-value is less than the significance level, the parameter effect is considered statistically significant.

2.3.2. Parameter Levels

The parameters levels considered in this study are provided in *Table 8*. A minimum and maximum value were selected for each of the parameters for the statistical analysis. This information was used in Minitab software (2022 release Version 20.3) to generate a simulation matrix of 16 runs necessary to statistically establish the significant parameters that affect the HRR. *Table 9* contains the simulation matrix used in this study, which was based on a fractional factorial design of experiment.

Table 8. Electrical cabinet parameter levels for statistical analysis

Parameters	**Name/ symbol adopted in Minitab**	**Parameter Levels**	
		Low	**High**
Volume (m^3)	V	0.25	0.50
Ventilation Area (m^2)	Av	0.01	0.02
Combustible Surface Area (m)	Ac	0.25	0.50
HRRPUA (kW/m^2)	HRRPUA	75	150
Burning Duration (seconds)	tbur	600	900
Combustible Configuration (m)	Conf	0.05	0.15
Ignition Temperature (^oC)	Tig	325	400
Ignition source Output (kW)	exp	15	45

Table 9. Simulation matrix for 1/16th fractional factorial analysis.

Run Order	**Volume (m^3)**	**Ventilation Area (m^2)**	**Combustible Surface Area (m^2)**	**HRRPUA (kW/m^2)**	**Burning Duration (seconds)**	**Combustible Configuration (m)**	**Ignition Temperature (^oC)**	**Ignition source HRR (kW)**
1	0.5	0.01	0.25	75	600	0.15	400	45
2	0.5	0.01	0.25	150	900	0.05	400	15
3	0.25	0.02	0.5	75	600	0.15	325	45
4	0.25	0.01	0.25	75	600	0.05	325	15
5	0.25	0.01	0.25	150	900	0.15	325	45
6	0.5	0.02	0.25	150	600	0.05	325	45
7	0.25	0.01	0.5	75	900	0.15	400	15
8	0.25	0.02	0.5	150	900	0.05	325	15
9	0.25	0.02	0.25	75	900	0.05	400	45
10	0.5	0.02	0.5	75	600	0.05	400	15
11	0.25	0.02	0.25	150	600	0.15	400	15
12	0.5	0.01	0.5	150	600	0.15	325	15
13	0.5	0.01	0.5	75	900	0.05	325	45
14	0.5	0.02	0.5	150	900	0.15	400	45
15	0.5	0.02	0.25	75	900	0.15	325	15
16	0.25	0.01	0.5	150	600	0.05	400	45

3. Results

The goal of this study is to facilitate the determination of the most influential parameters on the HRR of electrical cabinets. For this purpose, a series of FDS simulations were conducted to establish the statistically important factors that impact the HRR of electrical cabinets. The electrical cabinets were designed using the FDS algorithm. The simulation matrix of variable input parameters was built using design of experiments so that statistical analysis could be performed using simulation data to find the significant parameters that impact the HRR. The target values of interest include the peak HRR and average HRR of electrical cabinet.

Results of the grid convergence study are provided in *Table 10 and Figure 22*. The simulations were found to be adequately converged for a grid spacing of 0.05 and refined grid of 0.025 local to combustible material, which corresponds to a D*/dx of 7. Following this all the 16 FDS simulations were conducted with a grid spacing of 0.025 m.

Table 10. Average HRR and Computational Time corresponding to different FDS grid spacing

Grid Spacing (m)	Average HRR (kW)	Peak HRR (kW)	D*/dx
0.05	27.2	43.6	4
0.025	10.8	26.2	7
0.01	10.3	28.7	18

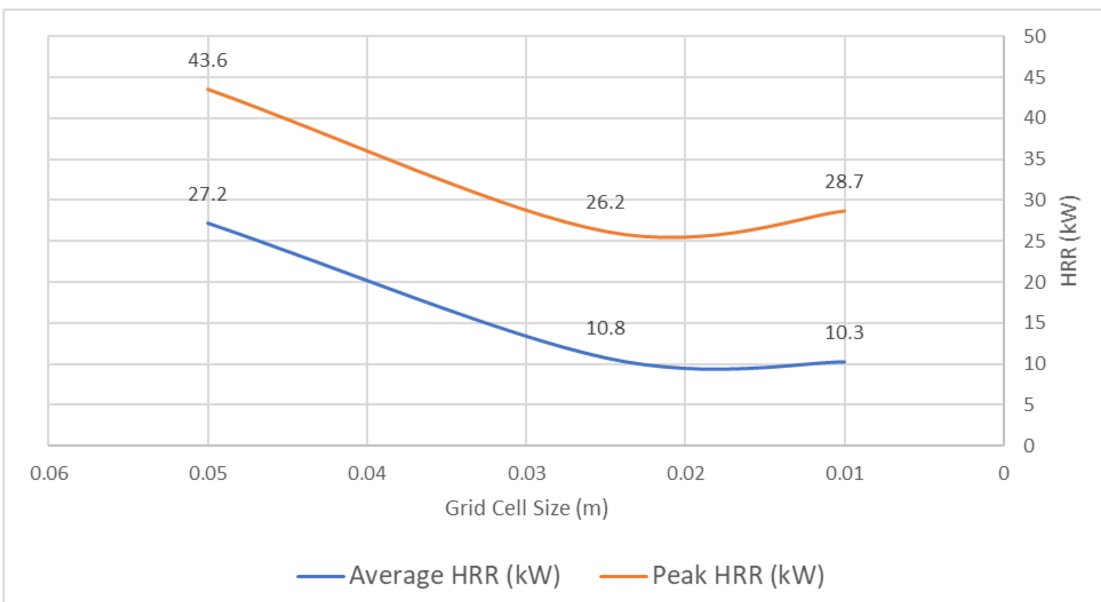


Figure 22. Convergence analysis to determine adequate spatial resolution

Figure 23 and Figure 24 show the HRR of the entire domain excluding the ignition source output obtained during the FDS simulations. The parameter values were defined in accordance with the values provided in *Table 8*. Following this result the average HRR and peak HRR information was utilized to conduct statistical analysis and establish the significant parameters.

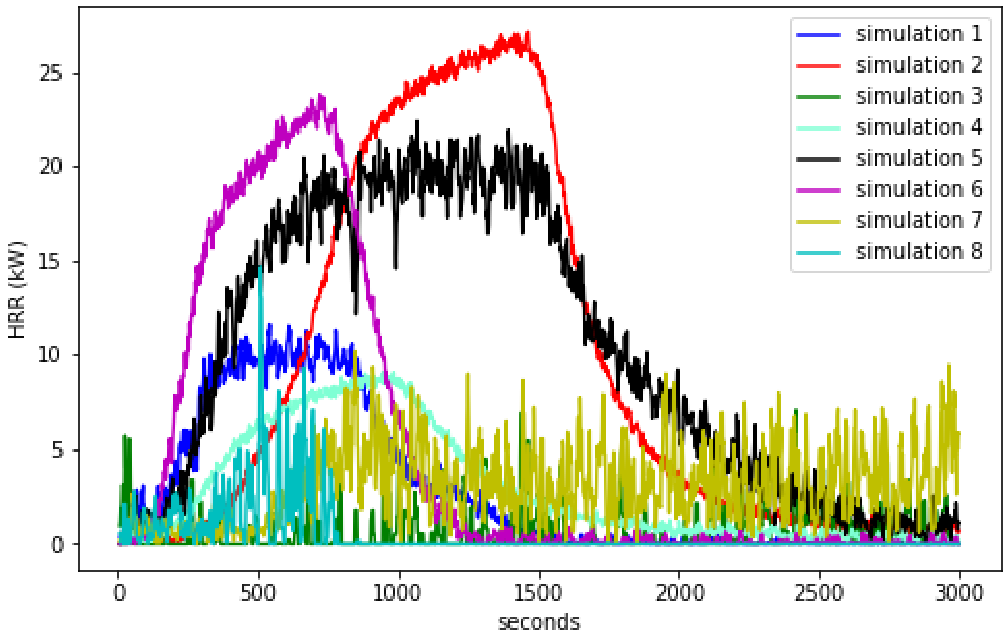


Figure 23. HRR vs time for FDS Simulations 1 – 8.

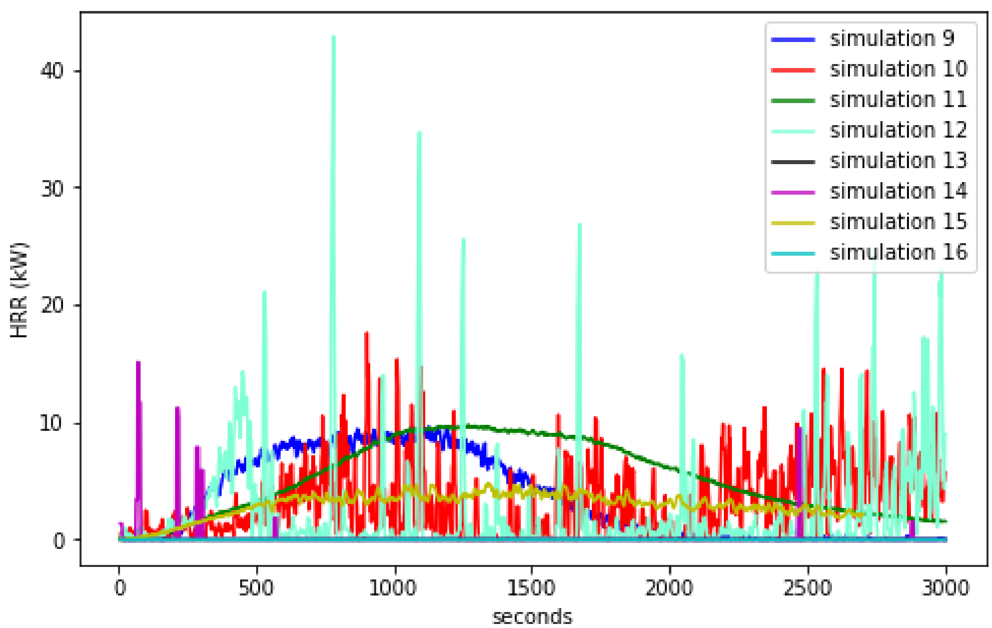


Figure 24. HRR vs time for FDS simulations 9 - 16

The Pareto charts in *Figure 25 and Figure 26* provide a comparison of the statistical significance of different parameters through fractional factorial design analysis. The statistical significance of each main effect and their two-way interactions was determined by comparing its T-ratio to the critical limit associated with confidence level of 95 %.

Factors A-H represent the electrical cabinet parameters: volume, ventilation area, combustible surface area, HRRPUA, burning duration, combustible configuration, ignition time, and ignition source output.; respectively. Combustible feature including HRRPUA (D) and burning duration (E) together with the volume of the cabinet (A) was found to be a statistically significant on peak HRR of the electrical cabinet. However, cabinet geometrical parameter including ventilation area and combustible features: combustible configuration, and ignition temperatures (F and G) were found to be insignificant on peak HRR. On the other hand, the influence of combustible fuel details including HRRPUA, combustible surface area, on the average HRR of the electrical cabinet proved significant. For the average HRR, main effects pertaining to cabinet geometry including ventilation area proved insignificant; however, the two-way interaction of volume and combustible configuration were significant indicating these parameters may be significant.

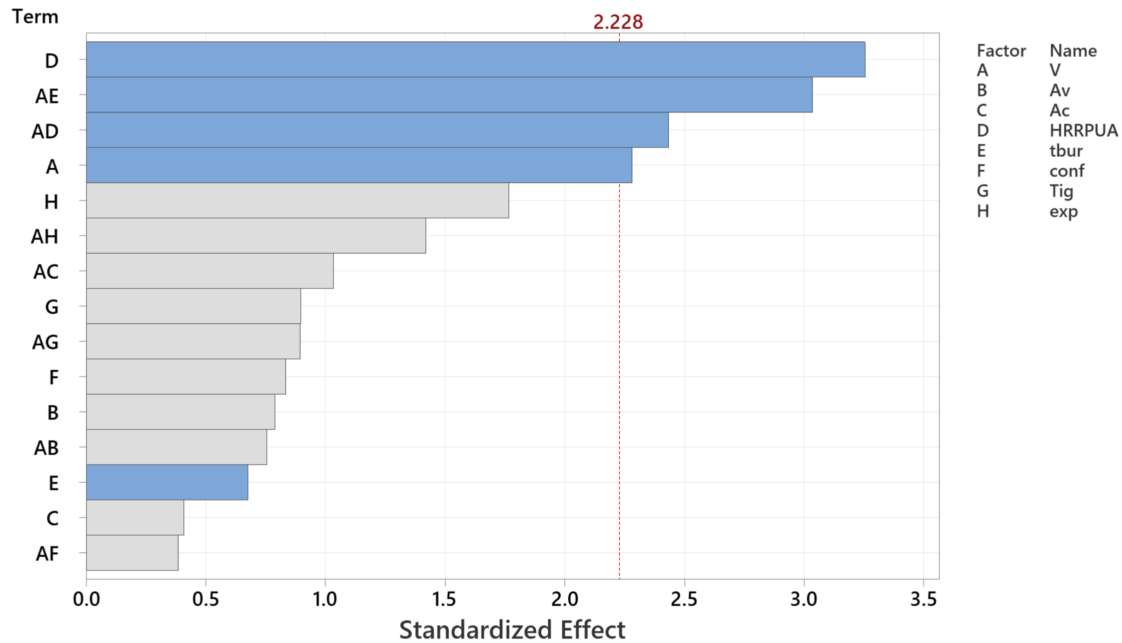


Figure 25. Pareto chart for standardized effect for peak HRR output response

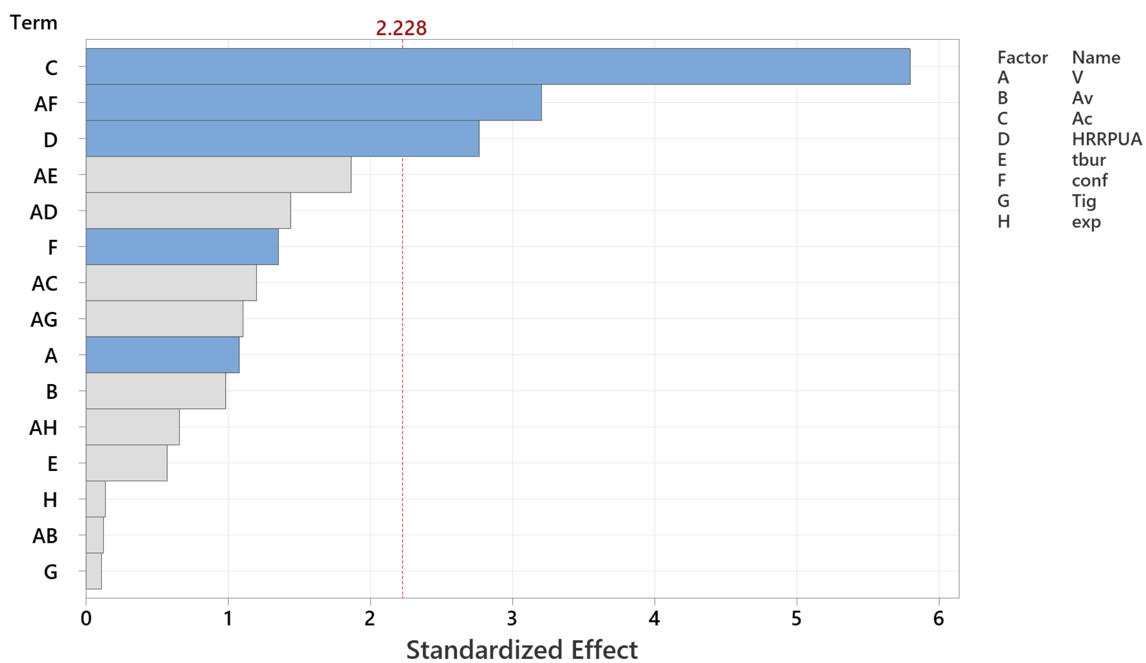


Figure 26. Pareto chart for standardized effect for average HRR output response

4. Conclusion

The focus of the research was to determine which factors have the most impact on the HRR of electrical cabinets. For this purpose, a $1/16^{th}$ fractional factorial design of experiment was used to generate simulation matrix and statistical analysis was conducted using the cabinet peak and average HRR using FDS.

Eight independent parameters were considered in this study including cabinet geometry features and combustible material features. The ignition source HRR output was also considered as one of the parameters in the statistical analysis. Through the statistical analysis, five of these parameters were identified as being statistically significant either due to their main effects or two-way interactions involving these parameters. The significant parameters included cabinet volume, HRRPUA, combustible surface area, combustible configuration, and burning duration.

The results of this initial study will be used to determine what parameters should be considered in more extensive simulations studies and experiments. Specifically, more simulations are being planned to explore the non-linear relationships between the parameters and the cabinet HRR. This will be done through non-linear design of experiments (central composite design) as well as Monte-Carlo analysis. Results of these simulations and analyses will be used to inform experiments that are needed to better quantify the HRR of electrical cabinet fires.

4. ASSESSING PARAMETER IMPORTANCE ON ELECTRICAL CABINET FIRE HEAT RELEASE RATE

Abstract

In several industries, a large majority of the electrical fire threats are caused by electrical or electronic cabinets. Several factors, such as cabinet size, ventilation, combustible characteristics, fuel arrangement, etc. can influence the development of these fires. Owing to the disparate nature of electrical cabinet parameters only few electrical cabinet factors have been experimentally explored and statistically analyzed to date in order to assess their impact on the fire heat release rate (HRR). Furthermore, combustible fuel details have not been thoroughly explored and altered for evaluating its relative significance to HRR. This study deviates from the standard practice and gives higher attention to combustibles accommodated inside the electrical cabinet. The Computational Fluid Dynamics (CFD) code Fire Dynamic Simulator (FDS) is used to model the combustible features together with geometrical aspects of the cabinet to predict electrical cabinet HRR. To rank the importance of parameters relative to HRR, a statistical analysis was conducted to assess both the main and interaction effects of these parameters. The first part of the study looked at the relevance of the factors in relation to the HRR while maintaining the combustible configuration constant. This was accomplished through the use of Central Composite Design (CCD) statistical analysis and HRR prediction from FDS. Electrical cabinet characteristics such as volume, combustible surface area, burning duration, HRRPUA, and ignition source were discovered to have a substantial influence on fire HRR. In addition, a series of simulations were conducted to predict HRR for various combustible configurations with all other parameters constant. When comparing its effect on HRR, both the combustible configuration and ignition source location was determined to have a significant impact.

1. Introduction

The fires which are of electrical origin are a major concern for industries, commercial electric plants, telecommunication buildings, and Nuclear Power Plant (NPP) facilities. They represent fires in rooms which harbor electrical components including switchgears, control panels, main control boards, distribution panels, etc. [41]. Electrical or electronic cabinets are responsible for the vast majority of electrical fires. Based on statistical analysis conducted on 2,111 fire events cataloged in Electric Power Research Institute Updated Fire Event Database (EPRI-FEDB) in [42], about 540 fire events were labelled as challenging. Fires initiated within an electrical cabinet represented a majority (40.7%) of all challenging fire events. An electrical cabinet is a metal enclosure that houses combustible electronic components and has natural or mechanical ventilation. The size of the cabinet and the components included within electrical enclosures can have a major impact on fire behavior. The relative importance of different cabinet parameters on the fire behavior is needed to determine which variables most significantly influence the fire behavior to support predicting electrical cabinet fire heat release rates (HRR).

Early work to understand the ignition of electrical cabinets typically varied a select number of parameters. Two studies conducted by Valtion Teknillinen Tutkimuskeskus (VTT) and Sandia National Laboratory (SNL) used full-scale electrical cabinet fire testing by incorporating cabinets of specific dimensions and varied ventilation area. Closed cabinet layouts with definite sizes were investigated in the VTT testing. Usually, fully open equipment racks to fully enclosed and securely sealed ventilation conditions were considered during the electrical cabinet fire experiments. The tests demonstrated that ventilation has a major impact on peak HRR [6, 7]. Additionally, another study conducted by Institute de Radioprotection et de Sûreté Nucléaire (IRSN) ascertained that ventilation area influences cabinet HRR [27]. Avidor et al. employed cabinet of definite size (undivided and shelved) with ventilation openings ranging from 0 to 0.0091 m^2 to determine if fires emanating from a ignition source can be sustained inside the cabinet. It was seen that when cabinet volume was halved by accommodating a shelf, 50-kW propane fire was sustained with significantly lower vent openings [26].

Only few measurements have been undertaken that sought to determine the influence of electrical cabinet combustible fuel details on the HRR. Experiments usually place combustible fuel in the center of the cabinet or along the side walls and ignite the combustible with an ignition source. Furthermore, most tests look into the effect of the overall mass and the material of the combustible contained within the cabinet on fire HRR. Studies conducted by National Institute of Standards and Technology (NIST), VTT and SNL used full-scale electrical cabinet fire testing by incorporating cabinets of specific dimensions and varied combustible fuel loads [36, 43, 44] The tests varied the fuel loads composed of different cables, circuit boards, circuit board rails and connectors and wiring. The results showed that the fire behavior is affected by the fuel load of combustibles inside the cabinet. IRSN conducted a series of 25 electric cabinet fire experiments under a hood calorimeter to measure the effect of different parameters on target values including peak HRR, steady state HRR, and the time to reach flashover conditions [27]. During the experiments, the percentage volume occupied by fuels such as PMMA, PVC, and PE was monitored on the cabinet HRR while the total mass occupied by the fuels remained constant at 10 kg. The effect of combustible configuration was also investigated during the experiment. The study appeared to be insufficient in determining the effect of combustible fuel on the HRR [5]. Despite these efforts, features that define combustible fuel details including ignition temperature, burning duration, and HRRPUA that predominantly define the fire behavior have not been thoroughly studied.

The main goal of this study is to rank the statistical significance of electrical cabinet parameters on the electrical cabinet HRR. This study used a computational model to predict the electrical cabinet HRR by systematically varying the different parameters so that statistical analysis could be used to rank parameter importance. In the first phase of the research, the combustible configuration and ignition source location were kept consistent while varying the other electrical cabinet parameters. The range of parameter levels for this study was defined using experimental data from electrical cabinet fire tests and cone calorimeter tests. The simulation matrix was developed using Central Composite Design (CCD), which allowed statistical analysis to determine parameter importance and nonlinear dependence of HRR on these parameters. A second series of simulations were conducted to vary the combustible configuration and ignition source location while keeping other parameters constant. The HRR values predicted for the different configurations were statistically compared to determine the importance of combustible configures and ignition source location.

2. Methodology

The methods given here were used to assess the statistical impact of typical electrical cabinet fire parameters on the overall fire HRR using simulations. The initial set of simulations evaluated the impact of various cabinet parameters while keeping the combustible configuration constant. This simulation matrix was developed based on DOE CCD method to allow for statistical analysis of the results. In addition, a series of simulations were performed to assess the impact of combustible configuration while keeping all other parameters constant. Details of these simulation input parameters are provided in the sections below. All simulations were conducted using Fire Dynamics Simulator (FDS), Version 6.7.7.

2.1. Variable Cabinet Fire Parameters with Fixed Combustible Configuration

A series of simulations with combustibles in a parallel plate configuration were used to evaluate the impact of different parameters on the electrical cabinet HRR. The following section describes the methods used to determine input values for the parameters as well as the simulation matrix generated using the CCD approach.

2.1.1. Electrical Cabinet Parameter Levels

According to a previous screening study, parameters including cabinet volume, combustible surface area, HRRPUA, and burning duration were found to have significant impact on HRR but ignition temperature was not statistically significant [49]. The Resolution IV of fractional factorial screening used in this previous study can only distinguish statistical significance of main effects, while the two-way interactions might be aliased with other interactions thus the significance cannot be ascertained with complete confidence. Furthermore, the parameter ranges were approximated. In the study provided in this paper, the analysis included all the significant parameters identified through previous screening study as well as ignition source HRR. This study defines the variable ranges related to cabinet geometry including volume (through height, width, and depth), ventilation area, ignition source HRR, and combustible surface area using information from [25, 26, 35, 42, 43, 49, 50]. The combustible material HRRPUA and burning duration were quantified using cone calorimeter test data in [25, 50-52]. The Python package Pandas was used to sort the data and explore the distribution to define the extremes of each parameters.

The cabinet geometrical parameter information acquired through NIST, VTT, UMD, IRSN experiments in [26, 27, 36, 43, 44, 53, 54] included height, width, depth, total ventilation area, and combustible surface area information of the cabinet. A series of 41 experimental tests were identified with unique geometrical features. *Figure 27a-c* depicts the distribution of cabinet height, width, and depth respectively after cataloging the data. The average depth and width of the cabinet utilized inside the fire experiments were 0.6 and 0.8 m, respectively. These values were fixed during all simulations. The height electrical cabinet was varied from 1.2 m to 2.4 m and was used to vary the cabinet volume in the simulations. Using this information, the high and low levels pertaining to cabinet volume were enlisted as 0.58 m^3 and 1.15 m^3 for the CCD definition. The total ventilation area was the summation of the total area of ventilation areas for the entire cabinet. In some cases, the total ventilation area also included the area defined as grids and holes across the ceiling of the cabinet. Given the majority of experimental data were identified between the levels of 0.05 to 0.25 m^2. Combustible surface area was derived from the surface area of the cables laid out inside the cabinet during the experiments. About 36 experiments were catalogued with distinct surface area information. The total combustible surface area levels were specified as 0.6 to 1.8 m^2 since the bulk of the studies up to 64 % of the catalogued experiments were completed within this range as seen in *Figure 27d.*

Parameter levels associated with the combustible fuel details were mainly identified through cone calorimeter experiments in [25, 50-52]. The cable information in HELEN fire experiments were further associated with CHRISTIFIRE experiments to derive relevant combustible burning information. The experiments provided HRRPUA, burning duration, imposed heat flux, and ignition time information of the material. A series of 56 unique experiments were catalogued with this information. Cone calorimeter experiments were primarily conducted at 50 kW/m^2 incident heat flux. Additionally, select experiments were also conducted at 25, 35, 75, and 100 kW/m^2 heat flux. Following this information, parameter levels relevant to HRRPUA and burning duration were derived for 50 kW/m^2 experiments. *Figure 27e-f* represents the distribution of burning duration and HRRPUA. Following the 10 to 90 percentile distribution of the data, HRRPUA levels were defined as 90 to 200 kW/m^2, whereas burning duration was defined from 300 to 1800 seconds for the CCD definition. Additionally for electrical cabinet fire experiments majority of the experiments had a ignition source output between 10 to 50 kW which is further defined as the low and high extremes in the CCD analysis.

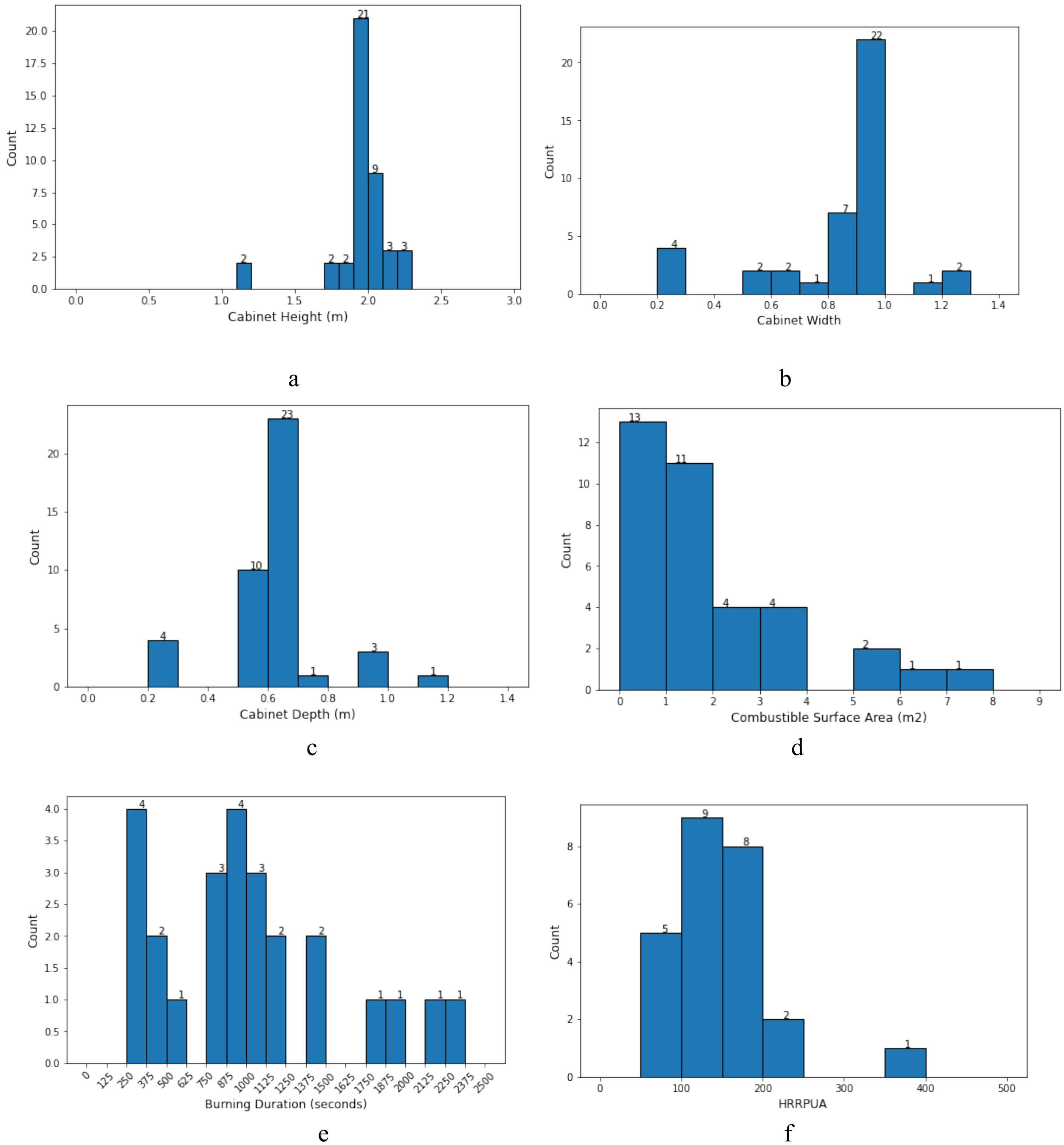


Figure 27. Parameter distribution obtained from historically conducted experiments varied input values including a) cabinet height, b) cabinet width, c) cabinet depth, d) combustible surface area, e) burning duration, and f) HRRPUA

2.1.2 Central Composite Design Analysis

The DOE CCD method was used to design a simulation matrix that would allow statistical analysis of the results which enables ranking the importance of different parameters. As shown in *Figure 28*, the parameter levels of CCD are characterized by points, namely central points and star points. Factorial points are vertices of an n-dimensional cube derived from a full factorial design with factor levels recorded as –1, + 1. The central point of the design space is the point in the middle. Axial points are symmetrically arranged on the axes of the coordinate system with regard to the central point at a distance from the design center on the axes of the coordinate system. The axial or star points represent lower and higher extreme values. The domain center points and star positions outside the domain allow the curvature of the response to be estimated further describing the non-linear relationship between parameters and response variable.

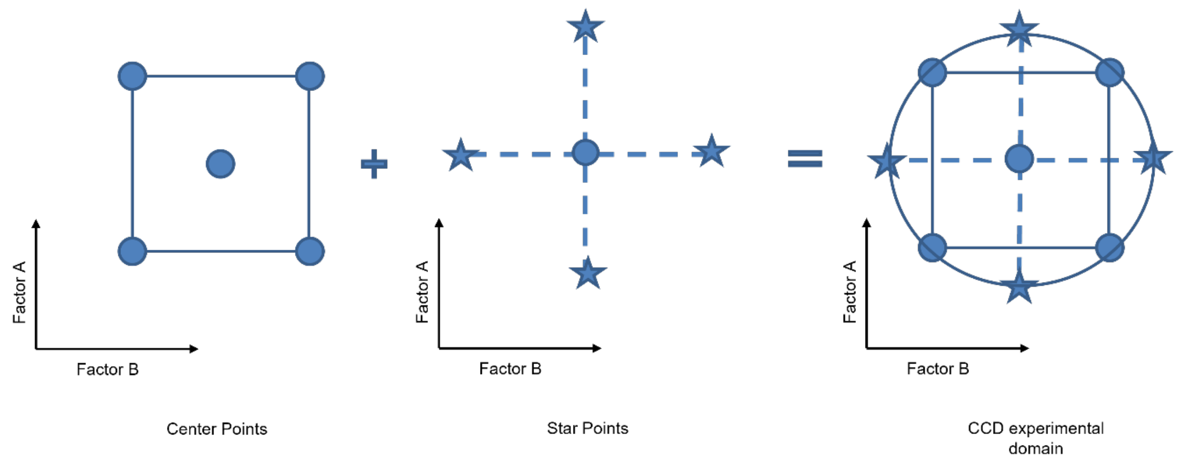


Figure 28. Point generation in a central composite design: at the research domain's center, plus star points outside the domain[55]

The face centered CCD experimental design was utilized in this research. A k factor three-level experimental design requires $2^k + 2\,k + C$ experiments, where k is the number of factors, 2^k points are in the corners of the cube representing the experimental domain, 2 k axial points are in the center of each face of the cube and C points are the replicates in the center of the cube that are necessary to estimate the variability of the output, informed the repeatability of the phenomenon which carries out the lack-of-fit or curvature test for the model. A total of 77 test run simulations were conducted without the replicates representing the center points. As shown in *Table 11*, a CCD in the form of full factorial design was used, in which six independent variables were transformed to dimensionless variables with coded values at three levels: – 1, 0, +1 [55].

Table 11. Arrangement of the CCD for the six independent variables used in the present study

Variable	**Symbol**	**Coded variable levels**		
		−1	**0**	**1**
Volume (m^3)	V	0.580	0.865	1.150
Ventilation Area (m^2)	A_v	0.05	0.15	0.25
Combustible Surface Area (m^2)	A_c	0.6	1.2	1.8
Heat Release Rate Per Unit Area (kW/m^2)	*HRRPUA*	90	145	200
Burning Duration (seconds)	t_{bur}	300	1050	1800
Ignition source Output (kW)	*exp*	10	30	50

Additionally, a CCD model was designed to fit the second order polynomial model, using a multiple regression routine according to Equation 9.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \epsilon \qquad (9)$$

where Y represents the response variable – electrical cabinet average and peak HRR. Here, x_i and x_j are independent coded variables, and β_o, β_i, β_{ii}, and β_{ij} the intercept term, linear, quadratic and interaction effects, respectively. Random error (ε) expresses the measure of difference between observed and predicted values. To give greater insight into the CCD results, Pareto analysis was used to calculate the percentage effect of each independent variable Furthermore, the suggested model adequacy and order of significance is tested using analysis of variance (ANOVA). The Minitab (2022 Release, Version 20.3) software was used for developing the simulation matrix and analyzing the obtained data.

2.1.3 Test for Significance of Electrical Cabinet Parameters

The Analysis of Variance (ANOVA) and Student's t-statistics was used to determine whether each main effect or interactions have a significant effect on the HRR. In this analysis, the impacts of each parameter are arranged from largest to smallest in the Pareto chart of standardized effects with a line denoting the threshold for statistical significance. In the Pareto chart, the standardized effects are t-statistics used to test the null hypothesis that the term has no effect, with greater t-statistics correlating to lower p-values.

A parameter can be deemed significant or not by the t-statistics of the parameter. The t-statistic is the ratio of the departure of the estimated value of a parameter (difference between the means of the two levels (effect)) from its hypothesized value to its standard deviation. The difference between the mean of the two levels, represents the effect of the parameter on the output response.

$$t_{Value} = \frac{Effect}{S_E} \qquad (10)$$

where, the standard deviation of the effect is given by

$$S_E = \frac{s}{\sqrt{n_f}} \qquad (11)$$

where, s is the estimate of standard deviation calculated over all the number of output response n_f and is same for all the parameters.

The effect of a parameter on the output response is the difference between the means of the two levels. Dividing the effect with respect to standardized deviation gives the t-value. The statistical significance of each effect and interaction is judged by comparing its t-statistics to the critical limit, denoted $t_{vp,\alpha}$ where v_p is the degree of freedom and $1 - \alpha$ is the confidence level. Any t-value which is greater than the critical value will be considered statistically significant. At a confidence level of 95% or significance of 0.05, the critical value of the parameter under consideration is obtained from the t-distribution table. Moreover, the significance of the effect can also be acknowledged by the p-value associated with the t-value. If the p-value is less than the significance level, the parameter effect is considered statistically significant. P-value or probability value is determined from the t-distribution table. The chance of incorrectly rejecting a hypothesis is measured by the P-value, which is derived from the t-distribution table. For example, if no factor effects are significant, a "Prob.>α" number on a t-test indicates the percentage of time it is anticipated to receive the specified t-statistics value.

The significance of the parameters relative to HRR can also be performed through ANOVA procedure. ANOVA utilizes the F-ratio or F-statistics to determine if the parameter is significant. F-ratio is the ratio between the regression mean square and the mean square error. This ratio is used to estimate the significance of the model under investigation in terms of the variance of all the elements contained in the error term at the specified significance level. It entails calculating the p-value, or probability value associated with the f-ratio from f-distribution table, which is related to the risk of incorrectly rejecting a hypothesis. F-statistic compares the "average" variability between the groups to the "average" variability within the groups. The F-statistic is calculated as the ratio of the between Mean Sum of Squares (MSB) to the error Mean Sum of Squares (MSE)

$$F = MSB/MSE. \tag{12}$$

The Mean Sum of Squares between the treatment groups, denoted MSB, is calculated by dividing the Sum of Squares between the groups by the between group degrees of freedom. That is, SS(T) is the sum of squares between the group means $\bar{X_\iota}$. and the grand mean $\bar{X}$. Where, *m* is the number of groups being compared.

$$MSB = SS(T)/(m-1). \tag{13}$$

$$SS(T) = \sum_{i=1}^{m} \sum_{j=1}^{n_i} (\bar{X_\iota} - \bar{X})^2 \tag{14}$$

The Error Mean Sum of Squares, denoted MSE, is calculated by dividing the Sum of Squares within the groups by the error degrees of freedom. Here, SS(Error) is the sum of squares between the data observations X_{ij} and the group means $\bar{X_\iota}$. It quantifies the variability within the groups of interest. Where, *n* is the total data points.

$$MSE = SS(E)/(n-m). \tag{15}$$

$$SS(E) = \sum_{i=1}^{m} \sum_{j=1}^{n_I} \left(X_{ij} - \bar{X_\iota}\right)^2 \tag{16}$$

2.2 Fixed Cabinet Fire Parameters with Variable Combustible Configuration

An electrical cabinet is a typically metallic enclosure of varying design and construction that houses various components in different layout. Additionally, the combustible configuration inside the cabinet has been found in previous experimental studies [27, 53] to have an impact on the HRR. Historically conducted electrical cabinet fire experiments have not thoroughly explored the impact of combustible configuration on HRR. As a result, a series of simulations were performed to determine the influence of different combustible configuration on the cabinet HRR. A series of 11 unique combustible configuration cases were identified and modeled in FDS. All other electrical cabinet parameters were kept consistent throughout the simulation at the levels shown in *Table 12*

Table 12. Parameter levels for variable combustible configuration analysis

Parameters	Holding values
Cabinet volume (m^3)	0.25
Ventilation area (m^2)	0.02
Ignition temperature (^oC)	325
Combustible surface area (m^2)	0.50
Burning duration (seconds)	900.00
HRRPUA (kW)	150.00

A typical combustible configuration as seen in HELEN fire experiments was loosely bundled cables placed on the either side walls of the electrical cabinet [36]. These cables ran through the entire length of the cabinet. Additionally, the cable bundles were ignited either on one end or both ends of the cable terminating inside a ignition source. *Figure 29* shows the FDS model of electrical cabinet where the combustible panel representing the thermal properties and surface area of the loosely bundled cables were placed on the either side walls running through the entire height of the electrical cabinet and ignition source positioned only on end. *Figure 30* represents a similar configuration but with the ignition source placed at both combustible ends. Additionally, the panels were ignited by means of an ignition source placed at the bottom of the combustible panels. Two independent simulations were conducted with one end and both end of the combustible panel being terminated inside the ignition source.

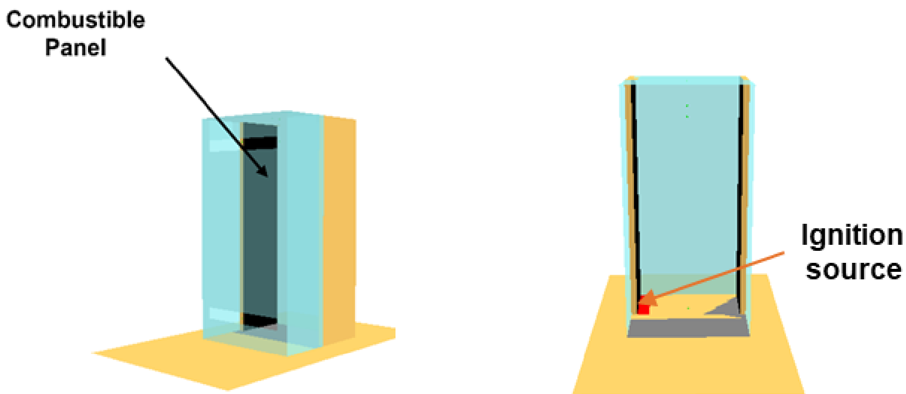


Figure 29. Combustible panel placed along both side walls and ignition source positioned on one panel end

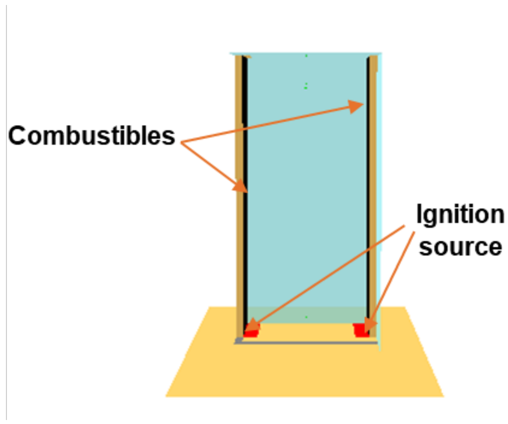


Figure 30. Combustible panel placed along both side walls and ignition source positioned on both panel end

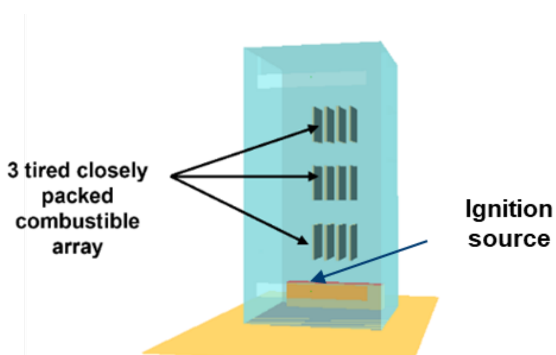


Figure 31. Combustibles laid in circuit board array configuration

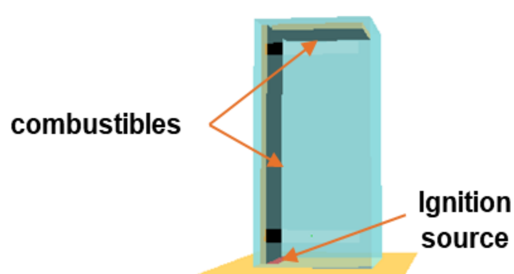


Figure 32. Combustibles along ceiling and side wall and ignition source positioned at bottom

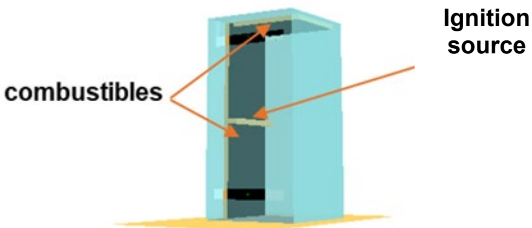


Figure 33. Combustibles laid along ceiling and side wall and ignition source place at mid-height of the cabinet

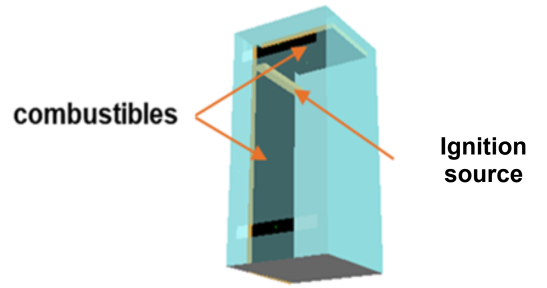


Figure 34. Combustibles along ceiling and side wall and ignition source positioned at top

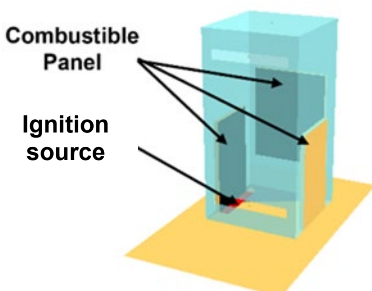


Figure 35. Combustibles laid along side wall together with circuit board relay and only one panel ignited

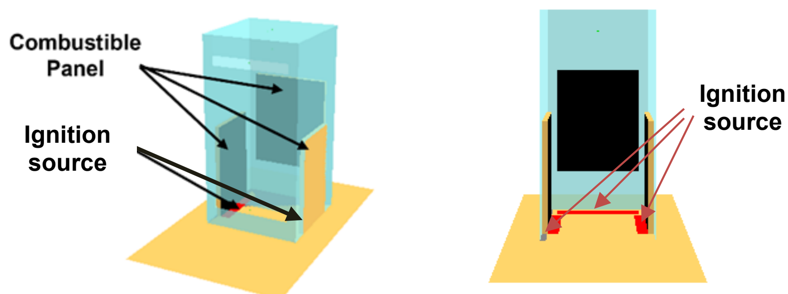


Figure 36. Combustibles laid along side wall together with circuit board relay and all panels ignited

Another typically combustible configuration inside electrical cabinet typically consisted of 3 or 4-tired series of circuit board array. The array of combustible was typically ignited with ignition source positioned directly below it. *Figure 31* shows the FDS model of the 3 tired closely packed combustible array configuration. Additionally, configuration 4, 5 and 6 depicted in *figures 32, 33, and 34* respectively represents loosely bundled cables routed along the side wall and ceiling of the cabinet. The ignition source elevation is increased from ground level to the ceiling for the three configuration respectively. On the other hand, as seen in *figures 37 and 38* bundles of cable might be routed only along the left, right wall, or the back wall, of the enclosure with their ends being terminated inside the ignition source placed at the lower position. Another configuration investigated in the fire experiments included cables accommodated on either side walls in addition to circuit board relay placed on the back wall of the cabinet as seen in [53]. The series of combustible were ignited with either one or all of them is terminated inside an ignition source placed at the bottom of the panels. *Figure 35* and *Figure 36* shows the FDS model of these two configuration.

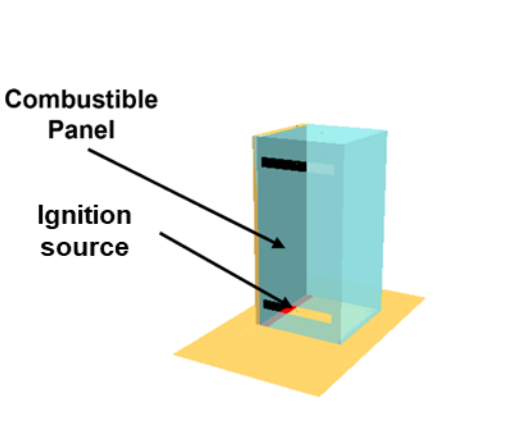


Figure 37. Combustibles laid along side wall and ignition source positioned at bottom

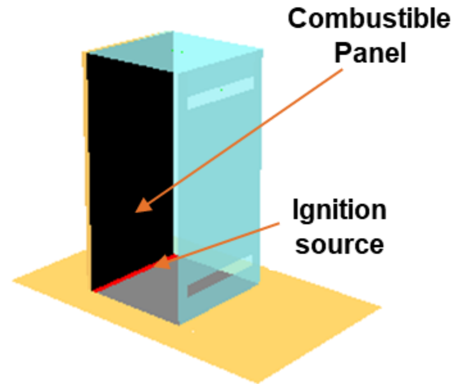


Figure 38. Combustibles along ceiling and side wall and ignition source positioned at bottom

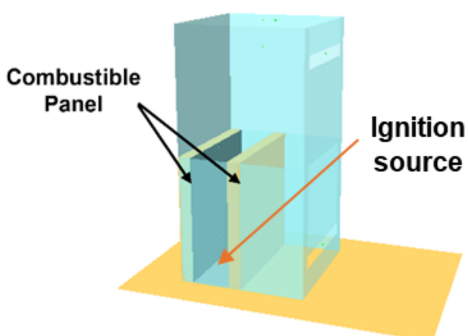


Figure 39. Combustibles in parallel configuration

2.3 Fire Dynamic Simulator

All simulations performed in this study were conducted using Fire Dynamics Simulator (FDS) Version 6.7.7, which was used to predict the fire-driven fluid flow as well as the smoke and heat transfer produced due to the electrical cabinet fire. FDS is a CFD code to predict buoyancy driven fluid flow, species transport, and heat transfer due to fires. The FDS is a conceptual framework that describes the various components of a fire, including its turbulent combustion and the transport of thermal radiation. For this purpose, FDS utilizes a series of governing equations encompassing species mass concentration, conservation of mass, momentum, energy, and the ideal gas equation state. FDS uses Large Eddy Simulation (LES) to solve the governing equations by applying a low-pass filter to the transport equations of mass, momentum, and energy to analyze the fire behavior of the component in a given domain. Additional information on FDS can be found in [48, 49]. Details on the FDS simulations to encapsulate the electrical cabinet HRR information in this study are provided below.

2.3.1. Electrical Cabinet Features in FDS

Electrical cabinet parameters can further be segregated into two categories. The geometrical parameters categories define the volume and ventilation area of the electrical cabinet. The other category is the combustible fuel details which includes surface area, HRRPUA, ignition temperature, and burning duration. The following sections describe the method incorporated to model these features in FDS.

2.3.1.1. Geometrical Parameters

The MATL, SURF and OBST features in FDS are used to define any obstruction and incorporate the material thermal properties with respect to which fire behavior is predicted. The electrical cabinet considered in this study is a steel structure with a thickness of 0.0028 m. The steel properties have a conductivity of 54.0 W/m-K, and specific heat and density of 0.47 kJ/kg-K, 7833 kg/m^3 respectively. The cabinet width and depth are kept consistent throughout the simulations at 0.8 m and 0.6 m respectively. The cabinet volume was varied by changing the height resulting in volumes of 0.58, 0.865, and 1.15 m^3 following CCD defined parameter levels. The front door of the cabinet has ventilation openings in the top and lower halves. The total ventilation areas of these two openings were 0.05, 0.15 and 0.25 m^2 in the FDS keeping a constant width of 0.50 m and varying the height to obtain the area. *Figure 40* shows the three different levels of electrical cabinet features modeled in FDS.

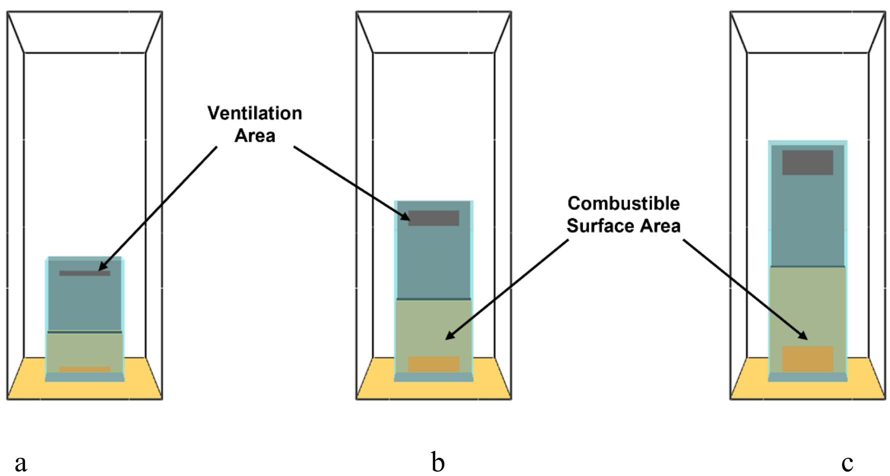


Figure 40. Cabinet volume, combustible surface area, and ventilation area modeled in FDS from lowest to highest level. a) cabinet with lowest level volume, combustible surface area, and ventilation area, b) cabinet with central level volume, combustible surface a

2.3.1.2. Combustible Fuel Details

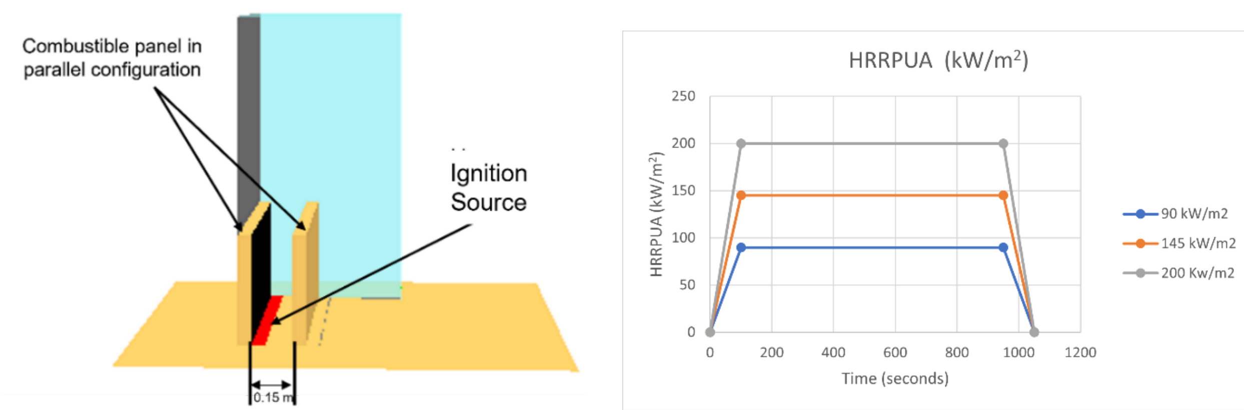
The HRR is predicted in FDS following material ignition. The material (specific heat, thermal conductivity, density defined in *Table 13*) is defined using MATL and SURF features in FDS. The temperature at which the material will ignite is defined through IGNITION TEMPEATURE feature. Additionally, the heat flux on the material influences material ignition and burning of the material. The CONE HEAT FLUX feature in FDS helps to simulate exposure heat flux on the material. The CONE HEAT FLUX for the material is set according to exposure heat flux values for the materials placed in cone-calorimeter experimental tests [39]. The sum of heat flux originating from the cone of the cone calorimeter and heat flux from the flame is the CONE HEAT FLUX, is equivalent to the reference heat flux at which the experiment is done, excluding the convective losses based on the average of the ignition and steady state temperatures. These features work in jointly to predict material ignition when the surface temperature exceeds a user defined ignition temperature at an exposure heat flux on the material.

Table 13. Combustible material thermal properties

Combustible Material	Density (kg/m^3)	Thermal Conductivity (W/m K)	Specific Heat (J/ kg K)
PVCWC	1605	0.10	1.50

Following material ignition, the subsequent burning of the material is defined as function of time using stylized HRRPUA information. These feature while working in jointly with material properties extrapolate the burning phenomenon and ignition feedback to predict HRR of the material during the FDS simulation. *Figure 41 b* shows the user defined HRRPUA curve as a function of time and is derived from cone calorimeter experiments [25, 50-52].This HRRPUA is defined for reference heat flux of 65 kW/m^2 in. Based on ignition temperature data presented in [39], the ignition temperature was estimated to be 325ºC. In this paper the values of thermal properties (specific heat, thermal conductivity) were determined by optimizing their values in FDS so that the predicted times to ignition from the model were within the experimental error of the measured ignition times for PVC [46] at exposure heat fluxes of 20, 40 and 70 kW/m^2 in a cone calorimeter. *Table 13* contains the thermal properties of the combustible materials determined through optimization.

PVC based cable insulation material is the most commonly used material in NPP facilities [45]. As shown in *Figure 41a*, the combustible panel considered in this study was placed in a parallel configuration at a distance of 0.15 m opposite the ventilation openings and the total combustible surface area was defined following the parameter levels obtained through the CCD analysis. The total combustible surface is the addition of the exposed surface area of the two panels facing the ignition source. Additionally, the combustible surface area had the same width throughout the simulation while varying the surface area along its height at three different levels. The surface area defined in the FDS were 0.6, 1.2 and 1.8 m^2. In order to define combustible material input burning rate during FDS simulations, the average HRRPUA of 90, 145, 200 kW/m^2 is stylized over a burning duration of CCD defined three levels of 300, 1050 and 1200 seconds. *Figure 41 b* shows HRRPUA stylized over a burning duration of 1050 seconds.



a b

Figure 41. a) Electrical cabinet geometry and combustible pane configuration with removed sidewall, b) stylized HRRPUA at three different levels for a burning duration of 1050 seconds.

2.3.1.3. Monitoring Devices

Devices were mounted along the surface of the combustible material and at the ventilation opening to predict the surface temperature, incident radiative heat flux, convective heat flux and total gauge heat flux with time. Devices were also placed along the ceiling of the cabinet to monitor the upper gas layer temperature. Additionally, the HRR was calculated for the entire domain using HRRPUV feature of the FDS algorithm.

2.3.1.4. Response Variables

The HRR was calculated for the entire domain using HRRPUV feature of the FDS algorithm. Two target values were considered for CCD analysis. Average HRR and peak HRR was used to explore the fire behavior and quantitatively evaluate the influence of electrical cabinet parameters. The average HRR was calculated between 5 to 95 % of the total heat released (THR) during the simulation. *Figure 42* represents the average HRR encapsulated between 5-95 % of THR. The FDS simulations were mostly conducted for a duration of 4000 seconds. Given the partial burning of the combustible panels due to lower ignition source output or gas temperature some of the simulations were conducted at a longer time period of 6000 – 8000 seconds. This increased time duration allowed the appropriate average HRR information to be calculated.

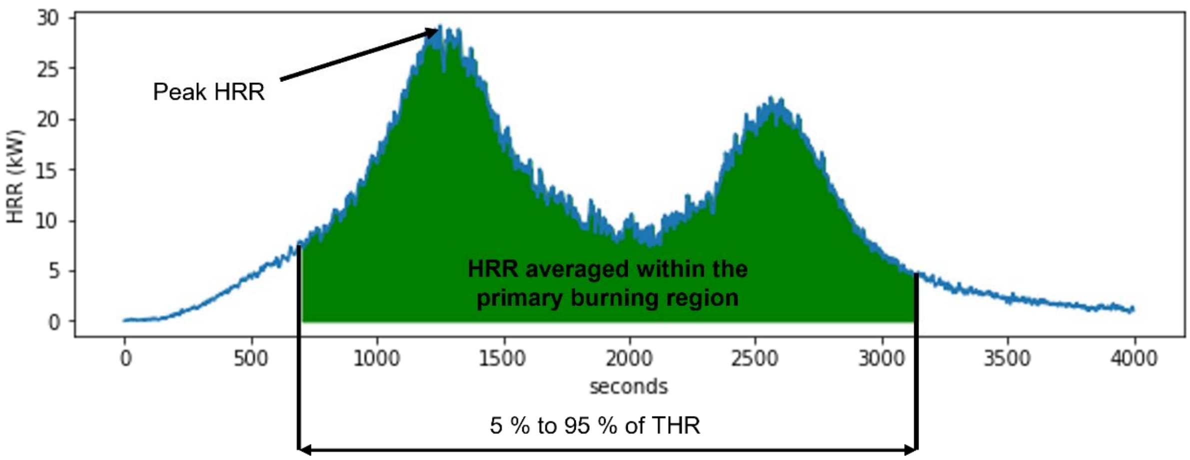


Figure 42. Average HRR computed within 5-95 percentile of the combustible burning

2.3.1.5. Convergence Criteria

In order to determine appropriate spatial resolution that is computationally efficient to execute the simulation, a convergence analysis was conducted over the FDS domain by spatially discretizing it into three different grid sizes. The FDS simulations used a grid size based on the characteristic fire diameter from equation 17.

$$D^* = \left(\frac{\dot{Q}}{p_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \quad (17)$$

where D^* is the characteristic fire diameter, $\dot{Q}$ is the expected heat release rate of the fire. At ambient conditions ρ_∞ is the air density of 1.204 kg/m^3 , c_p is the specific heat capacity and is around 1.005 kJ/kg-K of the air, and T_∞ is the ambient air temperature of about 293 Kelvin, and g is the acceleration due to gravity of about 9.81 m/s^2. The target mesh size is typically D*/dx of approximately 10 while also have several grid cells across source fire to adequately predict the mixing and combustion across the flames.

The FDS convergence study was evaluated with a grid cell size of 0.05 m across the domain except between the combustible surfaces. Between the combustible surfaces around the ignition source, the grid size was resolved to 0.05, 0.025 and 0.01 m in the convergence study to better predict conditions in this high gradient region of burning. *Figure 43* contains images of the FDS domain with grid cell size of 0.025 m near the combustible surface and ignition source. The combustibles effectively burned within a simulation period of 3000 seconds. The convergence was evaluated based on the average HRR calculated between 10 percent to 90 percent of the total heat released peak HRR representing the primary burning period, as well as the HRR versus time curve. Results of the grid convergence study are provided in *Table 14* and *Figure 44*. The simulations were found to be adequately converged for a grid spacing of 0.05 m and refined grid of 0.025 m local to combustible material, which corresponds to a spatial resolution of 7. Following this all the FDS simulations were conducted with a grid spacing of 0.025 m. However, for fixed parameters with variable configuration the gird cells locally defined across the combustible had a size of 1 cm. The grid cell size of 0.01 m was chosen in order to accommodate a closely packed combustible array configuration of circuit boards.

Table 14. Average HRR and Computational Time corresponding to different FDS grid spacing

Grid Spacing (m)	Average HRR (kW)	Peak HRR (kW)	Spatial Resolution (D*/dx)
0.05	27.2	43.6	4.0
0.025	10.8	26.2	7.0
0.01	10.3	28.7	18.0

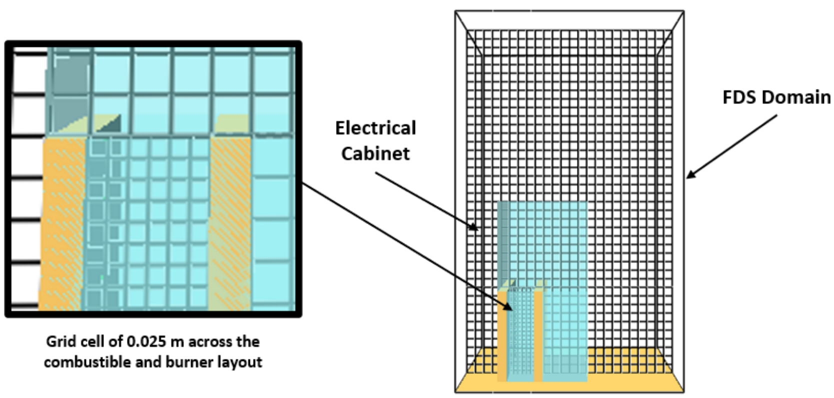


Figure 43. FDS domain simulation detail of grid cell size of 0.025 m between combustible panels and 0.05 m at all other locations.

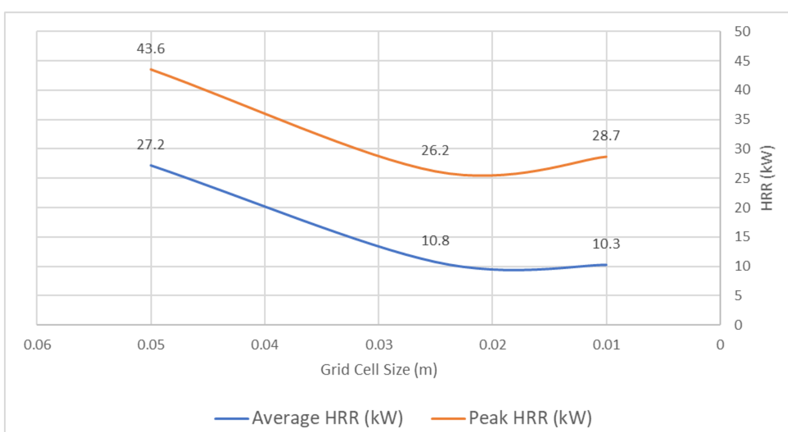


Figure 44. Convergence analysis to determine grid size between combustible panels. Grid size at other locations of the domain was 0.05 m.

3. Results and Discussion

The goal of this study is to test the significance of typical electrical cabinet fire parameters with respect to HRR. For this purpose, two independent studies were conducted with combustible configuration fixed or varying with respect to other parameters.

3.1. Fixed Combustible Configuration with Varying Parameter

For a fixed combustible configuration, the parallel plates of combustible were kept consistent and RSM – based CCD statistical framework was employed to determine significant parameters. A series of FDS simulations were conducted using information from simulation matrix generated through CCD. The Pareto charts in *Figure 45* and *Figure 46* provide a comparison of the statistical significance of different parameters with respect to peak HRR and average HRR output response respectively. The statistical significance of each main effect and their two-way interactions was determined by comparing its t-ratio to the critical limit associated with confidence level of 95 %. Additionally, as seen in *Table 16* and *Table 17* the ANOVA results for the fitting of the quadratic model indicates that in both the linear and square parameters, the main and interaction effects of the significant variables are significant on response, with p-values < 0.05.

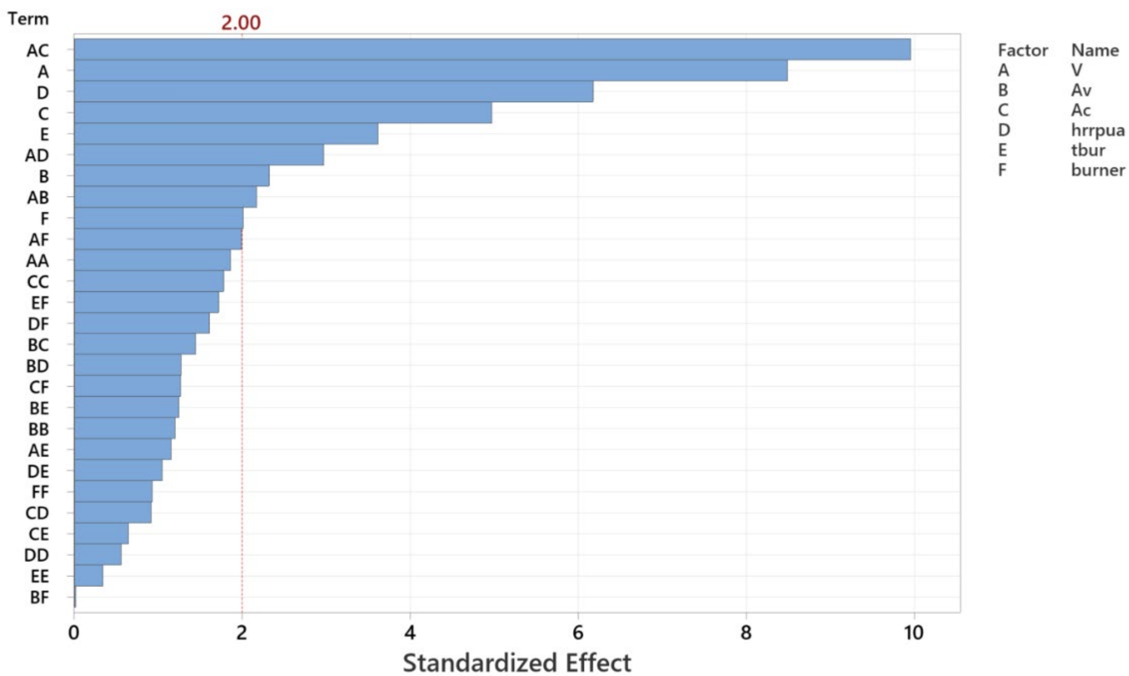


Figure 45. Pareto chart for standardized effect for peak HRR output response.

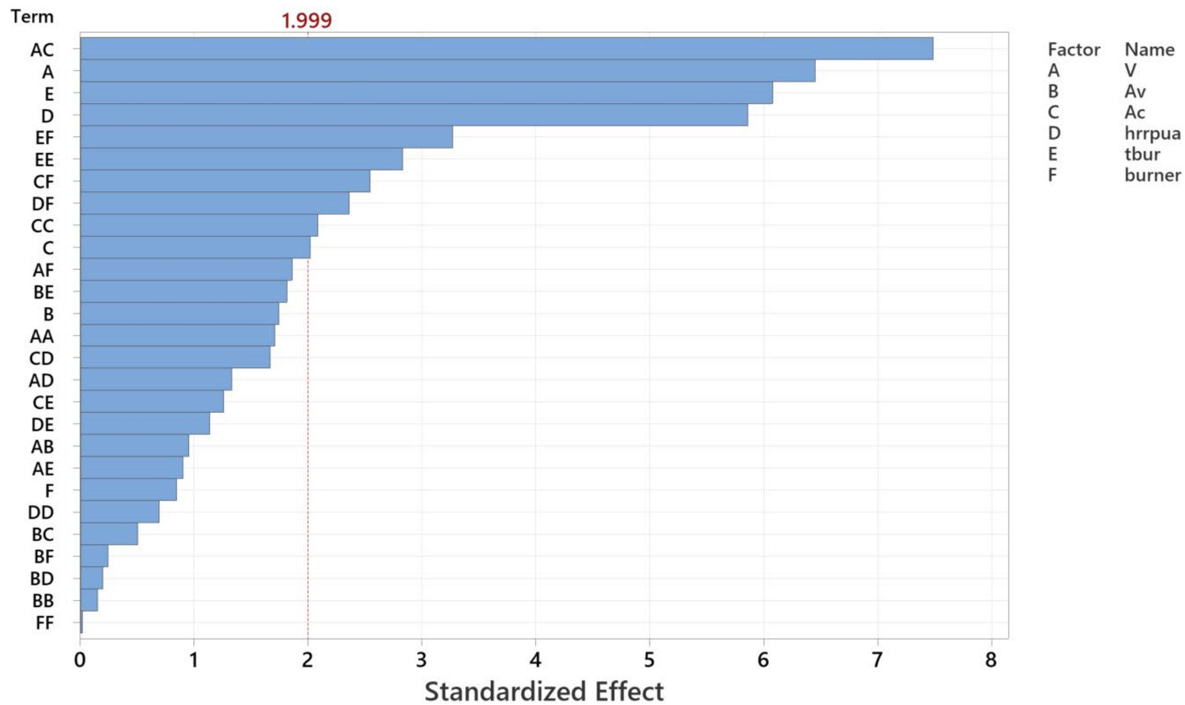


Figure 46. Pareto chart for standardized effect for average HRR output response

Factors A-F represent the electrical cabinet parameters: volume, ventilation area, combustible surface area, HRRPUA, burning duration, and ignition source output; respectively. *Table 15* represents the significant parameters including main and interaction effects identified following CCD analysis.

Table 15. Significant parameters for main and interaction effect

Response variable	Effect	Significant parameters
Peak HRR	Main	Cabinet volume (A), ventilation area (B), combustible surface area (C), HRRPUA (D), burning duration (E), ignition source output (F)
	Interaction	Volume-combustible surface area (AC), Volume- HRRPUA (AD), Volume-ventilation area (AB)
Average HRR	Main	Cabinet volume (A), combustible surface area (C), HRRPUA (D), burning duration (E)
	Interaction	Volume-combustible surface area (AC), burning duration – ignition source (EF), burning duration – burning duration (EE), combustible surface area – ignition source (CF), HRRPUA – ignition source (DF), combustible surface area – surface area (CC)

Table 16. ANOVA table for peak HRR model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
V	1	53965	53964.8	71.95	0
Av	1	4026	4026.2	5.37	0.024
Ac	1	18487	18487	24.65	0
hrrpua	1	28561	28561.3	38.08	0
tbur	1	9803	9803.2	13.07	0.001
ignition source	1	3027	3026.7	4.04	0.049
V*V	1	2587	2587	3.45	0.068
Av*Av	1	1075	1074.7	1.43	0.236
Ac*Ac	1	2371	2371.5	3.16	0.08
hrrpua*hrrpua	1	231	230.7	0.31	0.581
tbur*tbur	1	85	85	0.11	0.737
ignition source*ignition source	1	647	647.1	0.86	0.357
V*Av	1	3526	3526.4	4.7	0.034
V*Ac	1	74232	74232.4	98.98	0
V*hrrpua	1	6598	6597.7	8.8	0.004
V*tbur	1	991	990.9	1.32	0.255
V*ignition source	1	2977	2977.2	3.97	0.051
Av*Ac	1	1564	1564.3	2.09	0.154
Av*hrrpua	1	1208	1208	1.61	0.209
Av*tbur	1	1159	1159.3	1.55	0.218
Av*ignition source	1	0	0.2	0	0.986
Ac*hrrpua	1	625	625.4	0.83	0.365
Ac*tbur	1	312	311.8	0.42	0.521
Ac*ignition source	1	1199	1199.5	1.6	0.211
hrrpua*tbur	1	820	820.5	1.09	0.3
hrrpua*ignition source	1	1942	1942.1	2.59	0.113
tbur*ignition source	1	2215	2215.2	2.95	0.091

Table 17. ANOVA table for average HRR model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
V	1	5450.7	5450.73	43.27	0
Av	1	426.9	426.87	3.39	0.07
Ac	1	476.1	476.13	3.78	0.056
hrrpua	1	4249.6	4249.64	33.73	0
tbur	1	4845.3	4845.31	38.46	0
ignition source	1	110.8	110.84	0.88	0.352
V*V	1	372.9	372.92	2.96	0.09
Av*Av	1	3	2.95	0.02	0.879
Ac*Ac	1	556.7	556.66	4.42	0.04
hrrpua*hrrpua	1	60.1	60.08	0.48	0.492
tbur*tbur	1	1023.7	1023.74	8.13	0.006
ignition source*ignition source	1	0.1	0.06	0	0.982
V*Av	1	94.5	94.53	0.75	0.39
V*Ac	1	7317.1	7317.09	58.08	0
V*hrrpua	1	256.2	256.16	2.03	0.159
V*tbur	1	84.3	84.27	0.67	0.417
V*ignition source	1	483.7	483.67	3.84	0.055
Av*Ac	1	44.2	44.22	0.35	0.556
Av*hrrpua	1	10.2	10.21	0.08	0.777
Av*tbur	1	379.1	379.08	3.01	0.088
Av*ignition source	1	3	2.98	0.02	0.878
Ac*hrrpua	1	393.3	393.33	3.12	0.082
Ac*tbur	1	173.6	173.65	1.38	0.245
Ac*ignition source	1	884.2	884.17	7.02	0.01
hrrpua*tbur	1	190.9	190.92	1.52	0.223
hrrpua*ignition source	1	765.6	765.63	6.08	0.016
tbur*ignition source	1	1290.2	1290.25	10.24	0.002

The CCD fitted a regression model of six electrical cabinet parameters relative to the average and peak HRR. Equation 18 and 19 represent the fitted regression model for average and peak HRR respectively. These models were obtained for a constant parallel combustible plate configuration. Additionally, the quadratic model produced through this analysis yielded R^2 value of 88.6 % for average HRR and 88.9 % for peak HRR for modelling electrical cabinet fires

$$HRR_{avg} = -117.1 + 178\,V - 36\,Av + 74.1\,Ac - 0.316\,hrrpua + 0.0865\,tbur + 0.70\,burner - 153.8\,V*V - 111\,Av*Av - 42.4\,Ac*Ac + 0.00166\,hrrpua*hrrpua - 0.000037\,tbur*tbur - 0.0004\,burner*burner + 42.6\,V*Av + 62.53\,V*Ac + 0.1276\,V*hrrpua + 0.00537\,V*tbur + 0.482\,V*burner + 13.9\,Av*Ac + 0.073\,Av*hrrpua + 0.0325\,Av*tbur - 0.108\,Av*burner - 0.0751\,Ac*hrrpua - 0.00366\,Ac*tbur - 0.310\,Ac*burner + 0.000042\,hrrpua*tbur - 0.00314\,hrrpua*burner - 0.000299\,tbur*burner \tag{18}$$

$$HRR_{peak} = -153 + 374\,V + 215\,Av + 55\,Ac - 1.11\,hrrpua + 0.0443\,tbur + 3.34\,burner - 405\,V*V - 2121\,Av*Av - 87.5\,Ac*Ac + 0.00325\,hrrpua*hrrpua - 0.000011\,tbur*tbur - 0.0411\,burner*burner + 260\,V*Av + 199.2\,V*Ac + 0.648\,V*hrrpua + 0.0184\,V*tbur + 1.197\,V*burner + 82.4\,Av*Ac + 0.790\,Av*hrrpua + 0.0567\,Av*tbur + 0.03\,Av*burner + 0.095\,Ac*hrrpua - 0.00491\,Ac*tbur - 0.361\,Ac*burner - 0.000087\,hrrpua*tbur - 0.00501\,hrrpua*burner - 0.000392\,tbur*burner \tag{19}$$

In order to understand the influence of parameters on electrical cabinet HRR, the FDS simulation results were explored while changing the parameters on an individual level and keeping other parameters consistent throughout the simulation. *Figure 47 a-f* contains the HRR versus time for the two simulations each comparing the extreme levels of the following parameters cabinet volume, ventilation area, combustible surface area, HRRPUA, burning duration and ignition source output. The other parameter holding values were at volume at 0.58 m^3, ventilation area at 0.05 m^2, combustible surface area of 0.6 m^2, HRRPUA of 90 kW/m^2, burning duration of 300 seconds and ignition source output at 10 kW. Changing the levels of the variable electrical cabinet fire experiments ascertained a significant impact on average and peak HRR which is depicted in *tables 18-23*. The phenomena that trigger this considerable change in the HRR while varying the parameter variables are discussed in the next section.

Figure 47 a-f includes the HRR versus time whilst changing the parameters on an individual level. When changing the volume from 0.58 to 1.15 m^3, a significant drop in peak and average HRR was observed as seen in table 18. Similarly increasing the ventilation area advocates a decline in HRR. *Table 19* and *Figure 47* b depicts the decline in average HRR and peak HRR following increase in ventilation area from 0.05 to 0.25 m^2. This phenomenon can be associated to the oxygen content and gas temperature inside the cabinet. Increasing the volume and ventilation area, increases the air flow inside the cabinet, thus increasing the time required by the combustible to reach ignition temperature and consequently reducing the HRR. As seen in *Figure 47 a-b* the time required by the second combustible panel to reach ignition temperature is comparatively more which is represented by the second peak of the HRR vs time curve. Thus, slower burning rate is observed for the combustibles accommodated in cabinets with higher volume. Additionally, following results enlisted in table 20-22 and visualization of HRR vs time in *Figure 47 c-e* shows that increasing the combustible fuel detail including surface area, HRRPUA, and burning duration evidence the importance of excess combustible when placed inside the cabinet will eventually result in more burning of the material and increased HRR. Flames propagating vertically upward inside an enclosure is easier to spread than horizontally across the enclosure width. Conditions becomes favorable for flame propagation resulted in the participation of all combustibles inside an enclosure given higher burning duration. Additionally increasing ignition source output enabled faster ignition of the combustible and more burning of the material. This increase in ignition source output overall increased the gas temperature inside the cabinet further advocating an increase in peak and average HRR as shown in *Table 23* and *Figure 47.f.*

Table 18. Volume

Volume (m^3)	Average HRR (kW)	Peak HRR (kW)
0.58	*19.1*	*52.6*
1.15	*4.8*	*14.3*

Table 19. Total ventilation area

Total Ventilation Area (m^2)	Average HRR (kW)	Peak HRR (kW)
0.05	*19.1*	*52.6*
0.25	*8.7*	*7.5*

Table 20. Combustible surface area

Combustible Surface Area (m^2)	Average HRR (kW)	Peak HRR (kW)
0.6	*4.8*	*14.3*
1.8	*55.2*	*141.7*

Table 21. HRRPUA

HRRPUA (kW/m^2)	Average HRR (kW)	Peak HRR (kW)
90	*1.4*	*2.1*
200	*19.0*	*52.6*

Table 22. Burning duration

Burning duration (seconds)	Average HRR (kW)	Peak HRR (kW)
300	*1.4*	*2.1*
1800	*17.4*	*37.3*

Table 23. Ignition source output

Ignition source Output (kW)	Average HRR (kW)	Peak HRR (kW)
10	*4.8*	*14.3*
50	*33*	*59.5*

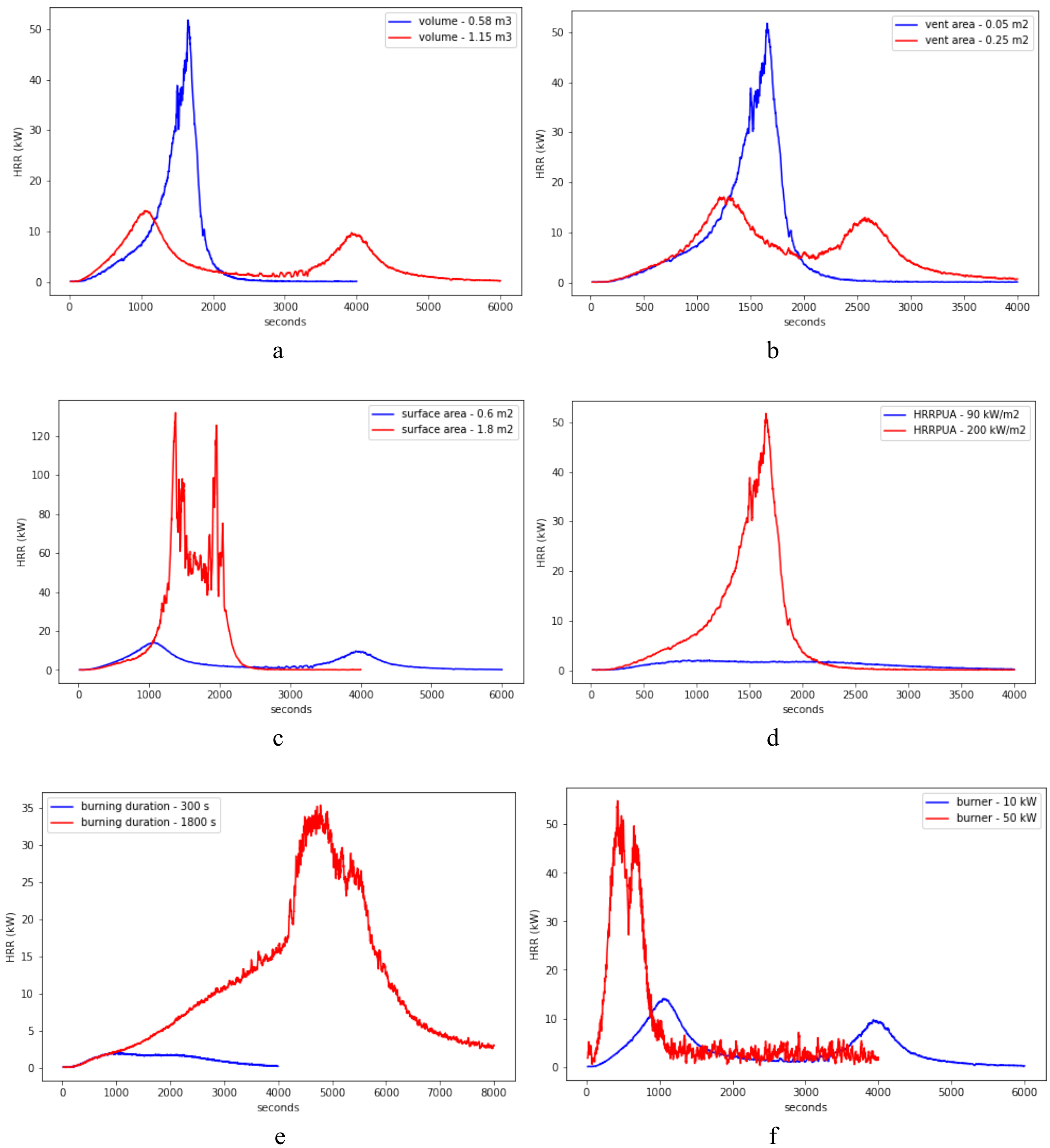


Figure 47. HRR vs Time for assessing the effect of individual parameters a) volume, b) ventilation area, c) combustible surface area, d) HRRPUA, e) burning duration, and f) ignition source output.

To further comprehend how parameter interaction affect electrical cabinet HRR, some of the significant interaction effects were studied through FDS derived results by changing the variable levels and maintaining the other factors constant throughout the simulation. The volume and combustible surface area interaction was ranked most significant. Increasing combustible surface area while keeping a consistent volume depicted an increase in peak and average HRR. For a combustible surface area of 1.8 m^2 changing volume from lower to higher level depicted a decrease in HRR response. For lower combustible surface area of 0.6 $m^{2,}$ altering cabinet volumes between two extremes a significant difference in peak and average HRR was not portrayed as seen in *Table 24*. However, the combustible accommodated inside the cabinet with higher volume showed a slower burning rate as seen in *Figure 48*. These phenomenon may be traced back to gas temperature inside the cabinet. *Figure 49* shows the difference in gas temperature measured for two different volumes near the top portion of the combustible surface. The increase in the air movement due to higher volume of the cabinet, is assumed to lower the gas temperature due to increase air flow inside the cabinet.

Table 24. Average HRR and peak HRR comparison for volume- combustible surface area levels

	Volume (m^3)	***Combustible Surface Area (m^2)***	***Average HRR (kW)***	***Peak HRR (kW)***
1	*0.58*	*0.6*	*1.4*	*2.1*
2	*1.15*	*0.6*	*1.1*	*2.3*
3	*0.58*	*1.8*	*7.8*	*12.8*
4	*1.15*	*1.8*	*2.4*	*4.2*

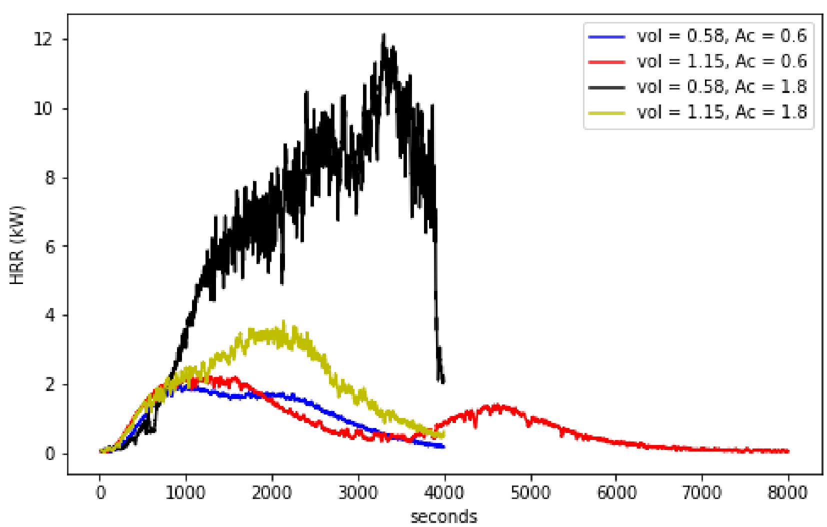


Figure 48. HRR vs time for comparing interaction between volume and combustible surface area.

Changing volume and ventilation area irrespective of the other level, showed that HRR decreases. Due to the increased air flow inside the cabinet as a result of increased volume and ventilation area, it is observed that the gas temperature is considerably lower near the combustible surface. *Figure 49* shows the difference in gas temperature measured for two different volumes near the top portion of the combustible surface. *Table 25* and *Figure 50* shows the average and peak HRR for the different volume and ventilation condition.

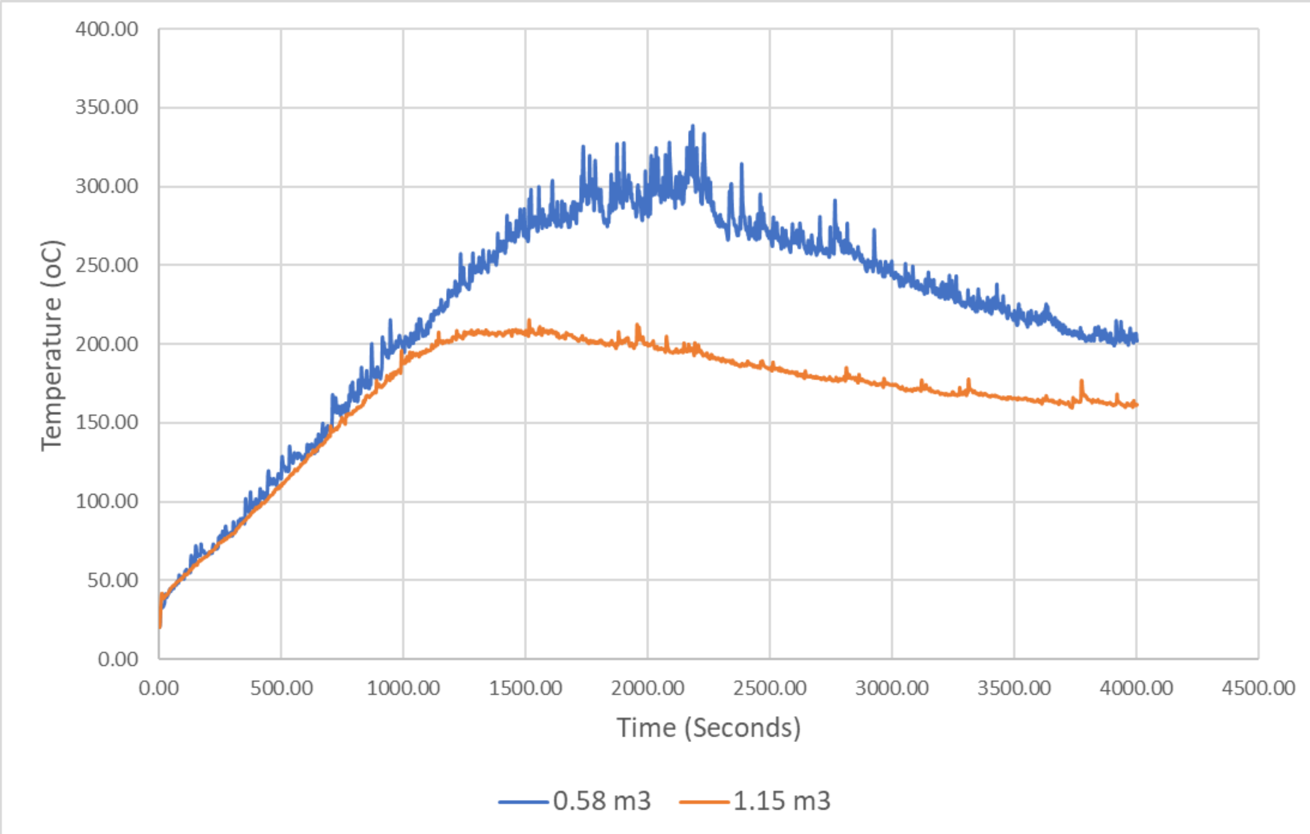


Figure 49. Gas temperature monitored near the top portion of the combustible surface for electrical cabinet with two different volumes

Table 25. Average HRR and peak HRR comparison for volume- ventilation levels

	Volume (m^3)	***Ventilation Area (m^2)***	***Average HRR (kW)***	***Peak HRR (kW)***
1	*0.58*	*0.05*	*19.0*	*52.6*
2	*1.15*	*0.05*	*4.8*	*14.3*
3	*0.58*	*0.25*	*8.7*	*17.5*
4	*1.15*	*0.25*	*5.5*	*12.5*

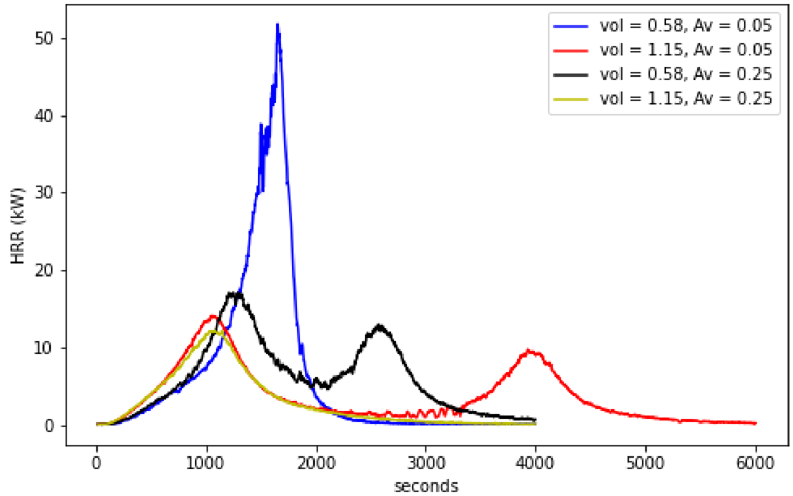


Figure 50. HRR vs time for comparing interaction between volume and ventilation area.

Interaction between combustible surface area and HRRPUA with respect to ignition source on HRR showed that increasing the magnitude of one factor irrespective of the other increase the average and peak HRR. *Table 26 and Table 27* and *Figure 51* and *Figure 52* shows the average and peak HRR while varying the combustible surface area and ignition source output.

Table 26. Average HRR and peak HRR comparison for combustible surface area-ignition source

	Combustible Surface Area (m^2)	***Ignition source (kW)***	***Average HRR (kW)***	***Peak HRR (kW)***
1	*0.6*	*10*	*1.1*	*2.3*
2	*1.8*	*10*	*2.4*	*4.2*
3	*0.6*	*50*	*18.7*	*34.9*
4	*1.8*	*50*	*36.8*	*72.7*

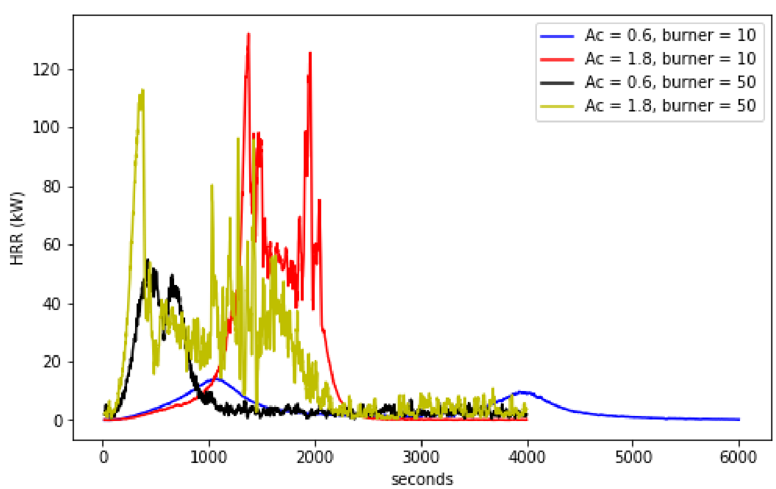


Figure 51. HRR vs time for comparing interaction between combustible surface area and ignition source.

Table 27. Average HRR and peak HRR comparison for HRRPUA-ignition source levels

	HRRPUA (kW)	Ignition Source (kW)	Average HRR (kW)	Peak HRR (kW)
1	90	10	1.1	2.3
2	200	10	4.8	14.3
3	90	50	18.7	34.9
4	200	50	33.0	59.5

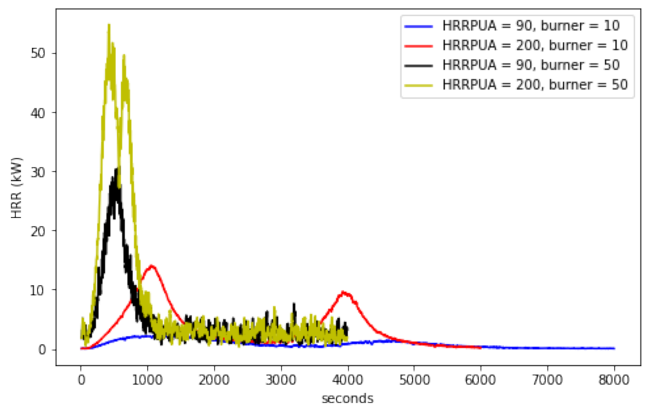


Figure 52. HRR vs time for comparing interaction between HRRPUA and ignition source output.

3.2. Varying Combustible with Fixed Parameters

A total of 11 different types of combustible configurations modeled in FDS. The following electrical cabinet parameters were kept consistent throughout the simulation: cabinet volume of 0.25 m^3, ventilation area of 0.02 m^2, ignition temperature of 325 ºC, combustible surface area of 0.50 m^2, burning duration of 900 seconds, and HRRPUA of 150 kW. *Figure 53* contains HRR vs time information for different combustible configuration. Following the average HRR and peak HRR information evidenced the importance of different configurations as seen in *Table 28*. The circuit board array configuration had the highest peak HRR and cables together with CBR showed the highest average HRR.

The highest average and peak HRR were observed for configurations 3, 4, and 8. These configurations represented combustibles laid in circuit board array layout, combustibles laid along sidewall and ceiling with ignition source at bottom and combustibles and circuit board relay all terminated inside an ignition source.

Table 28. Average HRR and peak HRR for different combustible configuration

Configuration	Label	Average HRR (kW)	Peak HRR (kW)
Combustible placed on either side walls and terminated in ignition source on one side (figure 29)	Configuration 1	44.2	32.2
Combustible placed on either side walls and terminated in ignition source on both side (figure 30)	Configuration 2	49.5	38.2
Circuit Board Array (figure 31)	Configuration 3	37.8	64.2
Combustible placed on ceiling and side wall and ignition source placed on the floor (figure 32)	Configuration 4	46.1	61.5
Combustible placed on ceiling and side wall and ignition source elevated to the middle (figure 33)	Configuration 5	30.3	39.5
Combustible placed on ceiling and side wall and ignition source elevated to the top (figure 34)	Configuration 6	4.5	7.1
Cables placed on either side wall and circuit board relay ignited only one combustible end (figure 35)	Configuration 7	35	58.3
Cables placed on either side wall and circuit board relay ignited all combustible end (figure 36)	Configuration 8	51.1	62.6
Combustible placed along left side of the enclosure (figure 37)	Configuration 9	36	46.6
Combustible placed along back side of the enclosure (figure 38)	Configuration 10	36.8	45.9
Combustible plates in parallel configuration (figure 39)	Configuration 11	7.7	9.7

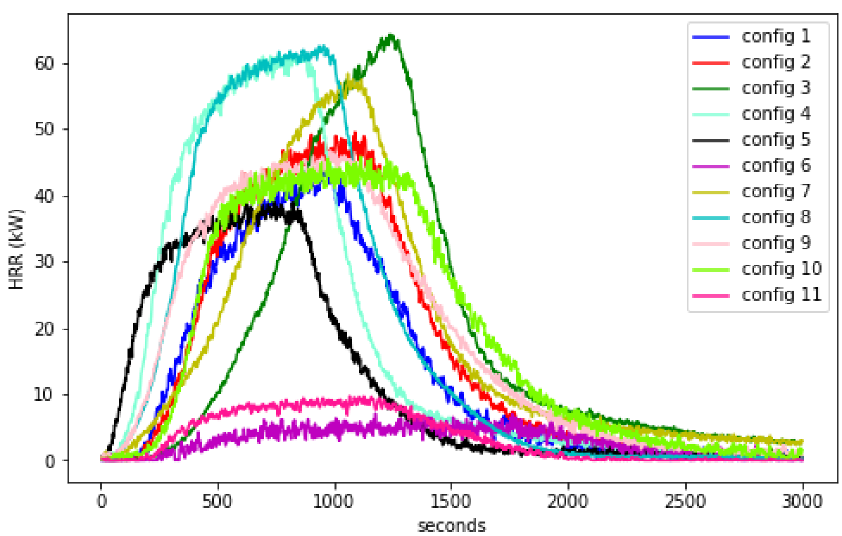


Figure 53. HRR vs time for varying combustible configuration

Increasing ignition source elevation for configuration 4-6 reduced fire HRR. This phenomenon can be attributed to rate of flame spread inside an enclosure. Vertical flame spread is faster compared to flames spreading horizontally across the enclosure width or downwards along the enclosure height. This enables more complete ignition of combustibles when ignition source is placed at a lower position resulting in more material ignition and higher temperatures.

4. Conclusion

The research focused on ranking the significance of the electrical cabinet parameters relative to the HRR fire response. The parameters included geometrical features of the cabinet: volume (A) and ventilation area (B) as well as combustible material features including surface area (C), HRRPUA (D), and burning duration (E). The ignition source HRR (F) was also considered in the statistical analysis. Given the heterogeneous nature of combustible configuration, two independent analyses were conducted.

In the first analysis, the parallel plates of combustible were kept consistent and RSM – based CCD statistical framework was employed to develop a simulation matrix. The CCD framework allows statistical analysis that ranks the importance of main and interaction effects of parameters relative to peak and average HRR. Electrical cabinet parameters including volume (A), combustible surface area (C), HRRPUA (D), burning duration(E), and ignition source HRR (F) were found to be significant relative to peak and average HRR. However, ventilation area (B) was found to not have a significant impact on peak and average HRR. a Additionally, the quadratic model produced through RSM-based CCD analysis yielded a R^2 value of 88.6 % for average HRR and 88.9 % for peak HRR.

In the second analysis, 11 different combustible configurations were analyzed. The highest average and peak HRR were observed for configurations 3, 4, and 8. These configurations represented combustibles laid in circuit board array layout, combustibles laid along sidewall and ceiling with ignition source at bottom and combustibles and circuit board relay all terminated inside an ignition source. The HRR predictions relative to different combustible configuration suggests that different configuration have significant impact on fire HRR. Additionally, it was found that varying the location of ignition source relative to consistent combustible configuration and electrical cabinet parameters affected the fire HRR.

When exploring the influence of combustible fuel detail on electrical cabinet HRR, until recently experiments typically explored the influence of total combustible mass, volume occupied and material of the combustibles. However, these research went beyond the conventional practice and explored the influence of combustible features including HRRPUA, ignition temperature, combustible surface area, and burning duration. It was found that HRRPUA, combustible surface area and burning duration have a significant effect on the electrical cabinet HRR. Additionally, previously reported experiments typically employed combustibles in a definite configuration (centrally or along sidewalls) and employed ignition source at a specific location of the cabinet. A series of simulation to investigate the effect of different combustible configuration and the location of ignition source on HRR indicated its significance on fire HRR. This observation suggests that combustible fuel details including HRRPUA, combustible surface area and burning duration together with its configuration should be given high priority during electrical cabinet fire experiments. Moreover, the ignition source has a major role to play in electrical cabinet fires

5. Acknowledgements

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5. CONCLUSION

The first part of the research focused on determining the most challenging fires that frequently occur in NPP facilities using EPRI – FEDB. Eleven types of fires were identified and further associated with experiments in accordance with primary combustible groups and forms. Following this correlation, it was identified that electrical cabinet fires contribute to a substantial portion (40%) of the challenging fires. In order to understand electrical cabinet parameter and fire HRR relation, historically conducted experiments explored select parameters including geometry and combustible features. Therefore, the subsequent part of the research went beyond conventional practice giving higher attention to details that effectively describe combustible fuels accommodated inside the cabinet while also exploring the influence of cabinet geometry on fire HRR using FDS.

The research focused on ranking the significance of the electrical cabinet parameters relative to the HRR fire response. The electrical cabinet parameters included volume, ventilation area, combustible fuel details including ignition temperature, surface area, burning duration, HRRPUA, combustible configuration and ignition source HRR. Fractional factorial DOE was employed to screen the parameters relative to HRR. Through the screening analysis, it was found that ignition temperature of the material was insignificant. The statistical analysis on results from the simulation matrix based on CCD was used to rank the significance of the electrical cabinet parameters relative to the peak and average HRR. In addition, the statistical analysis was used to develop a non-linear regression relationship between electrical cabinet parameters and HRR. Electrical cabinet parameters including volume, combustible surface area, burning duration, HRRPUA, and ignition source were found to be significant relative to peak and average HRR. However, ventilation area was found to be insignificant. In addition, a series of simulations were conducted to predict HRR for various combustible configurations while keeping all other electrical cabinet parameters constant. When comparing its effect on electrical cabinet HRR, some configurations created a worst-case scenario for electrical cabinet fire. The HRR predictions relative to different combustible configuration suggests that different configuration have significant impact on fire HRR. Additionally, it was found that varying the location of ignition source relative to consistent combustible configuration and electrical cabinet parameters affected the fire HRR.

When exploring the influence of combustible fuel detail on electrical cabinet HRR, until recently experiments typically explored the influence of total combustible mass, volume occupied and material of the combustibles. However, these research went beyond the conventional practice and explored the influence of combustible features including HRRPUA, ignition temperature, combustible surface area, and burning duration. It was found that HRRPUA, combustible surface area and burning duration have a significant effect on the electrical cabinet HRR. Additionally, previously reported experiments typically employed combustibles in a definite configuration (centrally or along sidewalls) and employed ignition source at a specific location of the cabinet. A series of simulation to investigate the effect of different combustible configuration and the location of ignition source on HRR indicated its significance on fire HRR. This observation suggests that combustible fuel details including HRRPUA, combustible surface area and burning duration together with its configuration should be given high priority during electrical cabinet fire experiments. Moreover, the ignition source can majorly influence the electrical cabinet fires.

6. FUTURE WORK

This research has provided a framework to identify important parameters affecting the fire behavior for electrical cabinets. The work needs to be expanded to achieve the overarching goals of the project to reduce the uncertainty of experimental data. The following future work is recommended:

1. Conduct a detailed comparison of existing experimental data with statistical important parameters to identify needed experiments to reduce the uncertainty in electrical cabinet fire HRR

2. Perform a Monte-Carlo analysis based on the important parameters identified to determine the expected distribution in the electrical cabinet HRR

3. Use the Monte-Carlo analysis results to train machine learning model that can predict the HRR of an electrical cabinet observed in the field

4. Conduct statistical analysis for important parameter determination as well as recommendations above for other fire scenarios shown to be significant through database analysis

APPPENDIX

A.1. CCD generated Test Matrix

After synthesizing the parameter levels for the 6 independent parameters: volume, ventilation area, combustible surface area, HRRPUA, burning duration and ignition source output. The CCD used to generate the test matrix as shown in *Table 29* were used to conduct the FDS simulations and predict HRR.

Table 29. CCD generated test matrix

Simulation Number	Volume (m^3)	Ventilation area (m^2)	Combustible surface area (m^2)	HRRPUA (kW)	Burning duration (seconds)	Ignition source output (kW)
1	0.58	0.05	0.6	90	300	10
2	1.15	0.05	0.6	90	300	10
3	0.58	0.25	0.6	90	300	10
4	1.15	0.25	0.6	90	300	10
5	0.58	0.05	1.8	90	300	10
6	1.15	0.05	1.8	90	300	10
7	0.58	0.25	1.8	90	300	10
8	1.15	0.25	1.8	90	300	10
9	0.58	0.05	0.6	200	300	10
10	1.15	0.05	0.6	200	300	10
11	0.58	0.25	0.6	200	300	10
12	1.15	0.25	0.6	200	300	10
13	0.58	0.05	1.8	200	300	10
14	1.15	0.05	1.8	200	300	10
15	0.58	0.25	1.8	200	300	10
16	1.15	0.25	1.8	200	300	10
17	0.58	0.05	0.6	90	1800	10
18	1.15	0.05	0.6	90	1800	10
19	0.58	0.25	0.6	90	1800	10
20	1.15	0.25	0.6	90	1800	10
21	0.58	0.05	1.8	90	1800	10
22	1.15	0.05	1.8	90	1800	10
23	0.58	0.25	1.8	90	1800	10
24	1.15	0.25	1.8	90	1800	10
25	0.58	0.05	0.6	200	1800	10
26	1.15	0.05	0.6	200	1800	10
27	0.58	0.25	0.6	200	1800	10
28	1.15	0.25	0.6	200	1800	10
29	0.58	0.05	1.8	200	1800	10
30	1.15	0.05	1.8	200	1800	10
31	0.58	0.25	1.8	200	1800	10
32	1.15	0.25	1.8	200	1800	10
33	0.58	0.05	0.6	90	300	50
34	1.15	0.05	0.6	90	300	50
35	0.58	0.25	0.6	90	300	50
36	1.15	0.25	0.6	90	300	50

37	0.58	0.05	1.8	90	300	50
38	1.15	0.05	1.8	90	300	50
39	0.58	0.25	1.8	90	300	50
40	1.15	0.25	1.8	90	300	50
41	0.58	0.05	0.6	200	300	50
42	1.15	0.05	0.6	200	300	50
43	0.58	0.25	0.6	200	300	50
44	1.15	0.25	0.6	200	300	50
45	0.58	0.05	1.8	200	300	50
46	1.15	0.05	1.8	200	300	50
47	0.58	0.25	1.8	200	300	50
48	1.15	0.25	1.8	200	300	50
49	0.58	0.05	0.6	90	1800	50
50	1.15	0.05	0.6	90	1800	50
51	0.58	0.25	0.6	90	1800	50
52	1.15	0.25	0.6	90	1800	50
53	0.58	0.05	1.8	90	1800	50
54	1.15	0.05	1.8	90	1800	50
55	0.58	0.25	1.8	90	1800	50
56	1.15	0.25	1.8	90	1800	50
57	0.58	0.05	0.6	200	1800	50
58	1.15	0.05	0.6	200	1800	50
59	0.58	0.25	0.6	200	1800	50
60	1.15	0.25	0.6	200	1800	50
61	0.58	0.05	1.8	200	1800	50
62	1.15	0.05	1.8	200	1800	50
63	0.58	0.25	1.8	200	1800	50
64	1.15	0.25	1.8	200	1800	50
65	0.58	0.15	1.2	145	1050	30
66	1.15	0.15	1.2	145	1050	30
67	0.865	0.05	1.2	145	1050	30
68	0.865	0.25	1.2	145	1050	30
69	0.865	0.15	0.6	145	1050	30
70	0.865	0.15	1.8	145	1050	30
71	0.865	0.15	1.2	90	1050	30
72	0.865	0.15	1.2	200	1050	30
73	0.865	0.15	1.2	145	300	30
74	0.865	0.15	1.2	145	1800	30
75	0.865	0.15	1.2	145	1050	10
76	0.865	0.15	1.2	145	1050	50
77	0.865	0.15	1.2	145	1050	30