NIST Technical Note 2215

# Characteristics of Nuclear Power Plant Fires Involving Electrical Enclosures

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**NIST Technical Note 2215**

# Characteristics of Nuclear Power Plant Fires Involving Electrical Enclosures

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## Abstract

**PRIMARY AUDIENCE**

Fire protection and fire probabilistic risk assessment engineers conducting or reviewing fire modeling that supports fire probabilistic risk assessments related to characteristics (e.g., ignition, fire growth, and peak heat release rate) of electrical enclosure fires in power plants.

**KEY RESEARCH QUESTION**

What are the characteristics (e.g., common causes, ignition mechanisms, detection type) of electrical enclosure fires; what impact does fire causal type have on the severity, duration, and damage type of electrical enclosure fires; and how does this vary for fires in electrical enclosures versus all fires in nuclear power plants (NPPs)?

**RESEARCH OVERVIEW**

This report provides an overview of the characteristics (e.g., ignition sources, severity, and damage type) of electrical enclosure fires that occurred in US nuclear power plants between 1990 and 2011, as reported in the Fire Events Database (FEDB). Key findings are summarized below. Note: to provide a broader perspective on the causes and results of these events, this report provides an overview of *all* reported fire events in NPPs, including “non-challenging” events. Certain steps in probabilistic risk analyses may only consider the outcomes or results (e.g., ignition frequencies or fire size distributions) of a subset of these fires (e.g., “challenging” or “potentially challenging” events). For further information regarding fire ignition frequencies and non-suppression probability, the reader is referred to NUREG 2169. Additionally, the reader is referred to NUREG 2230 for further guidance regarding the analysis of fire risk posed by growing vs. interruptible fires.

NUMBER AND TYPES OF EVENTS

- 1998 total fire events were analyzed, including 269 (13.5 %) that were reported to have occurred in electrical enclosures (i.e., “Component Start Group” = ‘Electrical Panel’). Note: for 51.2% of events in the FEDB, “Component Start Group” was listed as ‘Other’ or ‘Not Reported’.

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- Between 1990 - 2010, there are no significant year to year variations in reported "Component Start Group" frequencies (e.g., 'Cable/Wiring', 'Electrical Panel', 'Generator', or 'Transformer').
- Between 1990-1999, an average of 29 fire events were reported each year; between 2000-2009, an average of 168 fire events were reported each year. This increased frequency (5.8 x greater) of reported event occurred as:
  - The reported fraction of shorter fires (i.e., duration ≤ 5 minutes) increased from 46.3% to 72.3% and the fraction of fires reported as 'Not Challenging' increased from 15.9% to 41.1% while the fraction of fires reported as 'Challenging' decreased from 23.9% to 6.6%.
  - Generally, less detail was provided about (some facets of) events: for example, beginning in 2000, fire event location (i.e., "Building Start") was three times (3x) more likely to be reported as 'Other' or 'Not Reported' as compared to events reported prior to 2000 in the FEDB.

<u>CAUSES OF IGNITION</u>

- The primary causes of all fire events in the FEDB are electrical failures resulting in overheating, arcing, and/or sparks (High Energy Arc Fault, HEAF, and non-HEAF) (40.3 %), hot work (24.1 %), overheated materials (15%), mechanical malfunction or failure (4.4%), and personnel error (2.9 %).
- For electrical enclosure fires, 86.2% events reported their primary cause as some kind of electrical failure: overheating, arcing, or sparks (both HEAF and non-HEAF).
  - Compared to all fire events, electrical enclosure fires are significantly (2 times to 3 times) more likely to start due to an electrical failure leading to overheating, arcing, or sparks and, although the sample size is small, electrical enclosure fires are nearly 50% more likely to occur due to a HEAF.

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- In 79.2% of all fire events, the Combustible Initiating Group' is a solid material: either in-situ/permanent (e.g., structural or electrical components, interior finish materials, or cable jacketing) or transient (e.g., temporary thermal insulation materials, electrical wiring/equipment, cellulosics, and trash)
  - For approximately 10 % of all reported incidents, a flammable or combustible *liquid* (e.g., grease or lube, fuel, or transformer oil) is reported as the 'Combustible Initiating Group'
- The combustible initiating group in more than 95 % of electrical enclosure fires reported in the FEDB was some sort of solid (in-situ) material or cable jacketing/insulation material.
- A review of twenty six (26) written Licensee Event Reports (LERs), revealed:
  - In twelve (12) of these events, circuit breaker failure was identified as the as the reported cause of, or the first item to fail in, the fire event.
  - Aging appeared to be a primary or contributing factor in five events (e.g., due to insulation deterioration, thinning of conductive surfaces, development of high resistance connections, and delamination or mechanical failure of components).

SEVERITY

- Although the majority (67.1%) of all fire events reported in the FEDB last for less than five minutes, approximately 1 in 8 (12.5%) events are reported to last for twenty minutes or longer.
  - Fire events in electrical enclosures typically last longer than the average fire event reported in the FEDB
- Electrical enclosure fires are most likely (69.5 % of reported cases) discovered by personnel in the area (much like the trend for all fires in the FEDB, 81.4%); however, compared to all fires, they are 1.8 times and 3.2 times, respectively, more likely to be detected by 'failed equipment alarms' (e.g., Tripped pump, Ground,

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Low Lube Oil.) or by staff in the main control room (e.g., due to control or instrumentation failures)

- Although just 8.2% of all fire events in electrical enclosures were reported as ‘Challenging’, all fire events in electrical enclosures that were initiated by an ‘Explosion’ or ‘High Energy Arc Fault (HEAF)’ were reported as ‘Challenging’.
- The options for “fire cause” are not mutually exclusive and a single cause type may be used to describe a wide variety of events, which reflects the difficulty in determining the precise cause of a fire. Electrical malfunction, overheating, and arcing/sparking often occur together, and the option selected depends upon the reviewer. Consequently, except for severe events (e.g., fires caused by explosions or HEAF), it is difficult to draw conclusions directly connecting fire cause to severity (e.g., challenging determination or fire characterization type).

**FUTURE WORK**

The FEDB currently maintains a wide range of information from nearly 2000 fire events reported in US nuclear power plants since 1990. Valuable insight regarding the frequency, causes of ignition, damage types, and severity of these events can already be obtained from the database in its current form; however, improvements to the design and maintenance of the FEDB and to how new fire events are reported could improve its value and impact. Currently, the FEDB is maintained as a Microsoft Access database, which is limited in its capabilities for searching and filtering fire events and for presenting this information in a visually appealing and easy to interpret manner (i.e., as more than rows of strings and numerical data). A graphical user interface (GUI) with simple search tools that allow a user to access and view tabulated data and related reports from all, a subset of, or specific fire events based on identifying information would be valuable. Further, analytical and plotting tools that present visual representations of single data fields or combinations of data types (e.g., conditional analyses: if A then B), especially across varied time frames (e.g., all reported events, from n-year intervals, or as time-resolved outputs) are also warranted. The scripts developed for this report to analyze and produce such figures and tables are not particularly complicated to write (see

Appendix C); however, it would be valuable for future users of FEDB data to not have to rewrite such tools each time they wish to perform a new analysis.

Additionally, an investment into regular, timely addition of new fire events to (and general maintenance of) the FEDB could allow for automated analysis and updating of event statistics reported in this work. Coupled with the suggestions above, automatically updated visual representations FEDB data could reveal trends in real time, thus indicating new, or emerging, hazards of interest to focus on and how they evolve with time and across the lifespan of the plant. Currently, new events have been reviewed and added to the FEDB only twice since the creation of the initial database, when it was determined that a "critical mass" of new data was available for additional analysis.

Finally, as noted throughout this report, information provided for certain fire event data categories is often incomplete (e.g., approximately 46% of events in the FEDB list "Building Start" as 'Other (Specify in Comments)') or response options for categories that are provided to plant personnel who complete these reports are insufficiently detailed, such that the majority of events are defined by just one or two overlapping categories (e.g., the combustible initiating group of 90% of electrical enclosure fires was reported as 'Other solid in-situ materials'). As a specific example, more than half of all fire events in the FEDB report a "Component Start Group" as 'other' or 'not reported'; transient fires are often recorded in one of these two categories. Potential improvement to the FEDB could thus be made by making 'transient combustibles' an option in the "Component Start Group" category, potentially with more detailed subcategories of such transients (e.g., paper, wood, furniture, plastics, cleaning supplies, maintenance equipment). In several sections of this report, key categories are identified for which such information could be more carefully recorded in future fire event reports; further analyses of the FEDB may benefit if such detail is available.

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**WHY THIS MATTERS**

This report provides empirical evidence to assist U.S. Nuclear Regulatory Commission (NRC) staff and nuclear power plant engineers performing and reviewing fire probabilistic risk assessments based on a review of 1998 fire events reported over three decades in the Fire Events Database. The information provided in this report will support a more realistic assessment of both fires in electrical enclosures and the overall fire landscape in nuclear power plants.

**KEYWORDS**

Fire cause; Fire event frequency; Fire risk; Fire statistics; Nuclear Power Plant (NPP).

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## Glossary

| | |
|---|---|
| ACB | Air Circuit Breaker |
| AFFF | Aqueous Film Forming Foam |
| BWR | Boiling Water Reactor |
| CR | Condition Report |
| CSNI | Committee on the Safety of Nuclear Installations |
| DC | Direct Current |
| DER | Daily Event Report |
| EDG | Emergency Diesel Generator |
| ELIT | Emergency lighting Transformer |
| EPIX | Equipment Performance and Information and Exchange System |
| EPRI | Electric Power Research Institute |
| FEDB | Fire Events Database |
| FIRE | Fire Incidents Records Exchange |
| GUI | Graphical User Interface |
| HEAF | High Energy Arc Fault |
| INPO | Institute of Nuclear Power Operators |
| LER | Licensee Event Report |
| MCC | Motor Control Center |
| MOU | Memorandum of Understanding |
| NEA | Nuclear Energy Agency |
| NEIL | Nuclear Electric Insurance Limited |
| NIST | National Institute of Standards and Technology |
| NPP | Nuclear Power Plant |
| NRC | U.S. Nuclear Regulatory Commission |
| NUREG | NRC Reports or brochures on regulatory decisions, results of research, results of incident investigations, and other technical and administrative information. |
| OECD | Organization for Economic Cooperation and Development |
| OCB | Oil Circuit Breaker |
| PRA | Probabilistic Risk Assessment |
| PWR | Pressurized Water Reactor |
| RFI | Request for Information |
| SUT | Start Up Transformer |
| UAT | Unit Auxiliary Transformer |

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## 1. Introduction

Electrical enclosures include items such as (but not limited to) switchgears, relay cabinets, control and switch panels, motor control centers, fire protection panels, and DC distribution panels. Electrical enclosures present a fire risk in nuclear power plants (NPPs) because they contain both combustible materials and energized electrical circuits. Unwanted fires in electrical enclosures have the potential to disrupt power, instrumentation, and control in the plant. Specifically, in an analysis of global fire events in NPPs [1] it has been noted that electrical cabinets (i.e., electrical enclosures) and transformers are the components that provide the highest share of fire initiations (approximately 12 percent each). Further, it has been noted in that, “electrical cabinets, especially high voltage switchgear, are commonly identified in fire probabilistic risk assessments [PRAs] as one of the important sources of fire ignition in nuclear power plants.” [2]

Electrical enclosures may vary considerably in size, voltage, configuration, construction, and the density and type of components that they contain. These variations can have a significant impact on fire development in these enclosures. Specifically, it has been reported that enclosure size, its contents and their configuration, openings, electrical voltage, and the initial ignition source affect fire growth in an electrical enclosure [3]. To mitigate the hazard or risk posed by these fire events, significant effort has been made to better understand both the causes of and the factors affecting the evolution of unwanted electrical fires in NPPs.

This report provides an analysis of fire events in electrical enclosures (or related equipment) in U.S. Nuclear Power Plants that were reported between 1990-2011 Information about these fire events, including key details (e.g., factors leading to their development and fire severity) were obtained from the Fire Events Database (FEDB), which was developed by the Electric Power Research Institute (EPRI), first published in the early 2000s [4], and updated in 2013 [5]. The development of the FEDB was led by EPRI, with cooperation from the U.S. Nuclear Regulatory Commission’s (NRC’s) Office of Nuclear Regulatory Research in accordance with the EPRI-NRC memorandum of understanding [6]. The FEDB is the primary source of fire incident data for use in probabilistic risk assessments; it is intended to be “the most comprehensive and consolidated source of fire incident information available for nuclear power plants operating in the United States.” [5]

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A recent report by the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) [7] highlights the importance of strengthening the relationship between data projects that provide detailed reporting of incidents (and the information exchange that they allow for) and individuals and communities that conduct risk or safety assessments. A key objective of this manuscript is thus to facilitate the work of fire protection and probabilistic risk assessment engineers who conduct or review assessments of electrical enclosure fires in NPPs by analyzing the reported data contained in the FEDB, quantifying fire event frequencies, and generating insight into their root causes and typical resulting damages such that mechanisms for the prevention of these fire events and/or reduction of their consequences can be developed.

### 1.1. Literature Review

Electrical fires are fires that are "directly caused by the flow of electric current or by static electricity" [8]. Estimates indicate that 7.7 %, of all fires in the United States are due to electrical distribution (e.g., wiring, transformers, meter boxes, power switching gear, outlets, cords, plugs) [9]. In the context of NPP safety, electrical fires may be even more significant: a review of fire events reported in commercial NPPs (as summarized in the Organization for Economic Cooperation and Development's International Fire Data Exchange Project, OECD FIRE) reveals that close to fifty percent of these fire ignitions are due to electrical sources [1]. As of 2015, twelve countries support this project, providing information from 438 fire events occurring between the early 1980s and 2013 (with the bulk of incidents occurring during or after the mid-1990s). Further, of these, fires in electrical cabinets (i.e., enclosures) and transformers represent the components with the highest share (12% each) of all events in the OECD FIRE database. There are numerous potential ignition sources for electrical fires including (but not limited to): poor connections (e.g., due to aging/deterioration, and improper alterations or installation), overheating, arcing (in air or across carbonized paths), overload, excessive thermal insulation, external heating (e.g., due to direct flame impingement or external heating or simple product failure) [5, 9-12].

One key challenge in predicting electrical fires is that they have a particularly low failure rate. For example, it has been noted that many ignition phenomena have a strong probabilistic aspect to them [13] and that it is difficult for an arc to start a fire, even under better-than-average

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conditions [14]. Further, as reported in NUREG 6738 [2], only one "large" cable fire occurred in the US after 2000 total reactor-years of experience (and at least five large cable fires occurred in less than 1000 reactor-years in 'Soviet-designed' NPPs). Note: this document [2] was published in 1990 and thus does not include more recent fire events which occurred as the NPPs continued to age. Although this statistic does not account for smaller fire incidents (e.g., the hundreds of smaller fire events reported in the OECD FIRE database that were initiated by electrical sources [1]), it does highlight the challenging nature of assessing the problem: i.e., fire events in NPPs are rare and, although they may pose serious risks, determining statistics regarding event origin, cause, and consequence is a non-trivial task.

Multiple bench- and full-scale experimental studies and standard test methods have thus been developed to assess the fire performance of electrical components. Two thorough (though not-necessarily exhaustive) papers [15, 16] provide detailed reviews of dozens of such works, highlighting critical report results and test criteria (i.e., the metrics by which these electrical components are evaluated in their response to fire). These criteria include mass loss or heat release rate, damage (e.g., char) length, smoke generation and/or obscuration, critical times or temperatures (e.g., time to failure, to ignition, or of self-sustained burning), ease of ignition and extinction, and electrical continuity.

The proliferation of these test procedures and the various metrics by which they attempt to characterize material flammability highlights: (a) the complexity of this fire problem – that is, many factors affect ignitability, fire growth rate, and peak fire size of electrical enclosure fires – and (b) the inability of current bench-scale test methods to measure intrinsic fire properties that can be used to predict material flammability performance under a variety of fire conditions [15]. Consider just one metric: reported critical temperatures (for damage, loss of function, failure, and/or ignitability). Across fire and risk analysis codes in use in different countries, no clear, common critical temperature is agreed upon: threshold temperatures for both damage and ignition each vary by more than 150°C between various codes [17]. Although some general trends are apparent – e.g., material type (thermosets vs. thermoplastics) [18], cable shielding, armoring, bundling, and current/voltage loads [19] tend to systematically affect flammability and (for poly(vinyl chloride), PVC, at least) ignition of wires and cables due to electrical mechanisms will occur at lower temperatures in the presence of electric current [20] – this

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wide range of 'critical temperatures' ultimately reflects the uncertainty in trying to use a single parameter (or 'critical' value) to capture the variety of factors that affect electrical component damage and its probability [18, 21, 22].

Due to the relatively low likelihood of any single failure event causing a notable fire event, test methods (effectively, by necessity) are typically designed to recreate electrical fires by overstressing the device, in comparison to its typical use conditions [13]. This leaves open questions as to how well test protocols simulate realistic conditions. It is thus critically important to carefully define and understand the design and intended use of given test standards, methods, and/or protocols, the assumptions made in their development, and both the capabilities and limitations of their reported rating metrics (e.g., pass/fail criteria, reported measurements types and threshold values).

Given these challenges, quantitative prediction of whether or not any potential ignition source can ignite a self-sustaining fire, how quickly that fire will grow, and how large it can become under varied ambient conditions in an enclosure of arbitrary configuration, ventilation, and electrical and fuel loading remains beyond the capabilities of state-of-the-art fire models. Instead, a large number of experimental studies have been performed to allow for a probabilistic assessment of the growth rate and peak size of electrical enclosure fires. [1, 3, 21, 23-31]. While these studies provide the basis to assign peak fire size distributions for electrical enclosures of varied electrical function, contents, and size (given that a fire will occur), open questions remain regarding the causes of these fire events and how they affect ignition, development rate, fire growth, and damage frequency. The limited availability of such fire analysis data has previously been noted as "one of the major deficiencies in the present fire risk assessment" [17]. The review of 438 fire events in the OECD FIRE database represents a valuable first step towards such assessment of these causes [1]; in this report, a significantly larger dataset (1998 fire events reported in NPPs in the United States) is analyzed in further detail.

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## 1.2. Sources of Nuclear Power Plant Fire Event Data

This report provides an analysis of fire events in electrical enclosures that occurred in US Nuclear Power Plants, which were reported between 1990 and 2011 in the FEDB [5]. The FEDB Component Start classification: "Electrical Panel" was used to identify reported fire events of interest as this was the most accurate available option for reporting such fires in the FEDB. A total of 269 "Electrical Panel" incidents are analyzed in this report; this represents 13.5% of the 1998 total incidents included in the FEDB from this time period. Note: electrical enclosure fires account for a similar fraction of all fire incidents reported in both the FEDB and the OECD FIRE Database.

Fire events included in the FEDB were selected based on the data collection, screening, and evaluation scheme described as follows. For events obtained after 2000, the process starts with a broad and course screening of fire related events obtained by plants using a fire related keyword search of corrective action program or equivalent databases. The keyword fire records data search was performed at each participating plant in accordance with specified keywords (e.g. fire, smoke, burn, explosion, extinguish and their variants). Only rudimentary event identification information was requested at this stage (date, identification number, title) for event descriptions that include at least one of the keywords. No event review or screening by plant personnel was requested. The idea was for plant contacts to search their database(s) for fire data and return a list of all events identified that contain any of the keywords. A fire event search template was prepared to facilitate this activity. Between 1000 and 5000 keyword search record hits were typically obtained for each plant.

The results of the fire event keyword search were provided to EPRI for further screening. The PWR and BWR (Pressurized- and Boiling-Water Reactors, respectively) Owner's Groups assisted EPRI in performing that screening to identify potentially "real" fires. This substantially reduced the number of fire events that require more detailed review to about 100-300 events per plant. After that screening was completed, the plants were contacted again to obtain the full reports (as available) for the selected potentially "real" fire event records. Then EPRI performed a review of these more detailed fire event records to identify "real" fires. The screened real fire events are retained and coded within the updated FEDB. This resulted in the selection of around 5-50 events per plant that were coded into the FEDB. As the event records

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were typically condition reports (CRs) that were not intended to collect fire event details desired for the FEDB, it was necessary to request additional event information from plants for the most important fire events where key fire severity classification information was missing or ambiguous. As part of the request for information (RFI) the plants were requested to perform a check on the coding or existing information from the CRs in the FEDB.

This process was applied to fire event data collection for the period 2000-2009. There were additional fire events in the FEDB from the 1990-1999 time period that were retained from the original FEDB. Many had missing or questionable coding. They were also included in the plant fire record RFIs, again on an as available and practical basis. In addition, the plants were asked to identify and provide reports on any other fire events in that period that they were aware of including NEIL and EPIX reports. During and after the RFI process, many calls and emails were made to plants to ensure that the information was provided in as complete and accurate a manner as reasonably possible given the age of the information being requested.

Fire event data from 2010 and later has been collected and added to the EPRI database in a second major update. This most recent version of the database has not been shared with the U.S. Nuclear Regulatory Commission under the fire research MOU; therefore, this report does not consider data from 2010 and onwards. Additionally, this data is also not incorporated into fire frequency analysis for PRA practitioners [32].

All incidents reported in the FEDB and analyzed in this work are categorized by a series of unique identifiers and written descriptions including (but not limited to): Fire ID, event date, location in plant, plant power level, component start group and voltage, fire start type (ignition source), duration, challenging criteria, suppression method, and damage type. For this study, in addition to providing a statistical analysis of how each reported fire event was classified into these categories, more detailed written reports (e.g., licensee event reports) from a representative selection of these fire events were also reviewed. A summary of the findings of this analysis is presented in Section 2; a more detailed review of these written reports, including key excerpts, is provided in Appendix B.

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# 2. Statistics of Fire Events in Nuclear Power Plants

## 2.1. Overview of event information recorded in the Fire Events Database (FEDB)

The FEDB currently provides a description of 1998 fire events that occurred in U.S. Nuclear Power Plants, which were reported between 1990 and 2011 [5]. Figure 1 shows a histogram of when these events occurred; for two events, an event date was not reported, thus only 1996 events are plotted here. Using these results, it is possible to see if and how reported fire events varied over time (e.g., "do systematic trends in ignition source or damage severity exist?"). A time-resolved analysis of fire event descriptions is provided in Section 2.2 of this report for all fire events in the FEDB (1998 events). This time-resolved analysis is not repeated for the subset of electrical enclosure fires because fewer such events are reported (electrical enclosure fires represent 269 out of all 1998 fire events in the FEDB). Tabulated values of time-resolved fire event description data are provided in Appendix A of this report.

As seen in Fig. 1, most events reported in the FEDB occurred between 2000-2010. The sudden increase in the number events reported each year in the early 2000s versus in the previous decade is not necessarily an indication of more events occurring each year rather an outcome of possible underreporting in earlier years. Fire event data exhibits a discontinuity for the period 1990–1999 that is statistically significant. That anomaly may actually start a year or two earlier, but the detailed level of determination was not attempted in NUREG-2169 [32]. The discontinuity appears to be related to the nature of the fire event data sources and completeness of the collection of the potentially challenging fires in the 1990s. The 1990s has a smaller occurrence rate for reported fire events than later time periods, and this difference is statistically significant.

This supports but does not confirm the qualitative observation that the completeness of the fire data for the 1990s is limited and that the data might be missing some fire events important to the determination of fire ignition frequencies. That is, it is possible that there are some fire events that may have risen to the level of potentially challenging or challenging and would have been included in fire ignition frequency counts but were excluded due to under reporting.

Fire event data collected for the 2000–2010 period is believed to be the most complete and accurate data for characterizing fire events and estimating fire ignition frequencies for U.S. fire

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PRAs. The Institute of Nuclear Power Operators (INPO) have enhanced data collection efforts and established a standardized reporting process, which led to a change in the number and types of events reported. The data from this period were collected in a uniform manner and underwent extensive review for fire severity classification, ignition frequency binning, and suppression analysis. Although there is an increase in the number of total fire events, there is a decrease in the severity of reported fire events. That is, as detailed in Sections 2.2.5, 2.2.6, and 2.2.8 of this report, after the year 2000, the average reported fire event duration decreases, a larger fraction of events are reported as 'Non-Challenging' or 'Potentially Challenging' (rather than challenging), and a smaller fraction of events was reported as extinguished by team response from the plant fire brigade. This apparent decrease in the severity of events (and increase in reported number of events) is a result of the larger collection effort (see Section 1.2) by which they were first identified: in total, more events were identified – including smaller events which, previously, were typically under-reported – to allow for a better understanding of the fraction of total fire events that occur that are most relevant for risk analyses. When calculating fire event frequencies for probabilistic risk assessment, only challenging and potentially challenging fires are considered [32].

As a final note, although fire events reported in 2010 and 2011 are included in Fig. 1, only two fire events are reported in 2011, thus these are not included in further analysis (e.g., of fire event cause or severity). Events that occurred in 2010 are included in such analysis, though it should be noted that these 24 events may not be perfectly representative of all fire events that occurred during this year and caution should thus be maintained when using these results for evidence of time-dependent trends (e.g., more or fewer fires of a type as a function of year).

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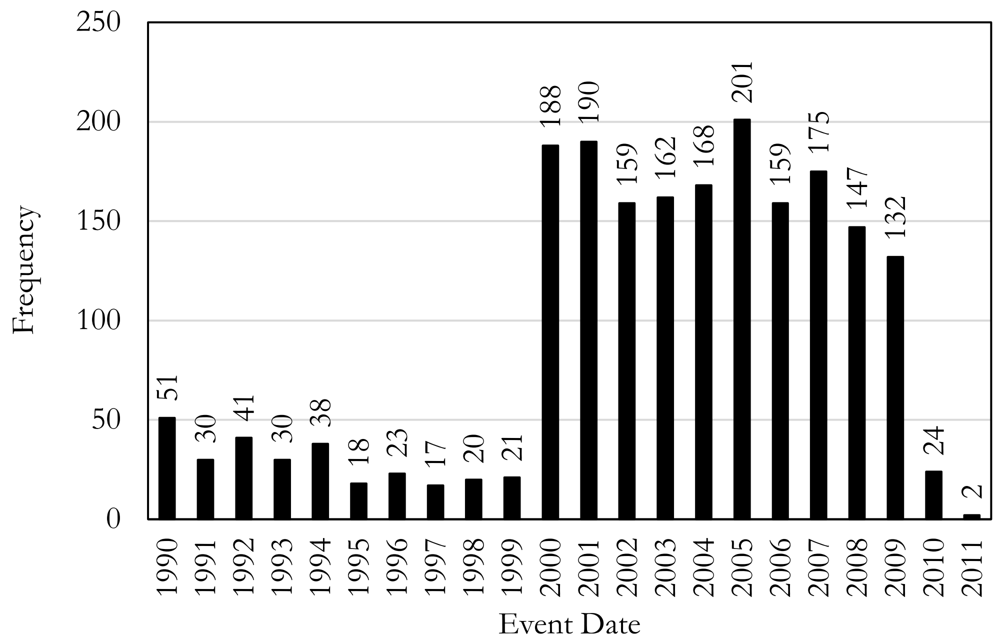


**Figure 1.** Frequency of all fire events in the FEDB by year

Each of the events in the FEDB is described by more than 80 data fields (information categories). To allow for consistent descriptions of various fire events that occur across different facilities, potential responses to many of these categories are limited to a selection of predefined options. In this report, nine of these information categories (each of which is listed in Table 1) are analyzed in detail; the results of this analysis are presented in detail in Sections 2.2 and 2.3 (for *all* fire events and for fire events in electrical enclosures, respectively) of this report. For most categories, response options are unambiguous; however, for fire event severity (FEDB classification: "ChallengingDetermination"), the meaning of these options should be clarified by a brief introduction before further analysis.

**Table 1.** Selected fire event information categories analyzed in this report

| Information Category | Category Description |
|---|---|
| **"BldgStart"** | Building where fire event started (e.g., control, reactor, or turbine building) |
| **"FireCauseStart"** | Initiating cause of fire event (e.g., electrical arcing, explosion, high energy arc fault, overheating) |
| **"CompStart"** | Component in which fire event started (e.g., Circuit breaker, Electric bus bar or bus duct, Relay rack, Switchgear) |
| **"CombustableInitiatingGroup"** | Electrical jacketing/insulation, liquid, solid (transient or in-situ) |
| **"FireDuration"** | Duration of Fire Event |
| **"FireCharacterizationType"** | Fire Event Type (e.g., arc, explosion, flaming combustion, overheating, smoldering combustion) |
| **"FireDetectPerf"** | Performance of installed fire detection systems – not installed, system actuated correctly, system did not actuate (yes/no indication of system failure) |
| **"PutOutFire"** | Who extinguished the fire (e.g., fire watch, fire brigade, maintenance staff, or fire self-extinguished) |
| "**ChallengingDetermination**" | 'Challenging', 'Not Challenging', 'Potentially Challenging', 'Undetermined (NC-PC)' |

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In the FEDB, fire event severity is classified as either Challenging, Potentially Challenging, or Non-Challenging [5]:

> Challenging (CH) – fire events that had "an observable and substantive effect on the environment outside the initiating source";
>
> Potentially Challenging (PC) – fire events that "were not judged to be [challenging] events, but … could have led to fire growth, fire spread, equipment damage or cable damage beyond the fire ignition source had the circumstances of the fire event been different"; or
>
> Not Challenging (NC) – fires that, "did not cause or would not have caused adjacent objects or components to become damaged or ignite regardless of location for essentially any amount of time."

Additionally, when limited information was available, fire events could also be classified as Undetermined (PC-CH) or Undetermined (NC-PC). These options are used to describe events that fall somewhere in between the three classifications above, when insufficient information is available to reasonably determine if the higher risk classification applies. Table 2 presents an overview of the factors used to characterize a fire event as CH, PC, or NC. Note: this table is reproduced from Table 4-1 of the EPRI report, 'The Updated Fire Events Database: Description of Content and Fire Event Classification Guide [5]'; a more detailed description of fire incident severity determination is provided in Section 4 of that report.

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**Table 2.** Characteristics used to characterize fire events in the FEDB

| Event Classification | Event Sub-classifications |
|---|---|
| **CHALLENGING (CH)**<br>One of the following: | Damage to or ignition of an adjacent object, cable or component occurred. This includes ignition of secondary combustibles. |
| | Damage to or ignition of an adjacent object, cable, or component would have readily occurred had the fire been in a different location. |
| | Damage to or ignition of an adjacent object, cable, or component could have occurred if significant suppression actions[1] had not been taken. |
| **UNDETERMINED (PC-CH)** | At least a PC fire, with insufficient information available to make a definitive CH finding. |
| **POTENTIALLY CHALLENGING (PC)**<br>Not "challenging" and one of the following: | Damage to or ignition of an adjacent object, cable, or component could have occurred if minor suppression actions[1] were not taken in a timely manner. Delayed detection could lead to a delay in taking such actions. |
| | Damage to or ignition of an adjacent object, cable, or component could have occurred if the fire were in a different location and if minor suppression actions[1] were not taken in a timely manner. Delayed detection could lead to a delay in taking such actions. |
| **UNDETERMINED (NC-PC)** | Potentially a fire, with insufficient information available to make a definitive PC finding. |
| **NOT CHALLENGING (NC)**<br>Not "potentially challenging" and one of the following: | Overheat condition only; no smoldering or flaming combustion. |
| | Smoldering fire self-extinguishes without any active intervention. |
| | Fire involves an ignition source that would not be expected in any area of interest to the fire PRA or in a location that has no relevance to plant operations or safety. |
| | Other specific smaller fire incidents with specific characteristics[2]. |

[1] Significant suppression actions include the manual use of hose streams and the automatic/manual activation of sprinklers, deluge systems, Halon systems, or $CO_2$ systems. Minor suppression activities include lesser actions such as the use of a single portable extinguisher or other relatively simple and prompt actions to suppress the fire. Section 4.3 [5] and Appendix B [5] provide additional discussion and examples.

[2] See Table 4.3 [5] for a list of specific PC to NC override types of fire events and Appendix B [5] for discussion of specific criteria used to determine PC to NC override classifications.

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## 2.2. Selected Statistics of all Fire Incidents reported in the FEDB between 1990-2011

### 2.2.1. Fire Location (Building)

Table 3 lists the location (“Building Start”) of all fire events in the FEDB. Often, fire location is not carefully recorded with a specific “Building Start” category description: approximately 46% of events in the database list “Building Start” as ‘Other (Specify in Comments)’ or ‘Not Reported’. However, when ‘Building Start’ information is available (i.e., when considering only the fire events for which a “Building Start” location is explicitly defined; rightmost column of Table 3), the largest number of reported fires in NPPs start in ‘Turbine’ [36.6%], ‘Containment (PWR)’ [12.3%], ‘Diesel Generator’ [9.6%], ‘Reactor (BWR)’ [8.4%], and ‘Auxiliary (PWR)’ [8.0%] buildings.

Figure 2 plots time-resolved frequencies for fire locations of reported events in the FEDB (i.e., fractions of events with a specific “Building Start” option out of all fire events recorded during that time period). Here, fire event frequencies are generally reported in one-year intervals except between 1990-1999; a longer time interval is used during these years to ensure that each interval contains at least 80 unique fire events (see Fig. 1), which allows for calculation of more meaningful distributions of event frequencies. Presented in this form, these results indicate no significant trend in fire location with time. That is, between 1990 and 2011, no single “Building Start” location shows a consistent increase or decrease in reported fire event frequency. Beginning in the year 2000, fire event location was three times more likely to be reported as ‘Other’ or ‘Not Reported’ as compared to from events in the FEDB reported prior to the year 2000. Tabulated values for the information plotted in Fig. 2 are available in Table A1 of Appendix A.

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**Table 3.** Location ('Building Start') of all fire events in the FEDB

| Building Start | Number of Events | Fraction of all Events | Fraction of known [a] events |
|---|---|---|---|
| 'Auxiliary Building (PWR)' | 87 | 4.4% | 8.0% |
| 'Circulating Water Pump house/Intake Structure' | 48 | 2.4% | 4.4% |
| 'Containment (PWR)' | 133 | 6.7% | 12.3% |
| 'Control building' | 71 | 3.6% | 6.6% |
| 'Diesel Generator Building' | 104 | 5.2% | 9.6% |
| 'Drywell (BWR)' | 23 | 1.2% | 2.1% |
| 'Main Transformer or Switch Yard' | 75 | 3.8% | 6.9% |
| 'Other (Specify in comments)' | 574 | 28.7% | - |
| 'Radwaste Building' | 42 | 2.1% | 3.9% |
| 'Reactor Building (BWR)' | 91 | 4.6% | 8.4% |
| 'Service Water Pump house' | 13 | 0.7% | 1.2% |
| 'Turbine Building' | 396 | 19.8% | 36.6% |
| Not Reported | 341 | 17.1% | - |
| Total | 1998 | 100.0% | 100.0% |

[a] These reported fractions are calculated excluding fire events in which "Building Start" was either not reported or reported as 'Other'

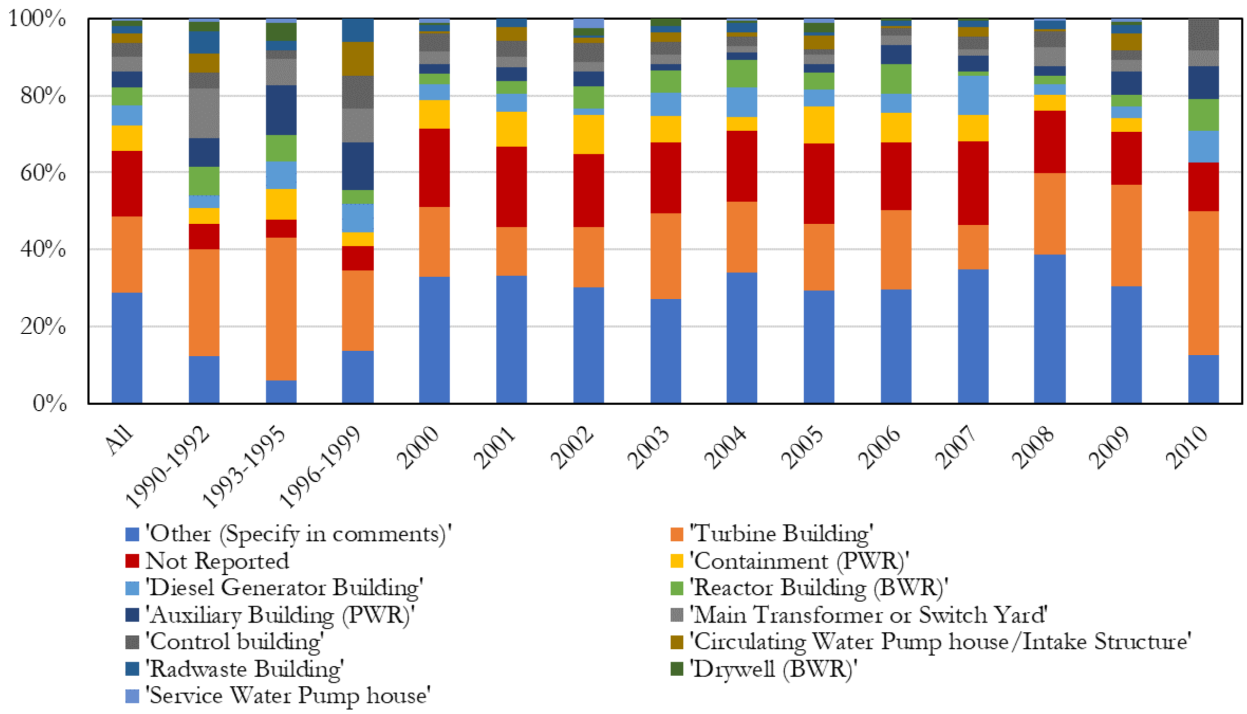


**Figure 2.** Starting location ("Building Start") frequency of reported fire events in the FEDB by year

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### 2.2.2. Fire Cause

Table 4 reports the frequencies of the initial cause (i.e., "fire cause start") of each fire event reported in the FEDB. As seen here, the primary causes of these fire events are electrical failures resulting in overheating, arcing, and/or sparks (HEAF and non-HEAF) [40.3 %], hot work [24.1 %], overheated materials [15%], mechanical malfunction or failure [4.4%], and personnel error (2.9 %). Figure 3 plots the reported cause of all fire events in the FEDB by year. Comparing fire events reported in the 2000s versus in the 1990s, there was a decrease in the number of electrical fires and a significant increase (+45%, relative increase) in the fraction of hot work fires (from 17.3% of fire events between 1990-1999 to 25.2% of fire events between 2000-2011). Between 2008 to 2010, there was a slight decrease in the fraction of events reported as 'Electrical Failure (overheating, spark, HEAF)' but there was a corresponding increase in 'Overheated Material' and 'Electrical arcing or sparks (non-HEAF)', which suggests that there was not a significant decrease in the total fraction of electrical failures leading to fire events reported during these years. Tabulated values for the information plotted in Fig. 3 are available in Table A2 of the Appendix.

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**Table 4.** Cause of all fire events in the FEDB

| Fire Cause Start | Number of Events | Fraction of all Events |
|---|---|---|
| ‘Electrical Failure (overheating, spark, HEAF)' | 1 | 0.1% |
| 'Electrical arcing or sparks (non-HEAF)' | 203 | 10.2% |
| 'Electrical failure resulting in overheating materials' | 588 | 29.4% |
| 'Electrical malfunction/failure' | 1 | 0.1% |
| 'Explosion (hydrogen gas ignition, fuel vapor ignition)' | 1 | 0.1% |
| 'Explosion (hydrogen gas ignition, fuel vapor ignition, other volatile fluid vapor ignition)' | 14 | 0.7% |
| 'False actuation of detector, no ignition or overheat condition' | 5 | 0.3% |
| 'High Energy Arc Fault (HEAF)' | 13 | 0.7% |
| 'Hot work (cutting/welding/grinding/etc.)' | 481 | 24.1% |
| 'Mechanical equipment malfunction/failure' | 87 | 4.4% |
| 'Mechanical malfunction/failure' | 1 | 0.1% |
| 'Misuse of heating devices' | 2 | 0.1% |
| 'Other (other personnel error, natural effect, etc. specify in comments)' | 128 | 6.4% |
| 'Other (personnel error, natural effect, etc. specify in comments)' | 1 | 0.1% |
| 'Overheated Material (lube oil, pump packing, thermal insulation, etc.)' | 299 | 15.0% |
| 'Personnel error during test and maintenance activity' | 11 | 0.6% |
| 'Personnel error: Misuse of heating devices' | 22 | 1.1% |
| 'Personnel error: Misuse of material ignited' | 25 | 1.3% |
| 'Suspicious' | 1 | 0.1% |
| 'Unknown' | 98 | 4.9% |
| Not Reported | 16 | 0.8% |
| Total | 1998 | 100.0% |

Note: Some “Fire Cause Start” categories appear to overlap, such that a given fire event could potentially be defined into multiple categories (e.g., ‘Electrical Failure resulting in overheating materials’ and ‘Overheated Material (…thermal insulation)’). Despite this potential challenge, frequencies and related analysis presented here are reported identically as defined in the FEDB.

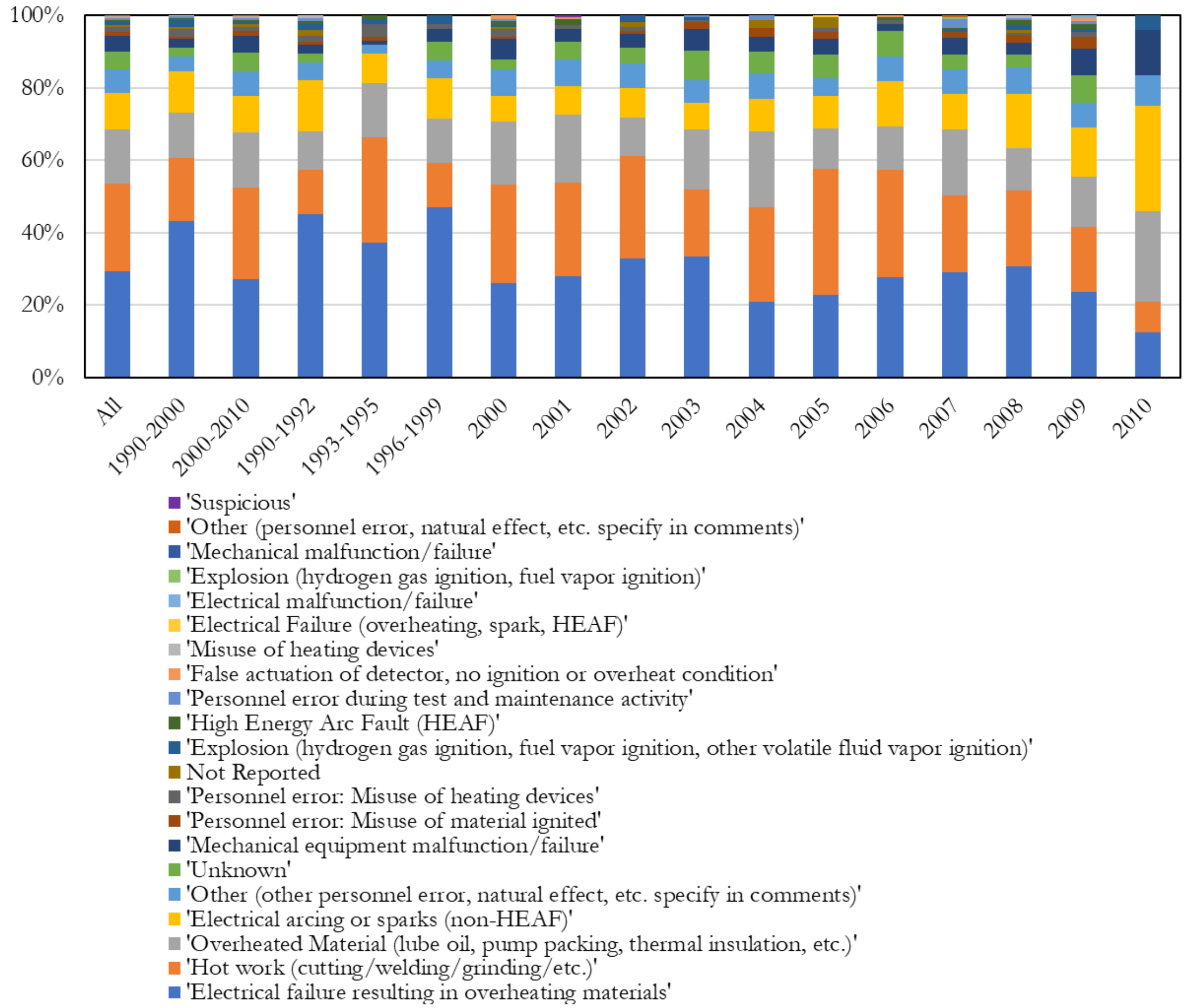


**Figure 3.** Cause of all fire events in the FEDB by year

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### 2.2.3. First Item Ignited

Table 5 provides frequency information for the first item ignited in all fire events reported in the FEDB. Here, first item ignited is identified by the FEDB information category: “Component Start Group”. For each fire event, one of eighteen (18) “Component Start Group” responses could be selected by the fire event report’s author. Section 2.2 of this report focuses on statistics of *all* fire events in the FEDB (i.e., events in which any of these 18 responses were noted as the first item ignited). Section 2.3 focuses only on fire events that have been reported with the “Component Start Group”: ‘Electrical Panel’, which was the most accurate option available in the FEDB for characterizing fire events that occurred in electrical enclosures. As seen in Table 5, this represents 269 unique fire events, or, approximately, 13.5% of all fire events reported in the FEDB. Note: more than half of the incidents in the FEDB list “Component Start Group” as ‘Other’ or ‘Not Reported’. When these incidents are neglected, and thus only considering fire events in which the first item ignited is *explicitly* reported, ‘Electrical Panels’ are listed as the first item ignited for 27.6% of incidents.

Figure 4 plots time-resolved frequencies of the first item ignited for all reported events in the FEDB. This figure reveals that there are no significant year-to-year variations in reported first item ignited; that is, between 1990 and 2011, no single “Component Start Group” option shows a consistent increase or decrease in reported fire event frequency. In years in which the first item ignited is significantly less often reported as ‘Other’ (e.g., 1990-1992, 2010) electrical panels, motors, pumps, and transformers are reported as the first item ignited for a larger fraction of fire events. Tabulated values for the information plotted in Fig. 4 are available in Table A3 of the Appendix.

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**Table 5.** First Item Ignited in all fire events reported in the FEDB

| Component Start Group | Number of Events | Fraction of all Events | Fraction of known [a] events |
|---|---|---|---|
| 'Air Compressors' | 21 | 1.1% | 2.2% |
| 'Batteries' | 9 | 0.5% | 0.9% |
| 'Boilers' | 4 | 0.2% | 0.4% |
| 'Bus Duct' | 5 | 0.3% | 0.5% |
| 'Cable/Wiring' | 98 | 4.9% | 10.0% |
| 'Crane' | 16 | 0.8% | 1.6% |
| 'Dryers' | 4 | 0.2% | 0.4% |
| 'Electric Motor' | 127 | 6.4% | 13.0% |
| 'Electrical panel' | 269 | 13.5% | 27.6% |
| 'Generator' | 105 | 5.3% | 10.8% |
| 'Junction Boxes' | 8 | 0.4% | 0.8% |
| 'Lighting Ballasts' | 28 | 1.4% | 2.9% |
| 'Lube Oil' | 15 | 0.8% | 1.5% |
| 'Other' | 788 | 39.4% | - |
| 'Outlets' | 7 | 0.4% | 0.7% |
| 'Pumps' | 155 | 7.8% | 15.9% |
| 'Transformers' | 105 | 5.3% | 10.8% |
| Not Reported | 234 | 11.7% | - |
| Total | 1998 | 100.0% | 100.0% |

[a] These reported fractions are calculated excluding fire events in which "Component Start Group" was either not reported or reported as 'Other'

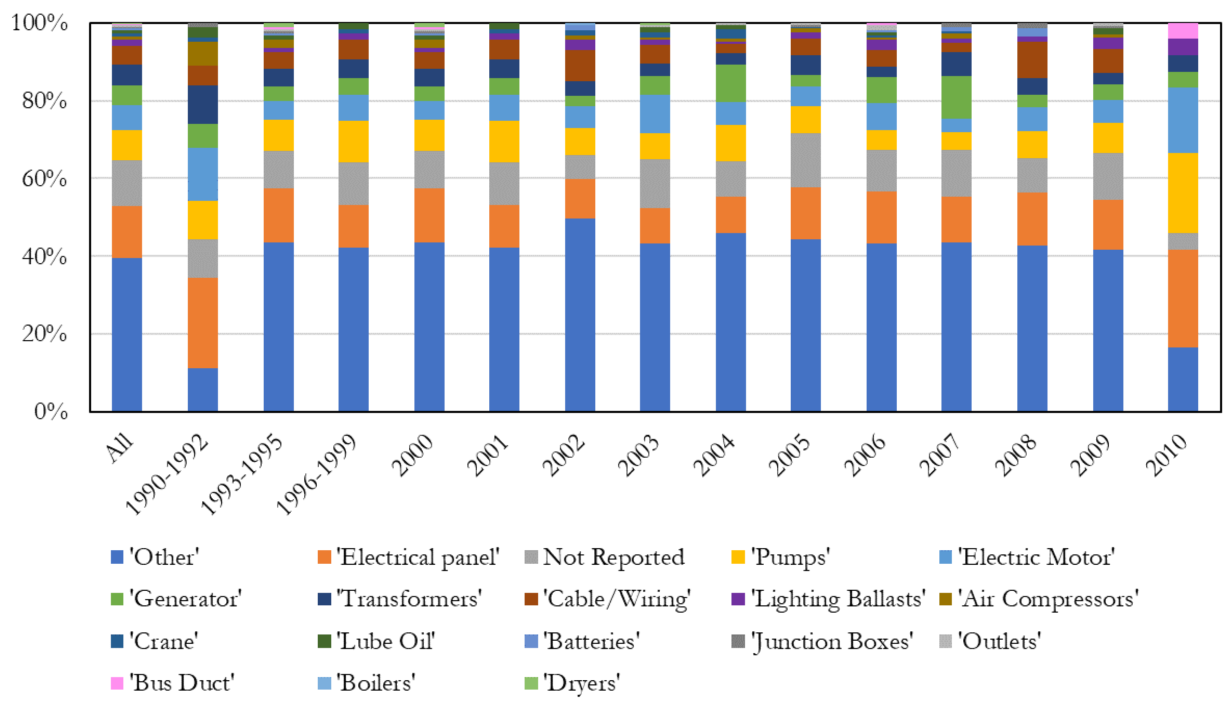


**Figure 4.** First item ignited ("Component Start Group") in all fire events reported in the FEDB by year

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### 2.2.4. Combustible Initiating Group

Table 6 reports the combustible initiating group of each fire event reported in the FEDB. In 79.2% of all fire events, the initiating combustible is a solid material: either in-situ/permanent (e.g., structural or electrical components, interior finish materials, or cable jacketing) or transient (e.g., temporary thermal insulation materials, electrical wiring/equipment, cellulosics, and trash). However, for approximately 10 % of all reported incidents, a flammable or combustible liquid (e.g., grease or lube, fuel, or transformer oil) was involved (i.e., reported as the initiating combustible). Comparing fire events reported after 2000 versus those reported between 1990 to 1999 (Fig. 5), there was a decrease in the fraction of events that were initiated by flammable or combustible liquids (from 14.2 % to 8.8%) and by 'Cable jacketing or electrical insulation materials' (from 13.5% to 2.4%). Primarily, a larger percentage of these more recent events were instead reported with 'Other' or 'Unknown'. Specifically, from 2004 to 2010, the fraction of fires reported to be initiated by 'Other solid in-situ materials' monotonically increased from 47.6 % to 66.7 % of events. Tabulated values for the information plotted in Fig. 5 are available in Table A4 of the Appendix.

**Table 6.** Combustible Initiating Group of all fire events in the FEDB

| Combustible Initiating Group | Number of Events | Fraction of all Events |
|---:|:---:|:---:|
| 'Cable jacketing or electrical insulation materials' | 80 | 4.0% |
| 'Flammable or combustible gas' | 44 | 2.2% |
| 'Flammable or combustible liquid' | 192 | 9.6% |
| 'Other gaseous transient materials' | 18 | 0.9% |
| 'Other liquid transient materials' | 7 | 0.4% |
| 'Other solid in-situ materials' | 988 | 49.4% |
| 'Other solid transient materials' | 594 | 29.7% |
| 'Source Combustible is unknown' | 65 | 3.3% |
| Not Reported | 10 | 0.5% |
| Total | 1998 | 100.0% |

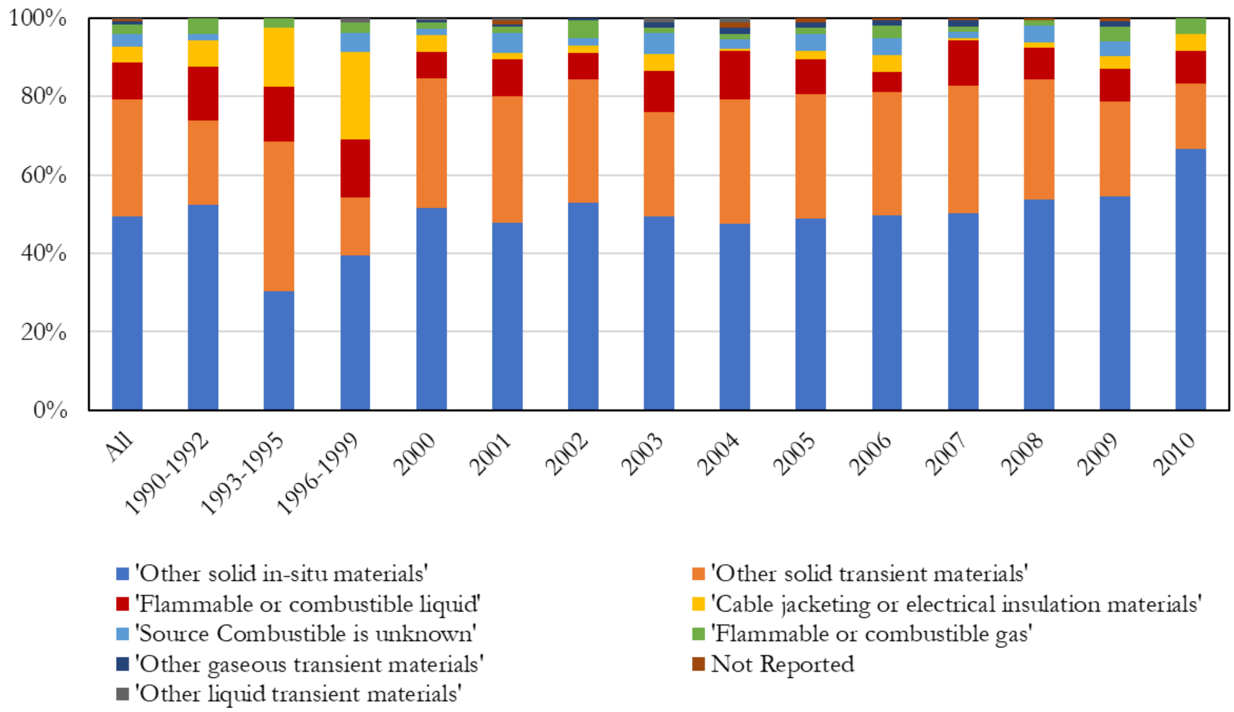


**Figure 5.** Combustible initiating group of all fire events in the FEDB by year

### 2.2.5. Fire Duration

Table 7 provides the reported duration of all fire events in the FEDB. For approximately 40% of events in the FEDB, a fire duration is not reported, thus only 1188 fire events are listed in this table. Note: fire duration could be listed as 0 minutes, thus the lack of information regarding the duration of a fire incident does not necessarily mean that a fire did not occur or was particularly short-lived. Additional review of licensee reports (individual written reports for each fire event) may yield further information on the fire duration of more of the events in the FEDB. This analysis is routinely performed for categories of interest (e.g., HEAF FAQ [33] and NUREG 2178 Volume 2 [34]); however, such a review is non-trivial (as described in Section 1.2, such an effort requires a significant investment of time and resources) and it is therefore assumed that the 1188 events in the FEDB for which fire durations are reported provide sufficient numbers for accurate statistics as required in this manuscript. As seen in Table 7, for the events in which fire duration is reported, the majority (67.1%) of incidents last for less than five minutes. However, approximately 1 out of 8 (12.5%) events in the FEDB are reported to last for twenty minutes or longer.

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As seen in Fig. 6, beginning in the year 2000, when there was a distinct increase in the total number of fires reported each year, there was a corresponding increase in the number of shorter fires (t < 5 min) but no notable change in the number of longer duration fires reported each year. In other words, after 2000, more fire events were reported but a large percentage of these were relatively shorter events. After 2004, the fraction of fire events that were reported each year to last for ten minutes or longer steadily increased from a low of 14.1 % (2004) to 28.6% (2010); however, this is still a smaller fraction of such events as reported between 1990-1999, when 48.9% of all fire events were reported to last for 10 minutes or longer. Tabulated values for the information plotted in Fig. 6 are available in Table A5 of the Appendix.

**Table 7.** Fire Duration of 1188 (of 1998) Fire Events in the FEDB

| **Fire Duration, *t*** | **Number of Events** | **Fraction of all Events** |
|---|---|---|
| $0 \leq t < 5$ min | 797 | 67.1% |
| $5 \leq t < 10$ min | 80 | 6.7% |
| $10 \leq t < 20$ min | 162 | 13.6% |
| $20 \leq t < 30$ min | 47 | 4.0% |
| $30 \leq t < 60$ min | 41 | 3.5% |
| $60 \leq t < 120$ min | 23 | 1.9% |
| $t \geq 120$ min | 38 | 3.2% |
| Total | 1188 | 100.0% |

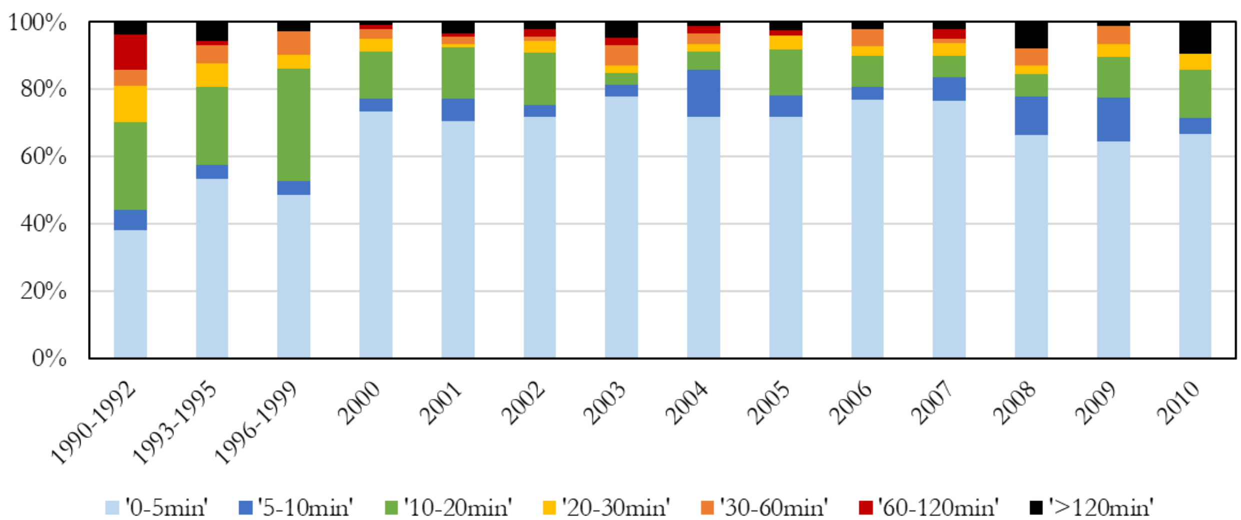


**Figure 6.** "Fire Duration" of all events in the FEDB by year

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### 2.2.6. Challenging Determination

Table 8 shows the reported challenging determination of all fire events in the FEDB. Most events (76.4%) in the FEDB are reported as ‘Not Challenging’ (NC) or ‘Potentially Challenging’ (PC); just under 10% of events in the FEDB are reported as ‘Challenging’ (CH). Section 2.1 of this report provides an overview of how this classification is determined. As seen in Fig. 1, there was a sudden increase (6 to 8 fold) in the number of fire events reported each year in the 2000s versus in the previous decade. Following the trend seen in fire event duration (reported in Section 2.2.5), it appears that this increase was primarily due to the increased reporting frequency of less challenging events, as seen in Fig. 7. Comparing fire events reported after 2000 versus those reported between 1990 to 1999, the fraction reported as not challenging increased from an average of 15.9% to 41.1% and the fraction reported as challenging decreased from an average of 23.9% to 6.6%. After 2000, the number of PC fire events increased, on average, from approximately 32.9% to 40.0% of all reported events each year. Between 2000-2010, there was no significant or systematic increase or decrease in the relative fractions of fire events reported each year as NC, PC, CH, or NC-PC. Tabulated values for the information plotted in Fig. 7 are available in Table A6 of the Appendix.

**Table 8.** Challenging Determination of all events in the FEDB

| Challenging Determination | Number of Events | Fraction of all Events |
|---:|:---:|:---:|
| 'Challenging' | 182 | 9.1% |
| 'Potentially Challenging' | 778 | 38.9% |
| 'Not Challenging' | 748 | 37.4% |
| 'Undetermined (NC-PC)' | 290 | 14.5% |
| Total | 1998 | 100.0% |

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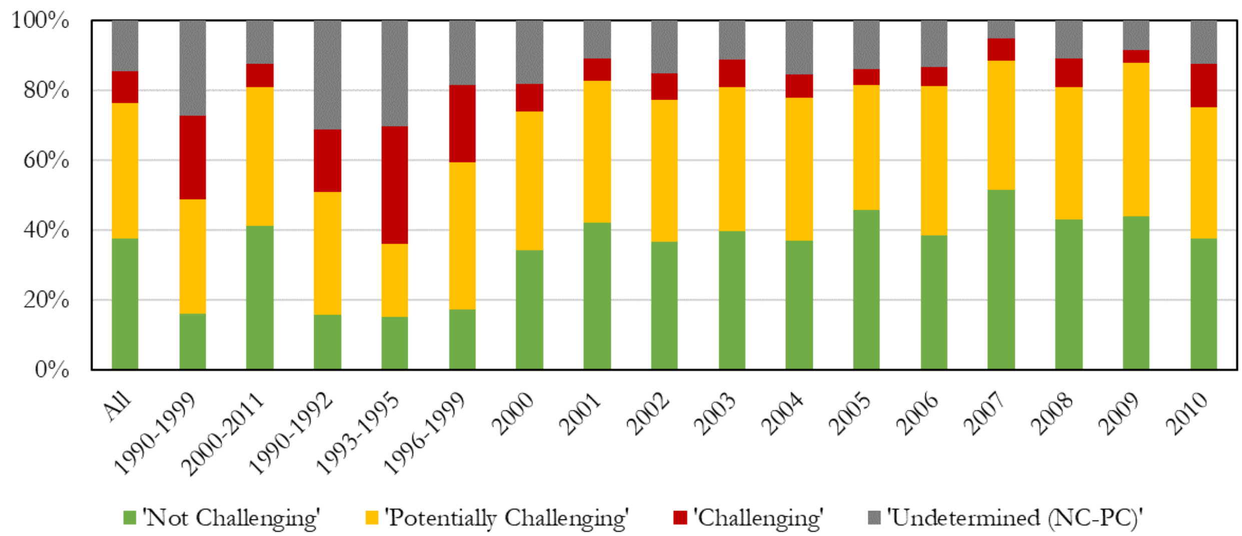


**Figure 7.** "Challenging Determination" of all fire events in the FEDB by year

### 2.2.7. Fire Characterization Type

Table 9 reports the "Fire Characterization Type" of all events in the FEDB. Between 1990-2011 (i.e., all events currently reported in the FEDB), most (52.6%) events reported flaming combustion (either internal or external to the component of origin), 18.1% reported smoldering combustion, 11.3% only reported overheating (without either flaming or smoldering combustion), and 7.0% reported arcs or electric discharges. Explosions are rare, but 14 such events have been reported in the FEDB at the rate of approximately one per year, beginning in the late 1990s. Unlike the trend for some other information categories, it appears that Fire Characterization Type was more carefully reported after 2000 as compared to between 1990-1999: specifically, the fraction of all fire events characterized as 'Other' and 'Unknown' decreased from 27.0% to 1.2% and from 6.2% to 0.6%, respectively. Correspondingly, all other "fire characterization" types, except explosions, were more commonly reported in the 2000s as compare to the 1990s.

To better understand yearly changes in reported fire characterization type, event frequencies were calculated by considering only the fire events for which a "characterization type" location is explicitly defined (i.e., by discounting fire events in which characterization type was not reported or was reported as 'other' or 'unknown'; these may be considered as 'known' cases).

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For this subset of fire events (1850 out of 1998 total events), comparing events that occurred in the 2000s to the 1990s, fewer events reported ‘flaming combustion - external to component’ (35.9% vs. 45.8%) and ‘smoldering combustion - internal to component’ (11.4 % vs. 18.2%) but more events reported ‘smoldering combustion - external to component’ (8.2% vs. 1.6%) and ‘overheating, with no smoldering or flaming’ (13.5% vs. 1.0 %). For most fire types, no significant change in reporting frequency was observed within a given decade; however, as seen in Fig. 8, the fraction of fires characterized by arc/electric discharge steadily increased throughout the 2000s from 5.1% to 17.1% of all ‘known’ cases. Tabulated values of the number of events reported yearly (between 1990 and 2010) with each “Fire Characterization Type” are available in Table A7 of the Appendix.

**Table 9.** Fire Characterization Type of all events in the FEDB

| Fire Characterization Type | Number of Events | Fraction of all Events |
|---:|:---:|:---:|
| 'Arc/electric discharge' | 139 | 7.0% |
| 'Explosion' | 14 | 0.7% |
| 'Fire not observed and fire type indeterminate from post-inspection' | 47 | 2.4% |
| 'Flaming combustion – external to component' | 684 | 34.2% |
| 'Flaming combustion – internal to component' | 367 | 18.4% |
| 'No Fire - False actuation of detection device' | 12 | 0.6% |
| 'Other (specify)' | 99 | 5.0% |
| 'Overheating – no smoldering or flaming combustion' | 225 | 11.3% |
| 'Smoldering combustion – external to component' | 139 | 7.0% |
| 'Smoldering combustion – internal to component' | 223 | 11.2% |
| 'Unknown' | 29 | 1.5% |
| Not Reported | 20 | 1.0% |
| Total | 1998 | 100.0% |

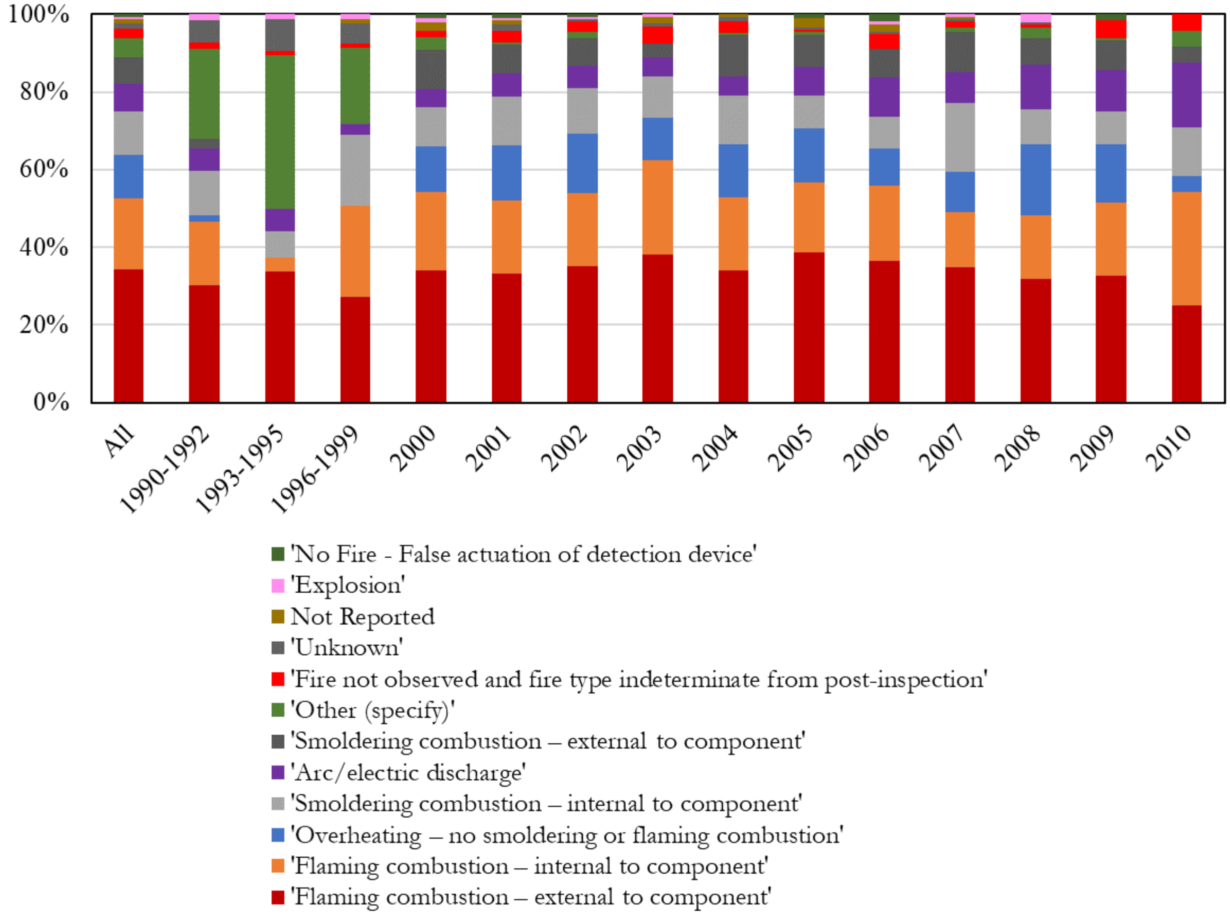


**Figure 8.** Fire Characterization Type of all events in the FEDB by year

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### 2.2.8. Fire Detection and Extinguishing Methods

Tables 10 and 11 list the fire detection and extinguishing methods, respectively, of all fire events reported in the FEDB. As seen here, the majority of the fire events (81.4 %) were first detected either by dedicated fire watch personnel or other plant personnel who were in the vicinity of the fire event as it occurred. Correspondingly, it is unsurprising that a majority (58.4%) of fire events were extinguished by a posted fire watch, staff working on the equipment of fire origin, or other nearby plant personnel. This observation was prevalent during multiple NRC auditing efforts of the FEDB and led to the creation of a specific override case for hot work events so as to not overwhelm the fire initiating frequencies for hot work activities which were controlled in the desired manner. The detailed guidance for applying override categories is provided in Appendix B of EPRI 1025284 [5] and states in part that: "A fire event will be categorized as NC if it is related to a fire caused by a hot work activity that is promptly detected by a posted fire watch and is then promptly suppressed by the fire watch using no more than a single fire extinguisher." Further, as seen in Table 10, only 6.1 % of events were detected by automated fire alarm systems (e.g., fire, smoke, heat, or sprinkler water flow detectors); an additional 4.3 % of reported events were identified by a "Failed Equipment Alarm" (e.g., low oil or tripped pump).

As seen in Figs. 9 and 10, Between 1990 and 2011, there are few significant, systematic trends/variations in reported fire detection or fire extinguishing methods. For detection, prior to 2000, there was, however, a continuous year to year decrease in the fraction of fire events detected by a failed equipment alarm; this value decreased from 13.1% of events reported between 1990-1992 to an average of 3.2% of events reported between 2000-2011. Additionally, during this same time period, there was an increase in the fraction of fires detected by staff conducting tests or maintenance on the equipment of fire origin from 2.8% of events reported between 1990-1999 to 8.7% of events reported between 2000-2011. For suppression, prior to 2000, 41.2% of all reported fires were put out by a team response from the plant fire brigade or response from the plant fire brigade with outside support; however, after 2000, only 11.7% of reported fires required a fire suppression effort of team fire brigade or greater. This trend may support previous observations (reported in Sections 2.2.5 and 2.2.6) that the increase in the number events reported each year in the 2000s (as compared to the

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previous decade) resulted from more frequent reporting of less challenging events. Tabulated values of the number of events reported each year with each fire detection and fire extinguishing method are available in Tables A8 and A9 of the Appendix.

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**Table 10.** Fire Detection Method of all Fire Events in the FEDB

| Fire Detection Method | Number of Events | Fraction of all Events |
|---|---|---|
| 'Dedicated Fire Watch' | 161 | 8.1% |
| 'Failed Equipment Alarm (Tripped pump, Ground, Low Lube Oil etc.)' | 85 | 4.3% |
| 'Fire Watch' | 167 | 8.4% |
| 'Gas Ionization' | 8 | 0.4% |
| 'Installed Fire detector - Type not specified' | 52 | 2.6% |
| 'Main control room staff (e.g., control/instrumentation failures)' | 63 | 3.2% |
| 'Other plant personnel (Roving watchstander or passerby)' | 12 | 0.6% |
| 'Other plant personnel (in vicinity or passerby)' | 1121 | 56.1% |
| 'Roving Firewatch' | 9 | 0.5% |
| 'Smoke detector' | 51 | 2.6% |
| 'Sprinkler or fire-water system flow alarm' | 4 | 0.2% |
| 'Staff conducting test/maintenance on equipment of fire origin' | 156 | 7.8% |
| 'Thermal detector (e.g., temperature or rate of rise)' | 4 | 0.2% |
| 'Ultraviolet flame detector' | 2 | 0.1% |
| 'Unknown' | 84 | 4.2% |
| Not Reported | 19 | 1.0% |
| Total | 1998 | 100.0% |

**Table 11.** Extinguishing method of all Fire Events in the FEDB

| **"Put Out Fire"** | **Number of Events** | **Fraction of all Events** |
|---|---|---|
| 'Fire Watch' | 282 | 14.1% |
| 'Not applicable (fixed suppression, self-extinguished)' | 271 | 13.6% |
| 'Other Plant Personnel' | 607 | 30.4% |
| 'Other [specify]' | 106 | 5.3% |
| 'Plant fire brigade – first responder' | 53 | 2.7% |
| 'Plant fire brigade – team response' | 285 | 14.3% |
| 'Plant fire brigade – with outside support (e.g., local fire department)' | 34 | 1.7% |
| 'Plant personnel that discovered fire' | 209 | 10.5% |
| 'Staff conducting test/maintenance on equipment of fire origin' | 68 | 3.4% |
| 'Unknown' | 44 | 2.2% |
| Not Reported | 39 | 2.0% |
| Total | 1998 | 100.0% |

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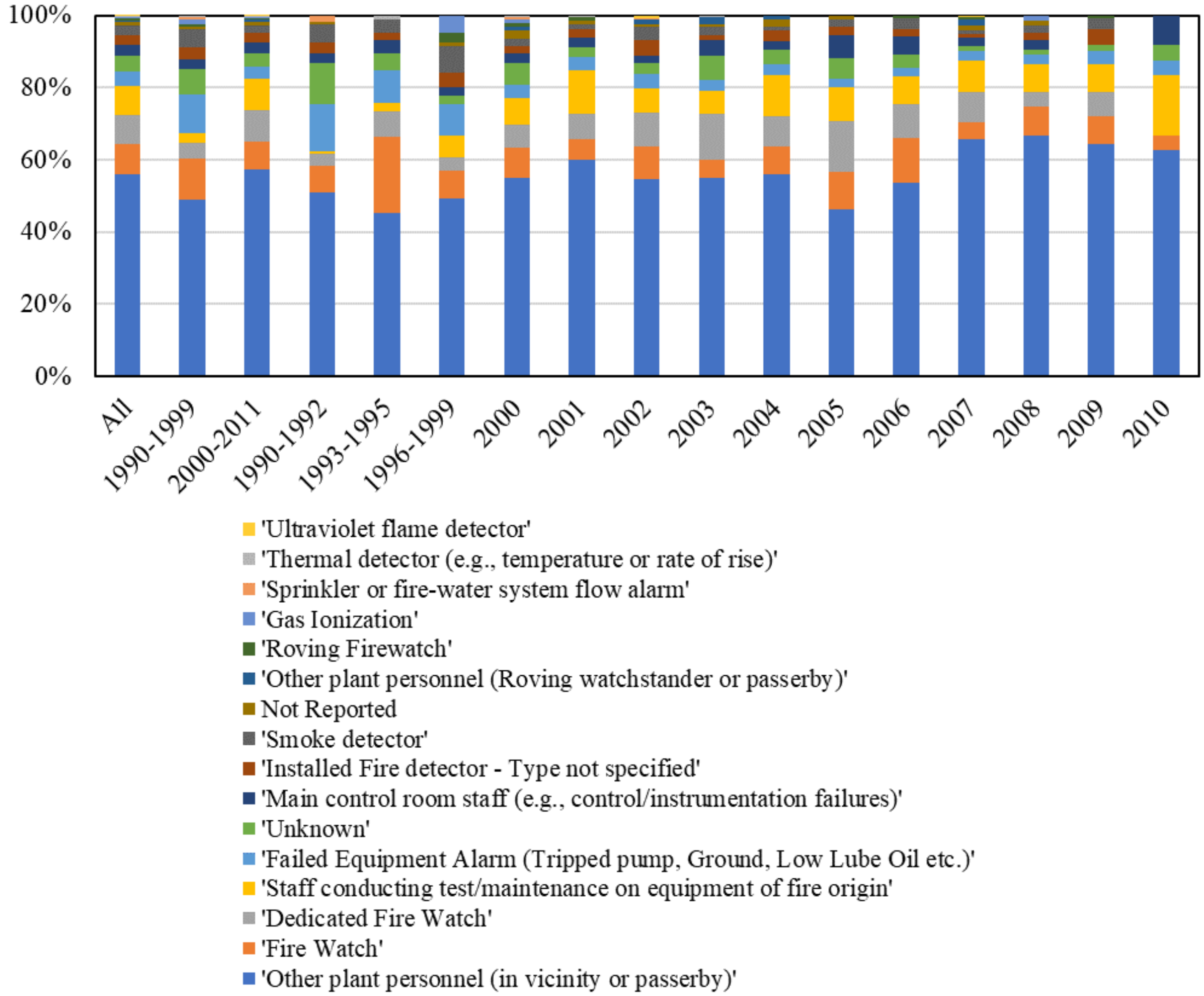


**Figure 9.** Fire Detection Method of all Fire Events in the FEDB by year

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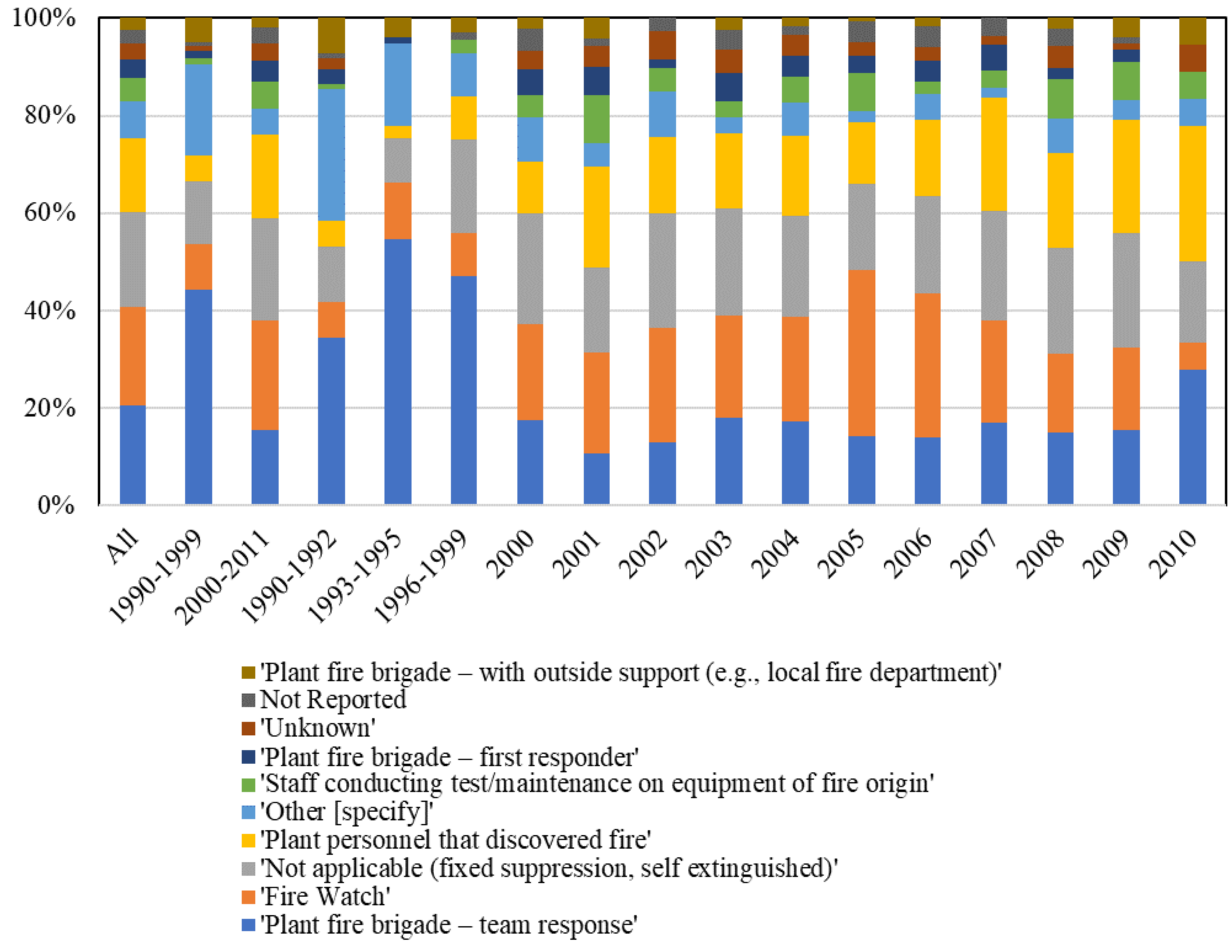


**Figure 10.** Extinguishing method of all Fire Events in the FEDB by year

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### 2.3. Selected Statistics of Fire Events in Electrical Enclosures reported in the FEDB between 1990-2011

#### 2.3.1. Fire Location

Figure 11 plots the relative frequencies of different starting locations ("Building Start") of fire events reported in the FEDB. Here, location frequencies are plotted both for all events reported in the FEDB and just those identified as occurring in electrical enclosures. In this work, electrical enclosure fires reported in the FEDB were identified as those reported with the component start group 'Electrical Panel', as this was the most accurate available option to describe such fire events. Consequently, in Fig. 11 (and throughout section 2.3), when discussing fires that occurred in electrical enclosures, these events are identified in figure legends with the title, 'Electrical Panels'.

For approximately 44% of fire events reported to occur in electrical enclosures (i.e., fire events in the FEDB with the Component Start classification: 'Electrical Panel') fire location is defined as 'Other (Specify in Comments)' or simply 'Not Reported'. This limited starting location reporting frequency for enclosure fires is consistent with the trend for all fire events in the FEDB. When "Building Start" information is available (i.e., when considering only the fire events in electrical enclosures for which a "Building Start" location is explicitly defined), the largest number of reported fires in electrical enclosures start in 'Turbine' (28.0%), 'Control' (17.3%), 'Auxiliary (PWR)' (15.3%), 'Main Transformer or Switch Yard' (8.7%), and 'Reactor' (8.7%) buildings. As seen in Fig. 11, as compared to total reported fire events in NPPs, fires in electrical enclosures are nearly twice as likely (1.9x) to occur in auxiliary (PWR) and 2.6x as likely to occur in control buildings. However, fires in electrical enclosures are approximately three times (3x) *less* likely to occur in Containment (PWR) buildings, as compared to all fire events reported in the FEDB.

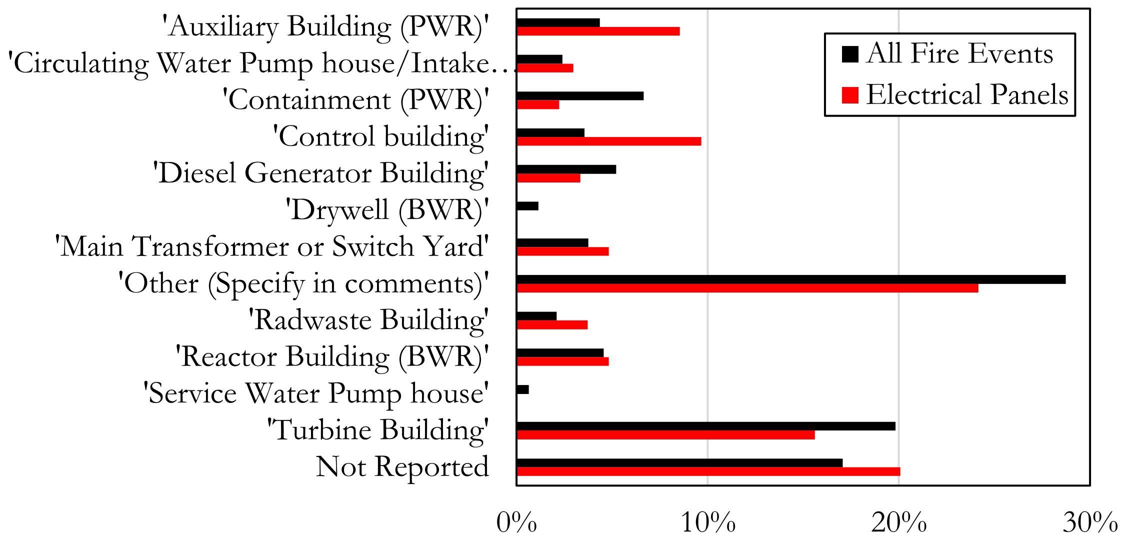


**Figure 11.** Starting location ("Building Start") frequency of fire events in the FEDB: comparison between all reported events and those starting in electrical panels.

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### 2.3.2. Fire Cause

Table 12 reports the total number (and relative frequency) of the initial cause (i.e., "Fire Cause Start") of each electrical enclosure fire event reported in the FEDB. As seen here, 86.2% of these fires were initiated by some kind of electrical failure: arcing, sparks, or overheating (both HEAF and non-HEAF). As seen in Fig. 12, compared to all fire events, electrical enclosure fires are significantly more likely to start due to an electrical failure leading to overheating or electrical arcing or sparks; additionally, although the sample size is small, electrical enclosure fires are also 50% more likely to occur due to a HEAF (as compared to all fires in NPPs). Electrical enclosure fires have not been reported to start due to hot work or failure or malfunction of mechanical equipment (two leading causes of total fires in the FEDB).

Additional information regarding the cause of reported fire events in electrical enclosures was obtained by careful review of more detailed written reports (e.g., licensee event reports) from twenty-six incidents. Selected excerpts from these written reports, which highlight text indicating the failure mechanisms or the events leading to failure in each fire event is provided in Appendix B of this document. The primary focus of this review of written documentation was to determine the specific cause (e.g., components, materials, or conditions) noted to initiate the fire event. In 12 out of 26 of these reports, a circuit breaker was noted in the early stages of the failure analysis; circuit breaker failures were reported to occur due to a variety of reasons including damaged internal components, mechanical flaws, personnel error / installation mistakes, or simply 'unidentified' reasons. Additionally, aging appeared to be at least a contributing factor in five of these events (e.g., due to insulation deterioration, thinning of conductive surfaces, development of high resistance connections, and delamination or mechanical failure of components).

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**Table 12.** Fire Cause Start of electrical panel fire events in the FEDB

| Fire Cause Start | Number of Events | Fraction of Events |
|---|---|---|
| 'Electrical arcing or sparks (non-HEAF)' | 48 | 17.8% |
| 'Electrical failure resulting in overheating materials' | 180 | 66.9% |
| 'Electrical malfunction/failure' | 1 | 0.4% |
| 'Explosion (hydrogen gas ignition, fuel vapor ignition, other volatile fluid vapor ignition)' | 1 | 0.4% |
| 'High Energy Arc Fault (HEAF)' | 3 | 1.1% |
| 'Other (other personnel error, natural effect, etc.)' | 9 | 3.3% |
| 'Overheated Material (lube oil, pump packing, thermal insulation, etc.)' | 6 | 2.2% |
| 'Personnel error during test and maintenance activity' | 3 | 1.1% |
| 'Unknown' | 13 | 4.8% |
| Not Reported | 5 | 1.9% |
| Total | 269 | 100.0% |

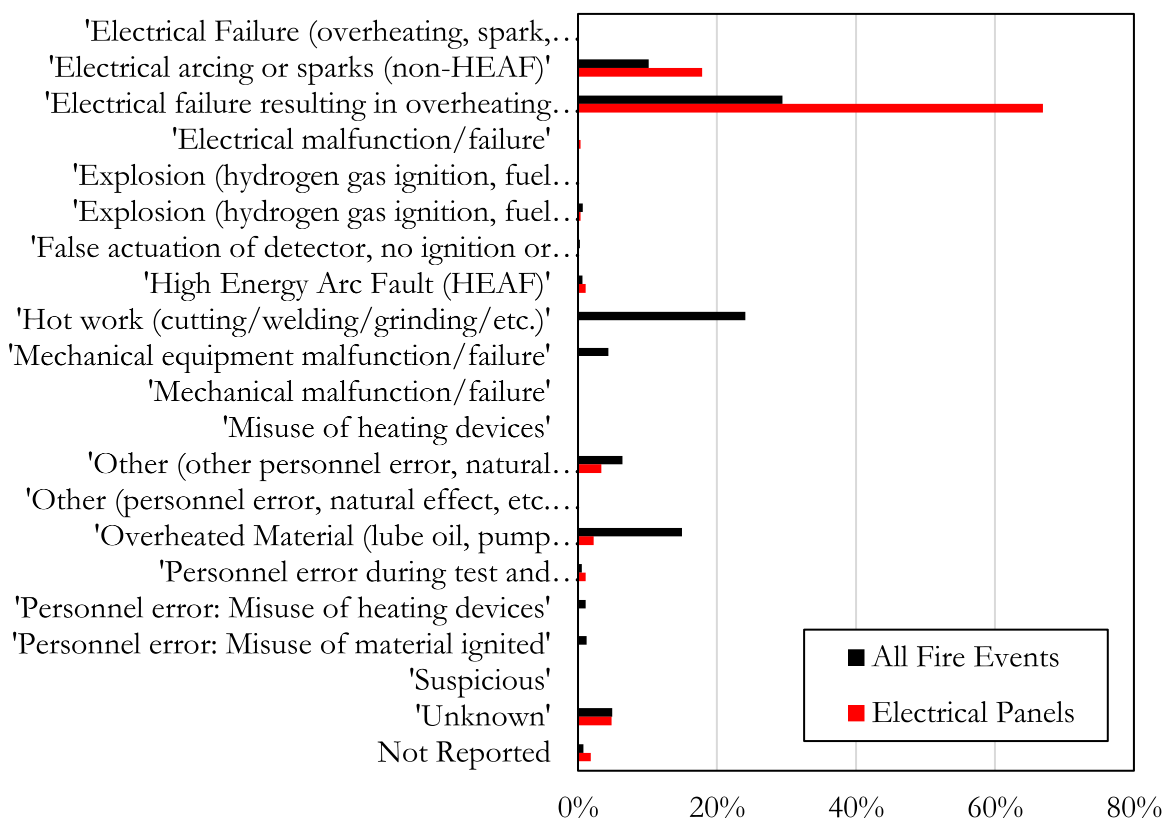


**Figure 12.** "Fire Cause Start" for events reported in the FEDB: comparison between all reported events and those starting in electrical panels.

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### 2.3.3. Combustible Initiating Group

Table 13 reports the combustible initiating group of each electrical enclosure fire reported in the FEDB; these values demonstrate that the combustible initiating group in more than 95 % of electrical enclosure fires was some sort of solid (in-situ) material or cable jacketing/insulation material. As seen in Fig. 13, compared to all fire events in the FEDB, the combustible initiating group for electrical enclosure fires is roughly twice as likely to be a 'solid in-situ material'. Correspondingly, for electrical enclosure fires, it is much less likely (though still reported for 9 out of 269 incidents) that the fire event will be initiated by *transient* solid materials or by flammable or combustible liquids.

**Table 13.** Combustible initiating group of all fire events reported in electrical enclosures in the FEDB

| Combustible Initiating Group | Number of Events | Fraction of Events |
|---|---|---|
| Cable jacketing or electrical insulation materials' | 16 | 5.9% |
| 'Flammable or combustible liquid' | 3 | 1.1% |
| 'Other solid in-situ materials' | 242 | 90.0% |
| 'Other solid transient materials' | 6 | 2.2% |
| 'Source Combustible is unknown' | 2 | 0.7% |
| Total | 269 | 100.0% |

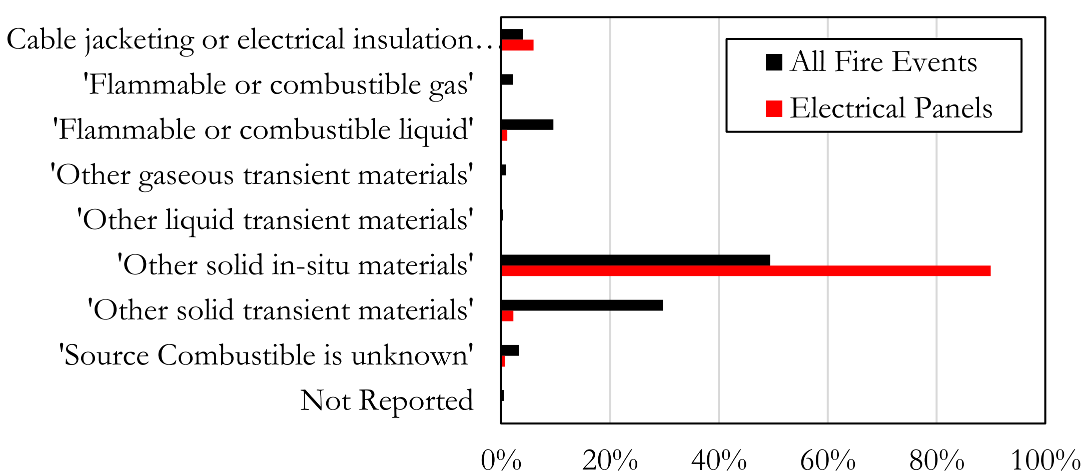


**Figure 13.** "Combustible initiating group" of events reported in the FEDB: comparison between all reported events and those starting in electrical panels.

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### 2.3.4. Fire Duration

Table 14 provides the reported duration of all fire events in electrical enclosures reported in the FEDB. For approximately 40% of these events, a fire duration is not reported, thus only 167 fire events are listed in this table; this fire duration reporting frequency is consistent with that for all fire types reported in the FEDB. Similarly, as for all fire events in the FEDB, for the fire events that occurred in electrical enclosures in which fire duration is reported, the majority (61.1%) of incidents lasted for less than five minutes. However, as seen in Fig. 14, fire events in electrical enclosures are typically longer than the average fire event reported in the FEDB: 31.1 % of fires in electrical enclosures lasted for 10 minutes or longer vs. just 26.2 % of all fire events in the FEDB. Note: this comparison considers *all* fire events (including those deemed NC); NUREG-2169 [32], which considers only CH and PC fires, notes that on average, PC and CH electrical fires have a shorter mean suppression time than all PC and CH fires in NPPs.

**Table 14.** Fire Duration of 168 (of 269) fire events reported in electrical enclosures in the FEDB

| Fire Duration, $t$ | Number of Events | Fraction of Events |
|---|---|---|
| $0 \le t < 5$ min | 102 | 61.1% |
| $5 \le t < 10$ min | 13 | 7.8% |
| $10 \le t < 20$ min | 28 | 16.8% |
| $20 \le t < 30$ min | 6 | 3.6% |
| $30 \le t < 60$ min | 8 | 4.8% |
| $60 \le t < 120$ min | 3 | 1.8% |
| $t \ge 120$ min | 7 | 4.2% |
| Total | 167 | 100.0% |

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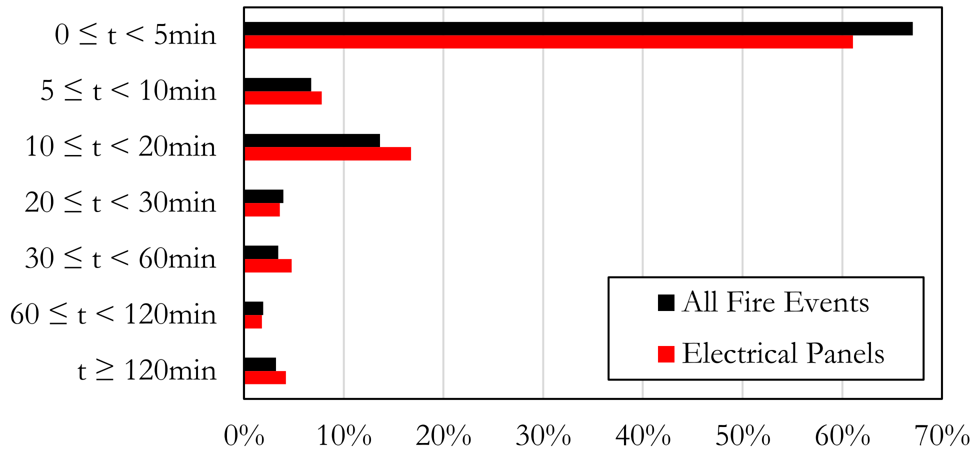


**Figure 14.** Duration of fire events reported in the FEDB: Comparison between all reported events and those starting in electrical panels.

#### 2.3.5. Challenging Determination

Table 15 shows the reported challenging determination of fire events reported in electrical enclosures. Most of these events (78.8%) are reported as either ‘Not Challenging’ (NC) or ‘Potentially Challenging’ (PC); only 8.2% of electrical enclosure fires in the FEDB were reported as ‘Challenging’ (CH). Recall: section 2.1 of this report provides an overview of how challenging determination is defined. As seen in Figure 15, the distribution of fire events in electrical enclosures reported as CH, PC, NC, or NC-PC is quite similar to (match within +/- 2%) the distribution of challenging determinations for all incidents in the FEDB.

**Table 15.** Challenging Determination of all fire events reported in electrical enclosures in the FEDB

| Challenging Determination | Number of Events | Fraction of Events |
|---:|:---:|:---:|
| 'Challenging' | 22 | 8.2% |
| 'Potentially Challenging' | 106 | 39.4% |
| 'Not Challenging' | 106 | 39.4% |
| 'Undetermined (NC-PC)' | 35 | 13.0% |
| Total | 269 | 100.0% |

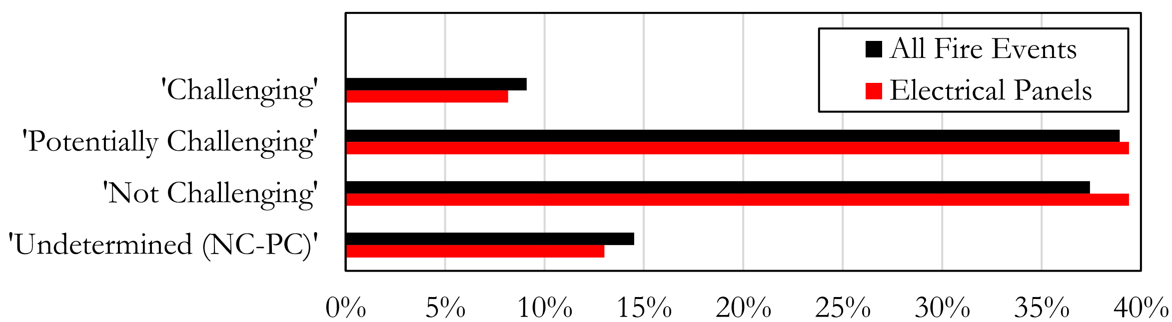


**Figure 15.** Challenging Determination of events reported in the FEDB: Comparison between all reported events and those starting in electrical panels.

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To better understand how fire severity varies given different fire causes, the fraction of fire events with each “Challenging Determination” given a specific fire cause (e.g., overheating, HEAF, personnel error) is plotted in Figure 16. Here, the numbers in bold across the top of the figure indicate the number of fire events with a specific fire cause. As seen here, high energy arc faults (HEAFs) and explosions are particularly dangerous. By definition (see Table 4-2 of the updated FEDB [5]), these fires are reported as challenging and thus having “an observable and substantive effect on the environment outside the initiating source (e.g., damage or ignition of neighboring components).” Because there is significant overlap in the “fire cause start” categories related to electrical failure (i.e., more than 85% of all electrical panel fires are reported to be caused by the related categories ‘electrical arcing or sparking’ or ‘electrical failure resulting in overheating’) it is challenging to define relationships between the challenging determination of these events and their reported causes. In section 2.3.6 of this report, the impact of “Fire Cause Start” on the specific type of reported fire behavior or damage is analyzed in further detail.

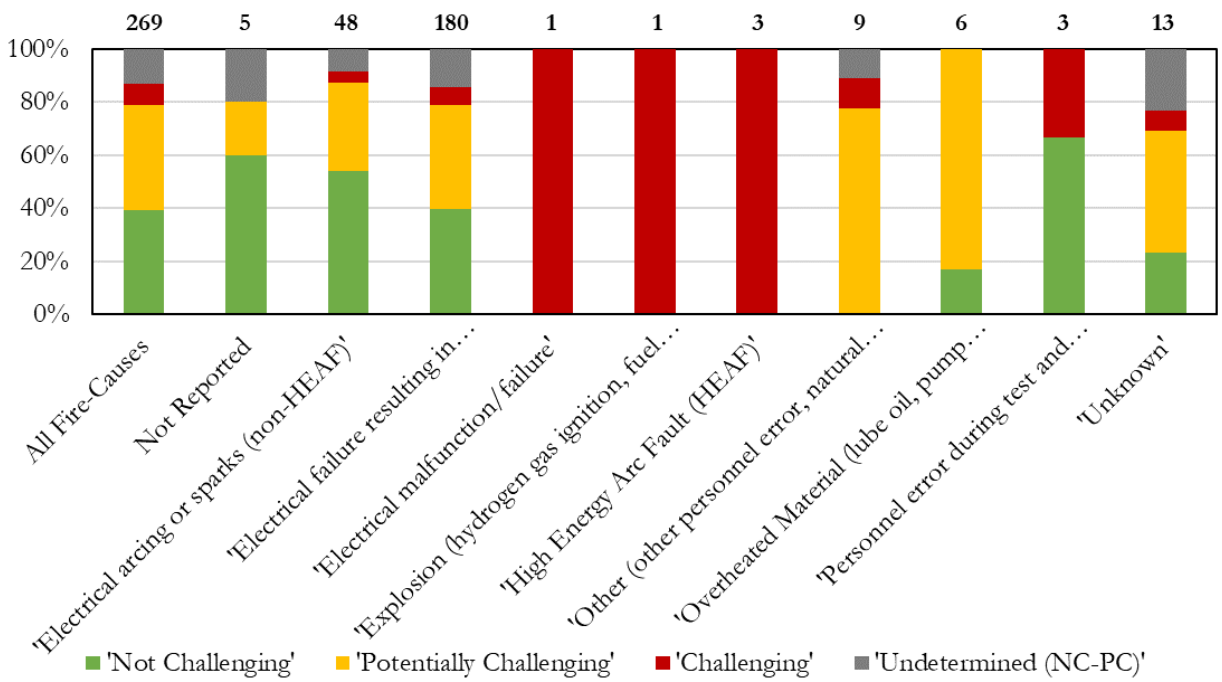


**Figure 16.** “Challenging Determination” of electrical enclosure fires in the FEDB given a specific fire cause.

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### 2.3.6. Fire Characterization Type

Table 16 shows the reported fire characterization type of all fire events in the FEDB that were reported to occur in electrical enclosures. As seen here, 42.4% of these events involved flaming combustion; 14.2 % arcs, electric discharges, or an explosion; 11.9% involved smoldering combustion; and 16.7% were just characterized by overheating. As compared to all fire events reported in the FEDB (see Fig. 17), those that occurred in electrical enclosures were substantially more likely (30.5% vs. 18.4%) to support internal flaming combustion but less likely to support external flaming combustion (11.9% vs 18.4%) and overall less likely to support any kind of flaming (42.4% vs. 52.6%). Fire events in electrical enclosures were twice as likely to be characterized by arcing or electric discharge as the average of all fire events in the FEDB.

**Table 16.** Fire Characterization Type of all fire events reported in electrical enclosures in the FEDB

| Fire Characterization Type | Number of Events | Fraction of Events |
|---|---|---|
| 'Arc/electric discharge' | 37 | 13.8% |
| 'Explosion' | 1 | 0.4% |
| 'Fire not observed and fire type indeterminate from post-inspection' | 13 | 4.8% |
| 'Flaming combustion – external to component' | 32 | 11.9% |
| 'Flaming combustion – internal to component' | 82 | 30.5% |
| 'Other (specify)' | 17 | 6.3% |
| 'Overheating –no smoldering or flaming combustion' | 45 | 16.7% |
| 'Smoldering combustion – external to component' | 1 | 0.4% |
| 'Smoldering combustion – internal to component' | 31 | 11.5% |
| 'Unknown' | 8 | 3.0% |
| Not Reported | 2 | 0.7% |
| Total | 269 | 100.0% |

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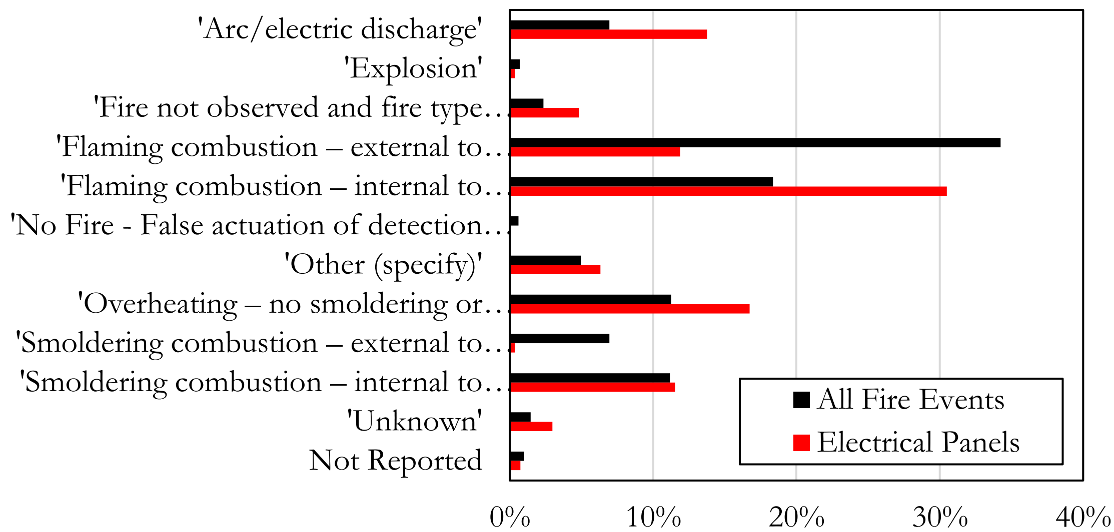


**Figure 17.** Fire Characterization of events reported in the FEDB: Comparison between all reported events and those starting in electrical panels.

The fraction of fire events with each "Fire Characterization Type" given a specific fire cause (e.g., overheating, HEAF, personnel error) is plotted in Fig. 18. Here, the numbers in bold along the top of the figure indicate the number of fire events with a specific fire cause. As noted in Section 2.3.5, the options for "fire cause" are not mutually exclusive and a single cause type may be used to describe a wide range of events; this reflects the difficulty in determining the precise cause of a fire. Electrical malfunction, overheating, and arcing or sparking often occur together, and the option selected when describing the event after it occurs may depends upon the reviewer. Consequently, except for severe events (e.g., fires caused by explosions or HEAF), it is difficult to draw conclusions directly connecting fire cause to severity.

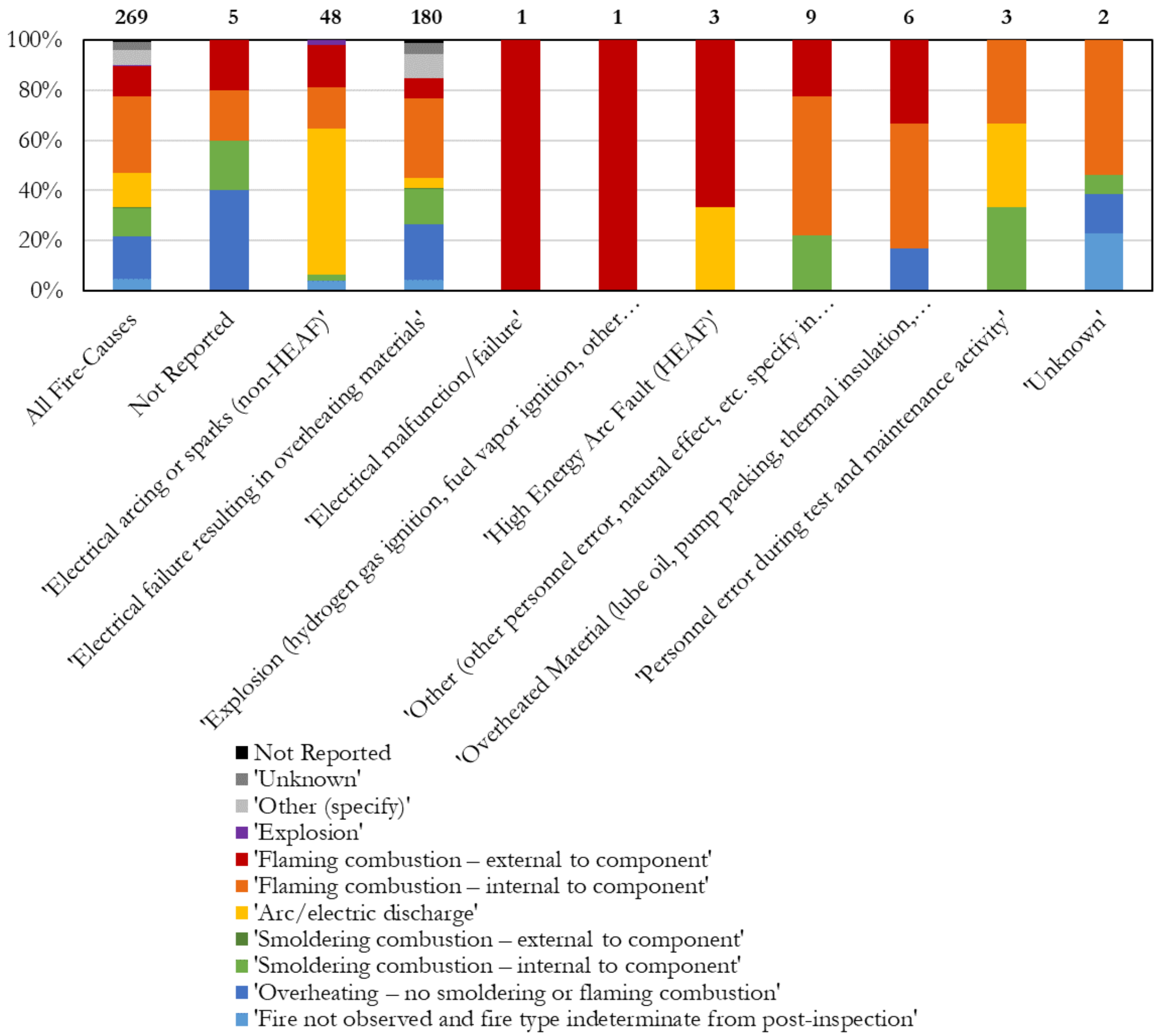


**Figure 18.** Fire Characterization Type of electrical enclosure fires in the FEDB given a specific fire cause.

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### 2.3.7. Fire Detection Method

Table 17 provides the reported fire detection method of all fire events in electrical enclosures in the FEDB. Electrical Enclosure Fires are most likely (69.5 % of reported cases) discovered by personnel in the vicinity of the event as it occurred. As seen in Fig. 19, compared to all fire events in the FEDB, electrical enclosure fires are 3.2x more likely to be detected by control or instrumentation failures in the main control room and 1.8x more likely to be identified by a failed equipment alarm. However, electrical enclosure fires are significantly less likely to be identified by a fire watch (dedicated or otherwise): 1.5 % for electrical panel fires versus 16.9% for all events in the FEDB.

**Table 17.** Fire Detection Method of all fire events reported in electrical enclosures in the FEDB

| Fire Detection Method | Number of Events | Fraction of Events |
|---:|:---:|:---:|
| 'Dedicated Fire Watch' | 1 | 0.4% |
| 'Failed Equipment Alarm (Tripped pump, Ground, Low Lube Oil etc.)' | 20 | 7.4% |
| 'Fire Watch' | 1 | 0.4% |
| 'Gas Ionization' | 3 | 1.1% |
| 'Installed Fire detector - Type not specified' | 11 | 4.1% |
| 'Main control room staff (e.g., control/instrumentation failures)' | 27 | 10.0% |
| 'Other plant personnel (Roving watchstander or passerby)' | 1 | 0.4% |
| 'Other plant personnel (in vicinity or passerby)' | 155 | 57.6% |
| 'Roving Firewatch' | 2 | 0.7% |
| 'Smoke detector' | 6 | 2.2% |
| 'Staff conducting test/maintenance on equipment of fire origin' | 27 | 10.0% |
| 'Unknown' | 13 | 4.8% |
| Not Reported | 2 | 0.7% |
| Total | 269 | 100.0% |

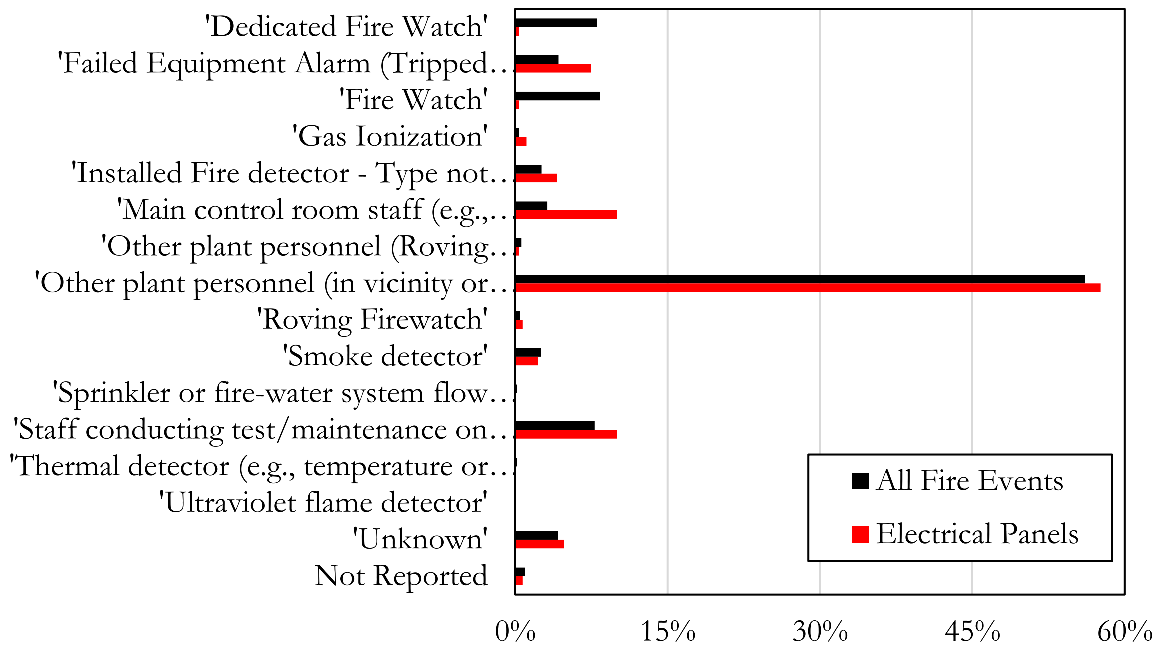


**Figure 19.** Fire Detection Method of events reported in the FEDB: comparison between all reported events and those starting in electrical panels.

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### 2.3.8. Fire Extinguishing Method

Table 18 illustrates the breakdown of extinguishing methods reported in electrical enclosures. The majority of electrical enclosure fires were put out by plant personnel – either those who discovered the fire, were working nearby at the time of the incident, or dedicated fire brigade. Approximately 25% of these fire events self-extinguished or were extinguished by fixed suppression; although this still represents a minority of cases, this is roughly a factor of two increase (relative percent, see Fig. 20) when compared to all NPP fire events. Significantly fewer electrical enclosure fires were put out by the 'fire watch' as compared all fire events reports in NPPs.

**Table 18.** Extinguishing method of all fire events reported in electrical enclosures in the FEDB

| **"Put Out Fire"** | **Number of Events** | **Fraction of Events** |
|---|---|---|
| 'Fire Watch' | 2 | 0.7% |
| 'Not applicable (fixed suppression, self-extinguished)' | 67 | 24.9% |
| 'Other Plant Personnel' | 86 | 32.0% |
| 'Other [specify]' | 16 | 5.9% |
| 'Plant fire brigade – first responder' | 3 | 1.1% |
| 'Plant fire brigade – team response' | 41 | 15.2% |
| 'Plant fire brigade – with outside support (e.g., local fire department)' | 4 | 1.5% |
| 'Plant personnel that discovered fire' | 28 | 10.4% |
| 'Staff conducting test/maintenance on equipment of fire origin' | 10 | 3.7% |
| 'Unknown' | 8 | 3.0% |
| Not Reported | 4 | 1.5% |
| Total | 269 | 100.0% |

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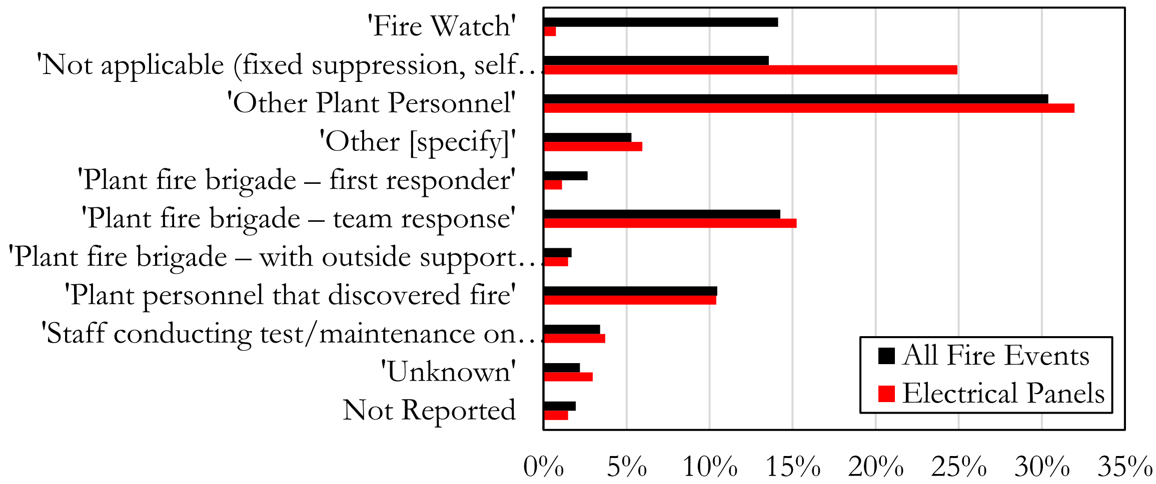


**Figure 20.** Fire Extinguishment method of fires reported in the FEDB: comparison between all reported events and those starting in electrical panels.

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## 3. Summary

Collectively, this report provides a summary of the key characteristics (e.g., ignition sources, severity, and damage type) of electrical enclosure fires that occurred in US nuclear power plants between 1990 and 2011, as reported in the Fire Events Database (FEDB). As detailed here, fires that occurred in electrical enclosures account for the largest share (269 out of 1998; i.e., 13.5 %) of reported fire events in the FEDB. Note: because the “Component Start Group” for more than half of the events in the FEDB is listed as ‘Other’ or ‘Not Reported’, when only considering fire events in which the first item ignited is *explicitly* reported, ‘Electrical Panels’ are listed as the first item ignited for 27.6% of incidents.

For electrical enclosure fires, the majority of events (86.2%) reported their primary cause as some kind of electrical failure: overheating, arcing, or sparks (both HEAF and non-HEAF). Compared to all fire events reported in the FEDB, electrical enclosure fires are significantly (factor of two or three) more likely to start due to an electrical failure leading to overheating, arcing, or sparks and, although the sample size is small, electrical enclosure fires are nearly 50% more likely to occur due to a HEAF. The combustible initiating group in more than 95 % of electrical enclosure fires reported in the FEDB was some sort of solid (in-situ) material or cable jacketing/insulation material. Twenty-six written Licensee Event Reports (LERs) were reviewed to provided further detail on the events leading to ignition in electrical enclosure fires. This analysis revealed that: (a) in twelve (12 of 26) of these events, circuit breaker failure was identified as the as the reported cause of, or the first item to fail in, the fire event and (b) aging appeared to be a primary or contributing factor in five (5 of 26) events (e.g., due to insulation deterioration, thinning of conductive surfaces, development of high resistance connections, and delamination or mechanical failure of components).

Of all fire events reported to occur in electrical enclosures, 8.2 % and 39.4 % were reported as `Challenging' or `Potentially Challenging', respectively. In this reporting system, `Challenging' fire events are those that had ``an observable and substantive effect on the environment outside the initiating source"; `Potentially Challenging' events ``were not judged to be [challenging] events, but … could have led to fire growth, fire spread, equipment damage or cable damage beyond the fire ignition source had the circumstances of the fire event been different". The analysis presented in this report also revealed that fire events in electrical enclosures typically

last longer than the average fire event reported in the FEDB. Collectively, these results demonstrate why electrical cabinets (and high voltage switchgear) are ``commonly identified in fire PRAs as one of the important sources of fire ignition in nuclear power plants" [2].

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## Appendix A: Time Resolved Statistics of descriptions of fire events in the FEDB

**Table A1.** Starting location ("Building Start") frequency of reported fire events in the FEDB by year

| Location | 1990 to 2011 | 1990 to 1992 | 1993 to 1995 | 1996 to 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | NR [a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Auxiliary Building (PWR)' | 87 | 9 | 11 | 10 | 5 | 7 | 6 | 3 | 3 | 4 | 8 | 7 | 4 | 8 | 2 | 0 | 0 |
| 'Circulating Water Pump house/Intake Structure' | 48 | 6 | 0 | 7 | 1 | 7 | 2 | 4 | 2 | 7 | 1 | 4 | 1 | 6 | 0 | 0 | 0 |
| 'Containment (PWR)' | 133 | 5 | 7 | 3 | 14 | 17 | 16 | 11 | 6 | 19 | 12 | 12 | 6 | 5 | 0 | 0 | 0 |
| 'Control building' | 71 | 5 | 2 | 7 | 9 | 8 | 8 | 5 | 4 | 3 | 3 | 6 | 6 | 3 | 2 | 0 | 0 |
| 'Diesel Generator Building' | 104 | 4 | 6 | 6 | 8 | 9 | 3 | 10 | 13 | 9 | 8 | 18 | 4 | 4 | 2 | 0 | 0 |
| 'Drywell (BWR)' | 23 | 3 | 4 | 0 | 1 | 0 | 3 | 3 | 1 | 5 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| 'Main Transformer or Switch Yard' | 75 | 16 | 6 | 7 | 6 | 5 | 4 | 4 | 3 | 5 | 4 | 3 | 7 | 4 | 1 | 0 | 0 |
| Not Reported | 341 | 8 | 4 | 5 | 38 | 40 | 30 | 30 | 31 | 42 | 28 | 38 | 24 | 18 | 3 | 1 | 1 |
| 'Other (Specify in comments)' | 574 | 15 | 5 | 11 | 62 | 63 | 48 | 44 | 57 | 59 | 47 | 61 | 57 | 40 | 3 | 1 | 1 |
| 'Radwaste Building' | 42 | 7 | 2 | 5 | 3 | 4 | 1 | 3 | 4 | 2 | 2 | 3 | 3 | 3 | 0 | 0 | 0 |
| 'Reactor Building (BWR)' | 91 | 9 | 6 | 3 | 5 | 6 | 9 | 9 | 12 | 9 | 12 | 2 | 3 | 4 | 2 | 0 | 0 |
| 'Service Water Pump house' | 13 | 1 | 1 | 0 | 2 | 0 | 4 | 0 | 1 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 'Turbine Building' | 396 | 34 | 32 | 17 | 34 | 24 | 25 | 36 | 31 | 35 | 33 | 20 | 31 | 35 | 9 | 0 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported



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**Table A2.** Cause (“Fire Cause Start”) of all fire events in the FEDB by year

| **Fire Cause** | **1990 to 2011** | **1990 to 1992** | **1993 to 1995** | **1996 to 1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **NR [a]** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Electrical arcing or sparks (non-HEAF)' | 203 | 17 | 7 | 9 | 13 | 15 | 13 | 12 | 15 | 18 | 20 | 17 | 22 | 18 | 7 | 0 | 0 |
| 'Electrical Failure (overheating, spark, HEAF)' | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Electrical failure resulting in overheating materials' | 588 | 55 | 32 | 38 | 49 | 53 | 52 | 54 | 35 | 46 | 44 | 51 | 45 | 31 | 3 | 0 | 0 |
| 'Electrical malfunction/failure' | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 'Explosion (hydrogen gas ignition, fuel vapor ignition)' | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 'Explosion (hydrogen gas ignition, fuel vapor ignition, other volatile fluid vapor ignition)' | 14 | 2 | 1 | 2 | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 0 | 0 |
| 'False actuation of detector, no ignition or overheat condition' | 5 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| 'High Energy Arc Fault (HEAF)' | 13 | 1 | 1 | 0 | 2 | 3 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 0 | 0 | 0 |
| 'Hot work (cutting/welding/grinding/etc.)' | 481 | 15 | 25 | 10 | 51 | 49 | 45 | 30 | 44 | 70 | 47 | 37 | 31 | 24 | 2 | 0 | 1 |
| 'Mechanical equipment malfunction/failure' | 87 | 3 | 1 | 3 | 11 | 7 | 6 | 10 | 7 | 9 | 3 | 8 | 5 | 10 | 3 | 1 | 0 |
| 'Mechanical malfunction/failure' | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Misuse of heating devices' | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Not Reported | 16 | 2 | 0 | 0 | 1 | 0 | 2 | 0 | 4 | 6 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 'Other (other personnel error, natural effect, etc. specify in comments)' | 128 | 6 | 2 | 4 | 14 | 14 | 11 | 10 | 12 | 10 | 11 | 12 | 11 | 9 | 2 | 0 | 0 |



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| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Other (personnel error, natural effect, etc. specify in comments)' | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 'Overheated Material (lube oil, pump packing, thermal insulation, etc.)' | 299 | 13 | 13 | 10 | 33 | 36 | 17 | 27 | 35 | 22 | 19 | 32 | 17 | 18 | 6 | 0 | 1 |
| 'Personnel error during test and maintenance activity' | 11 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 4 | 1 | 1 | 0 | 0 | 0 |
| 'Personnel error: Misuse of heating devices' | 22 | 2 | 3 | 1 | 4 | 2 | 2 | 1 | 0 | 2 | 2 | 0 | 1 | 2 | 0 | 0 | 0 |
| 'Personnel error: Misuse of material ignited' | 25 | 1 | 1 | 0 | 1 | 0 | 1 | 3 | 4 | 4 | 0 | 3 | 3 | 4 | 0 | 0 | 0 |
| 'Suspicious' | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Unknown' | 98 | 3 | 0 | 4 | 5 | 9 | 7 | 13 | 10 | 13 | 11 | 7 | 5 | 10 | 0 | 1 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported

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**Table A3.** First item ignited ("Component Start Group") in all fire events reported in the FEDB by year

| Item Ignited | 1990 to 2011 | 1990 to 1992 | 1993 to 1995 | 1996 to 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | NR [a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Air Compressors' | 21 | 1 | 1 | 5 | 4 | 0 | 2 | 1 | 1 | 2 | 1 | 2 | 0 | 1 | 0 | 0 | 0 |
| 'Batteries' | 9 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 3 | 0 | 0 | 0 | 0 |
| 'Boilers' | 4 | 1 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Bus Duct' | 5 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| 'Cable/Wiring' | 98 | 5 | 4 | 4 | 8 | 10 | 13 | 8 | 4 | 9 | 7 | 4 | 14 | 8 | 0 | 0 | 0 |
| 'Crane' | 16 | 1 | 1 | 1 | 0 | 2 | 2 | 2 | 4 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 'Dryers' | 4 | 1 | 0 | 0 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Electric Motor' | 127 | 6 | 4 | 11 | 9 | 13 | 9 | 16 | 10 | 10 | 11 | 6 | 9 | 8 | 4 | 1 | 0 |
| 'Electrical panel' | 269 | 33 | 10 | 19 | 26 | 21 | 16 | 15 | 16 | 27 | 21 | 21 | 20 | 17 | 6 | 1 | 0 |
| 'Generator' | 105 | 5 | 5 | 5 | 7 | 8 | 4 | 8 | 16 | 6 | 11 | 19 | 5 | 5 | 1 | 0 | 0 |
| 'Junction Boxes' | 8 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 2 | 1 | 0 | 0 | 0 |
| 'Lighting Ballasts' | 28 | 0 | 0 | 0 | 2 | 3 | 4 | 2 | 1 | 3 | 4 | 2 | 2 | 4 | 1 | 0 | 0 |
| 'Lube Oil' | 15 | 1 | 0 | 2 | 2 | 3 | 0 | 2 | 2 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 |
| Not Reported | 234 | 22 | 24 | 8 | 18 | 21 | 10 | 20 | 15 | 28 | 17 | 21 | 13 | 16 | 1 | 0 | 0 |
| 'Other' | 788 | 12 | 21 | 9 | 82 | 80 | 79 | 70 | 77 | 89 | 69 | 76 | 63 | 55 | 4 | 0 | 2 |
| 'Outlets' | 7 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 2 | 0 | 0 | 1 | 0 | 0 | 0 |
| 'Pumps' | 155 | 13 | 6 | 8 | 15 | 20 | 11 | 11 | 16 | 14 | 8 | 8 | 10 | 10 | 5 | 0 | 0 |
| 'Transformers' | 105 | 19 | 8 | 8 | 9 | 9 | 6 | 5 | 5 | 10 | 4 | 11 | 6 | 4 | 1 | 0 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported

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**Table A4.** "Combustible Initiating Group" of all fire events in the FEDB by year

| Combustible Initiating Group | 1990 to 2011 | 1990 to 1992 | 1993 to 1995 | 1996 to 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | NR [a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Cable jacketing or electrical insulation materials' | 80 | 8 | 13 | 18 | 8 | 3 | 3 | 7 | 1 | 4 | 7 | 1 | 2 | 4 | 1 | 0 | 0 |
| 'Flammable or combustible gas' | 44 | 5 | 2 | 2 | 3 | 3 | 7 | 2 | 2 | 3 | 5 | 2 | 2 | 5 | 1 | 0 | 0 |
| 'Flammable or combustible liquid' | 192 | 17 | 12 | 12 | 13 | 18 | 11 | 17 | 21 | 18 | 8 | 20 | 12 | 11 | 2 | 0 | 0 |
| Not Reported | 10 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 2 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| 'Other gaseous transient materials' | 18 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 3 | 3 | 2 | 3 | 0 | 2 | 0 | 0 | 0 |
| 'Other liquid transient materials' | 7 | 0 | 0 | 1 | 1 | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Other solid in-situ materials' | 988 | 64 | 26 | 32 | 97 | 91 | 84 | 80 | 80 | 98 | 79 | 88 | 79 | 72 | 16 | 2 | 0 |
| 'Other solid transient materials' | 594 | 26 | 33 | 12 | 62 | 61 | 50 | 43 | 53 | 64 | 50 | 57 | 45 | 32 | 4 | 0 | 2 |
| 'Source Combustible is unknown' | 65 | 2 | 0 | 4 | 3 | 10 | 3 | 9 | 4 | 9 | 7 | 3 | 6 | 5 | 0 | 0 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported

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**Table A5.** "Fire Duration" of all events in the FEDB by year

| **Duration** | **1990 to 2011** | **1990 to 1992** | **1993 to 1995** | **1996 to 1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **NR [a]** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| '0-5min' | 797 | 32 | 39 | 35 | 74 | 65 | 64 | 67 | 66 | 89 | 76 | 75 | 51 | 49 | 14 | 0 | 1 |
| '5-10min' | 80 | 5 | 3 | 3 | 4 | 6 | 3 | 3 | 13 | 8 | 4 | 7 | 9 | 10 | 1 | 1 | 0 |
| '10-20min' | 162 | 22 | 17 | 24 | 14 | 14 | 14 | 3 | 5 | 17 | 9 | 6 | 5 | 9 | 3 | 0 | 0 |
| '20-30min' | 47 | 9 | 5 | 3 | 4 | 1 | 3 | 2 | 2 | 5 | 3 | 4 | 2 | 3 | 1 | 0 | 0 |
| '30-60min' | 41 | 4 | 4 | 5 | 3 | 2 | 1 | 5 | 3 | 0 | 5 | 1 | 4 | 4 | 0 | 0 | 0 |
| '60-120min' | 23 | 9 | 1 | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| '>120min' | 36 | 3 | 4 | 2 | 1 | 3 | 2 | 4 | 1 | 3 | 2 | 2 | 6 | 1 | 2 | 0 | 0 |
| Total | 1186 | 84 | 73 | 72 | 101 | 92 | 89 | 86 | 92 | 124 | 99 | 98 | 77 | 76 | 21 | 1 | 1 |

[a] Not Reported

**Table A6.** "Challenging Determination" of all events in the FEDB by year

| **Challenging Determination** | **1990 to 2011** | **1990 to 1992** | **1993 to 1995** | **1996 to 1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **NR [a]** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Challenging' | 182 | 22 | 29 | 18 | 15 | 12 | 12 | 13 | 11 | 9 | 9 | 11 | 12 | 5 | 3 | 1 | 0 |
| 'Potentially Challenging' | 778 | 43 | 18 | 34 | 75 | 77 | 65 | 67 | 69 | 72 | 68 | 65 | 56 | 58 | 9 | 1 | 1 |
| 'Not Challenging' | 748 | 19 | 13 | 14 | 64 | 80 | 58 | 64 | 62 | 92 | 61 | 90 | 63 | 58 | 9 | 0 | 1 |
| 'Undetermined (NC-PC)' | 290 | 38 | 26 | 15 | 34 | 21 | 24 | 18 | 26 | 28 | 21 | 9 | 16 | 11 | 3 | 0 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported

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**Table A7.** Fire Characterization Type of all events in the FEDB by year

| Fire Characterization | 1990 to 2011 | 1990 to 1992 | 1993 to 1995 | 1996 to 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | NR [a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Arc/electric discharge' | 139 | 7 | 5 | 2 | 9 | 11 | 9 | 8 | 8 | 15 | 16 | 14 | 17 | 14 | 4 | 0 | 0 |
| 'Explosion' | 14 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 3 | 0 | 0 | 0 | 0 |
| 'Fire not observed and fire type indeterminate from post-inspection' | 47 | 2 | 1 | 1 | 3 | 6 | 4 | 7 | 5 | 1 | 6 | 3 | 1 | 6 | 1 | 0 | 0 |
| 'Flaming combustion – external to component' | 684 | 37 | 29 | 22 | 64 | 63 | 56 | 62 | 57 | 78 | 58 | 61 | 47 | 43 | 6 | 0 | 1 |
| 'Flaming combustion – internal to component' | 367 | 20 | 3 | 19 | 38 | 36 | 30 | 39 | 32 | 36 | 31 | 25 | 24 | 25 | 7 | 2 | 0 |
| 'No Fire - False actuation of detection device' | 12 | 0 | 0 | 0 | 2 | 2 | 1 | 0 | 0 | 2 | 3 | 0 | 0 | 2 | 0 | 0 | 0 |
| Not Reported | 20 | 0 | 0 | 1 | 4 | 2 | 0 | 3 | 1 | 5 | 3 | 1 | 0 | 0 | 0 | 0 | 0 |
| 'Other (specify)' | 99 | 28 | 34 | 16 | 6 | 1 | 3 | 0 | 1 | 2 | 0 | 2 | 4 | 1 | 1 | 0 | 0 |
| 'Overheating – no smoldering or flaming combustion' | 225 | 2 | 0 | 0 | 22 | 27 | 24 | 18 | 23 | 28 | 15 | 18 | 27 | 20 | 1 | 0 | 0 |
| 'Smoldering combustion – external to component' | 139 | 3 | 0 | 0 | 19 | 14 | 11 | 6 | 18 | 16 | 12 | 18 | 10 | 10 | 1 | 0 | 1 |
| 'Smoldering combustion – internal to component' | 223 | 14 | 6 | 15 | 19 | 24 | 19 | 17 | 21 | 17 | 13 | 31 | 13 | 11 | 3 | 0 | 0 |
| 'Unknown' | 29 | 7 | 7 | 4 | 0 | 3 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported

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**Table A8.** Fire Detection Method of all events in the FEDB by year

| Detection Method | 1990 to 2011 | 1990 to 1992 | 1993 to 1995 | 1996 to 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | NR [a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Dedicated Fire Watch' | 161 | 4 | 6 | 3 | 12 | 13 | 15 | 21 | 14 | 28 | 15 | 15 | 6 | 9 | 0 | 0 | 0 |
| 'Failed Equipment Alarm (Tripped pump, Ground, Low Lube Oil etc.)' | 85 | 16 | 8 | 7 | 7 | 7 | 6 | 5 | 5 | 5 | 4 | 5 | 4 | 5 | 1 | 0 | 0 |
| 'Fire Watch' | 167 | 9 | 18 | 6 | 16 | 11 | 14 | 8 | 13 | 21 | 20 | 8 | 12 | 10 | 1 | 0 | 0 |
| 'Gas Ionization' | 8 | 0 | 0 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| 'Installed Fire detector - Type not specified' | 52 | 4 | 2 | 3 | 4 | 5 | 7 | 2 | 5 | 5 | 3 | 2 | 3 | 6 | 0 | 1 | 0 |
| 'Main control room staff (e.g., control/instrumentation failures)' | 63 | 3 | 3 | 2 | 5 | 5 | 3 | 7 | 4 | 13 | 8 | 4 | 4 | 0 | 2 | 0 | 0 |
| Not Reported | 19 | 1 | 0 | 1 | 4 | 2 | 1 | 1 | 3 | 2 | 0 | 2 | 2 | 0 | 0 | 0 | 0 |
| 'Other plant personnel (in vicinity or passerby)' | 1121 | 62 | 39 | 40 | 103 | 114 | 87 | 89 | 94 | 93 | 85 | 115 | 98 | 85 | 15 | 0 | 2 |
| 'Other plant personnel (Roving watchstander or passerby)' | 12 | 0 | 0 | 0 | 2 | 0 | 2 | 3 | 2 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| 'Roving Firewatch' | 9 | 0 | 0 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| 'Smoke detector' | 51 | 6 | 3 | 6 | 4 | 2 | 6 | 4 | 2 | 4 | 5 | 2 | 3 | 4 | 0 | 0 | 0 |
| 'Sprinkler or fire-water system flow alarm' | 4 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Staff conducting test/maintenance on equipment of fire origin' | 156 | 1 | 2 | 5 | 14 | 23 | 11 | 10 | 19 | 19 | 12 | 15 | 11 | 10 | 4 | 0 | 0 |
| 'Thermal detector (e.g., temperature or rate of rise)' | 4 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 'Ultraviolet flame detector' | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 'Unknown' | 84 | 14 | 4 | 2 | 11 | 5 | 5 | 11 | 7 | 11 | 6 | 2 | 2 | 2 | 1 | 1 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported

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**Table A9.** Fire Extingsuishing Method ("Put Out Fire") of all events in the FEDB by year

| **Extingsuishing Method** | **1990 to 2011** | **1990 to 1992** | **1993 to 1995** | **1996 to 1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **NR [a]** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 'Fire Watch' | 282 | 7 | 9 | 6 | 26 | 25 | 25 | 26 | 25 | 48 | 34 | 23 | 14 | 13 | 1 | 0 | 0 |
| 'Not applicable (fixed suppression, self extinguished)' | 271 | 11 | 7 | 13 | 30 | 21 | 25 | 27 | 24 | 25 | 23 | 25 | 19 | 18 | 3 | 0 | 0 |
| Not Reported | 39 | 1 | 0 | 1 | 6 | 2 | 3 | 5 | 2 | 6 | 5 | 4 | 3 | 1 | 0 | 0 | 0 |
| 'Other [specify]' | 106 | 26 | 13 | 6 | 12 | 6 | 10 | 4 | 8 | 3 | 6 | 2 | 6 | 3 | 1 | 0 | 0 |
| 'Other Plant Personnel' | 607 | 26 | 9 | 13 | 56 | 69 | 52 | 39 | 52 | 60 | 44 | 64 | 60 | 55 | 6 | 0 | 2 |
| 'Plant fire brigade – first responder' | 53 | 3 | 1 | 0 | 7 | 7 | 2 | 7 | 5 | 5 | 5 | 6 | 2 | 2 | 0 | 1 | 0 |
| 'Plant fire brigade – team response' | 285 | 33 | 42 | 32 | 23 | 13 | 14 | 22 | 20 | 20 | 16 | 19 | 13 | 12 | 5 | 1 | 0 |
| 'Plant fire brigade – with outside support (e.g., local fire department)' | 34 | 7 | 3 | 2 | 3 | 5 | 0 | 3 | 2 | 1 | 2 | 0 | 2 | 3 | 1 | 0 | 0 |
| 'Plant personnel that discovered fire' | 209 | 5 | 2 | 6 | 14 | 25 | 17 | 19 | 19 | 18 | 18 | 26 | 17 | 18 | 5 | 0 | 0 |
| 'Staff conducting test/maintenance on equipment of fire origin' | 68 | 1 | 0 | 2 | 6 | 12 | 5 | 4 | 6 | 11 | 3 | 4 | 7 | 6 | 1 | 0 | 0 |
| 'Unknown' | 44 | 2 | 0 | 0 | 5 | 5 | 6 | 6 | 5 | 4 | 3 | 2 | 4 | 1 | 1 | 0 | 0 |
| Total | 1998 | 122 | 86 | 81 | 188 | 190 | 159 | 162 | 168 | 201 | 159 | 175 | 147 | 132 | 24 | 2 | 2 |

[a] Not Reported

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## Appendix B: Summary of Reported Causes of Selected Fire Events

In a previous report providing guidance for PRAs in NPPs (NUREG 6738), it has been noted that, “the most useful information [for a given fire event is] typically obtained from narrative descriptions of the fire, through discussions with knowledgeable individuals and through the reconstruction of the detailed time line or chain of events for each fire. This reinforces… [that] the details of an incident are extremely important and the recording or cataloging of incidents using a formatted reporting structure often masks information that at some later point may be of specific interest” [2]. Detailed source documentation (e.g., Licensee Event Reports, LERs, Daily Event Reports, DERs, or Root Cause Analyses) were only embedded in the available version of the FEDB for a small number of events. Though the NRC, in conjunction with a national laboratory contractor, maintains a database of LERs that could be used for further review, the database has been non-functional for several months (at the time of writing this report) with no estimate on future availability. Any further review would require a manual search for the appropriate source documentation, which is resource intensive. Such an expenditure of resources is not consistent with the goal of this effort, which is to develop a holistic understanding of ignition phenomena. Therefore, the LERs that were reviewed for this effort are only those that were readily available through the FEDB.

In total, detailed reports from 26 fire events (all of which indicated ‘Electrical Panel’ as their “Component Start Group”) were carefully reviewed. These 26 reports varied in length from 1 to 452 pages (LERs were typically between 5 and 10 pages long) and provided varying levels of detail from short summaries of the incident to exhaustive reports including administrative and operability notes, photographs of incident damage and further analysis testing, root cause evaluation reports with event narratives, and summaries of corrective actions taken. For this manuscript, the primary focus of this review effort was to determine the primary cause of the fire and the factors contributing to ignition and early fire growth.

Appendix B provides a summary of the information gathered from each of these events including: Fire ID number, LER (or other report type) number, the fire characterization type and challenging determination, and excerpts of the written description of the cause of (or contributing factors to) the fire event. Whenever possible, excepts provided here are taken verbatim from the detailed reports as direct quotations. Minimal editing has been provided for clarity and conciseness; additions, clarifications, and/or comments are indicated by square brackets. Emphasis has been added, by highlighting key text **in bold**, based on the reviewers' (i.e., the authors of this document) judgement as to the most important elements of these detailed reports. Table B1 provides a brief summary of the reported causes and/or first items to fail or to ignite in each of these 26 fire events.

In some cases, only the first component to fail (but not its reason for failing) is reported: e.g., Fire ID 106 ("Event was caused when breaker faulted, causing arcing, localized overheating and starting a fire within the breaker cubicle … the exact cause of the breaker fault could not be conclusively determined"). For some of these reports (e.g., Fire ID 146) information regarding the location, potential cause, and behavior of the fire is even less precise due to limited description provided in the original report (DER). It should be noted that the summary provided in this section is not exhaustive, and a complete review of all reported information on fire events in the FEDB is available by directly reviewing all plant reports, including event reports, corrective action reports, and root cause analyses.

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**Table B1.** Reported root cause of fire events as described in associated written reports

| Fire ID | Reported Cause |
|---|---|
| 18 | "Personnel stuck his hands into the open breaker cubicle… fire and explosion resulted" |
| 29 | Poor alignment of power stabs into their respective bus bars created a high resistance connection, which led to overheating |
| 38 | "Cause of… breaker failure was a short in the run contactor coil" |
| 41 | "Poor fit between the primary disconnects (RWS breaker) and the stabs led to arcing in the breaker cubicle when the 'D' pump was started, resulting in the fire." |
| 45 | "Electrical fire started in the intake structure outside the plant protected area" |
| 69 | "The cause of the fire appears to have been the breakdown of insulation in a [control cable]… result of the accumulated effects of 25 years of deterioration" |
| 74 | "Improper automatic bus transfer… when the UAT breaker tried to open, it failed internally creating ionizing gases." |
| 83 | "Delamination [(mechanism bonding failure)] of transformer core resulting in a short… resulting in an electrical overload" |
| 89 | "An internal short in the control power transformer (NRC Cause Code X) which caused the failure of the HGA control relay" |
| 98 | "Fire in emergency diesel generator control pane… heavy smoke" |
| 106 | "Event was caused when breaker faulted, causing arcing, localized overheating and starting a fire within the breaker cubicle." |
| 112 | Poor electrical connection [due to thinning of silver coating on connection surface over time] between the breaker… primary disconnect assembly and the 1MY bus stab… [this] led to a high resistance connection and overheating" |
| 119 | "Breaker…failed to clear arc and the incoming breaker tripped on overload… fire appears to have occurred within the breaker compartment" |
| 142 | "There were no flames, only smoke." |
| 144 | "[A] misalignment of circuit breaker stabs [created a] high resistance connection that likely resulted in arcing" |
| 152 | "[High resistance connection at bus/stab interface lead to arcing], which caused to a phase to phase fault that vaporized the bottom of each bus bar, leading to ignition of MCC plastic base pan/space heater wires" |
| 161 | "Unidentified failure in circuit breaker. Control rod mechanism in breaker tripped, 30 minutes later, a 6 in. [15 cm] flame was observed… The cause of the circuit breaker failure has not been identified" |
| 180 | "The failure of circuit breaker 52/24 to open and isolate 4kV Bus 4 is the root cause of the fire event … The circuit breaker failed due to mechanical flaw in the trip circuit. [This lead to a] feeder cable failure in which the cable insulation failed, resulting in an arc flash and cable fire." |
| 188 | "lightning strike" |
| 191 | "Smoke coming from… breaker" |
| 203 | Motor Control Center burned |
| 206 | Missing piece for "center phase shorting bus" allowed field breaker to continuously short during operation |
| 20357 | Accident: "an internal cover plate fell, contacted electrical bus, and caused a phase to ground short circuit… after the cover plate shifted, an explosion occurred" |

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Fire ID:18 | LER: (DER) 18886

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Four workmen were modifying a current transformer. **One of the contract personnel stuck his hands into the open breaker cubicle, touching an energized 4160 v line in the cubicle and electrocuted himself**. two were "very seriously" injured. The third individual had lesser injuries. **The fire and explosion resulted from the individual killed, and cubicle cable burning.**

---

Fire ID: 29 | LER: 3681991007

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Initial inspection revealed that the "C" and "B" phase **power stabs had not been properly engaged with their respective bus bars**. Contact between the stabs and bus bars was insufficient to carry the current with the turning gear running at its higher speed. This resistance created a large amount of heat which melted part of the breaker cubicle stabs. The molten metal came into contact with the ground bus located below the stabs. This resulted in a trip of the main feeder breaker for 2B64.

[In summary: poor alignment of power stabs into bus bars produced high-resistance overheating, which led to - melting and eventually smoking/flaming]

---

Fire ID: 38 | LER: 2491992010

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Challenging

Description / Detailed Failure / Cause:

The **cause** of the 3A RPS MG Set Drive Motor Breaker failure was **a short in the run contactor coil. This short drew excessive current in the control power transformer** causing it to fail. Maintenance history [for both unit's RPS MG Set Drive Motor Breakers]: Four previous corrective maintenance activities performed subsequent to reportable events.

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Fire ID: 41 | LER: [3311992010]

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Investigation into the cause of the fire identified that the fit between the 'D' RWS breaker primary disconnects and the associated breaker cubicle stabs was inadequate. The **poor fit between the disconnects and the stabs led to arcing in the breaker cubicle** when the 'D' pump was started, **resulting in the fire**.

The remaining RWS breakers, which had recently been replaced along with the 'D' breaker, as part of a design modification package, were found to be susceptible to the same problem. It was later determined that the root cause of the event was a lack of thorough inhouse review of the breaker interface design specifications during the design process.

---

Fire ID: 45 | LER: (DER) 23956

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

At 0415, an electrical fire started in the intake structure outside the plant protected area. At 0425, licensee declared an unusual event due to a fire lasting longer than 10 minutes. **Licensee is investigating the cause of the fire.**

---

Fire ID: 69 | LER: 2931994005

Fire Characterization Type: Other
Challenging Determination: Undetermined (NC-PC)

Description / Detailed Failure / Cause:

ACB-104 (Air Circuit Breaker) being closed lead to / was one step in a series of failures that led to the scram from load rejection. The cause of ACB-104 self-closing on August 28, 1994, was fire damaged cables in its control cabinet (located in the switchyard). **The cause of the fire appears to have been the breakdown of insulation in an ACB-104 control cable**. The insulation breakdown was located **where the insulation came in contact with a protruding tap of a wire wound power resistor in the control cabinet**. The insulation breakdown is believed to be the **result of the accumulated effects of 25 years of deterioration** due to water intrusion, the contact with the resistor and intermittent heat generated by the resistor.

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Fire ID: 74 | LER: 3821995002

Fire Characterization Type: Flaming combustion – external to component
Challenging Determination: Challenging

Description / Detailed Failure / Cause:

Initiated by a failed phase C lightning arrestor. **The root cause of the fire in the A2 switchgear was the improper automatic bus transfer from the UAT** [Unit Auxiliary Transformer] **to the SUT** [Start up Transformer]**.** The "fast dead bus transfer" allowed the SUT breaker to close although the UAT breaker failed to trip. This condition caused the A2 bus to temporarily connect SUT 'A' to the main generator [TB-GEN] which then provided power to the grid via the UAT and A2 bus at that time. **When the UAT breaker attempted to open, it tried unsuccessfully to interrupt the current.** During this time, the main generator was rotating faster than the system frequency. Just prior to the time the breaker attempted to open, the Waterford switchyard fault recorder indicated the **current flow on the 4 KV bus to be excessive and approaching 180 degrees out of phase. When the UAT breaker tried to open, it failed internally creating ionizing gases. The ionizing gases were the most likely cause of the fire in the A2 switchgear.**

---

Fire ID: 83 | LER: 5281996001

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

The **root cause of failure** for the ELIT [Emergency Lighting Transformer] has been determined to be a loss of mechanical bonding of the varnish insulation material within the third harmonic choke, thereby allowing normal transformer vibration to result in **delamination of the transformer core** (SALP [Cause Code B: Design). **This delamination failure resulted in a short of the loose core plate to the transformer winding and an intermittent open winding in the third harmonic choke, resulting in an electrical overload and fire in the fifth harmonic choke.**

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Fire ID: 89 | LER: 2491996016

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Both the **Control transformer** in MCC 28-1, **and the HGA control relay suffered internal damage as a result of an electrical fault.** The remaining components were externally damaged as a result of exposure to excessive heat. The failure analysis identified the **cause of the failure was an internal short** in the control power transformer (NRC Cause Code X) which caused the failure of the HGA control relay.

---

Fire ID: 98 | LER: (DER) 34889

Fire Characterization Type: Smoldering combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Alert declared due to fire in emergency diesel generator control panel: an operator noticed heavy smoke coming from the EDG [Emergency Diesel Generator] control panel. The fire self-extinguished. Based upon visual inspection, damage appears to be limited to the local control panel.

---

Fire ID: 106 | LER: 3622001001

Fire Characterization Type: Arc/electric discharge
Challenging Determination: Challenging

Description / Detailed Failure / Cause:

**Event was caused when breaker faulted, causing arcing, localized overheating and starting a fire within the breaker cubicle.** The fire consumed much of breaker 3A0712's non-metallic parts and caused substantial melting of current carrying components. Consequently, the exact cause of the breaker fault could not be conclusively determined.

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Fire ID: 112 | LER: 2822001005

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Root cause of the event was a **poor electrical connection** between the Breaker 12-4 Cphase primary disconnect assembly (PDA) and the 1MY bus stab, **which led to overheating** of the PDA, **which in turn led to a failure of the PDA one or two seconds after Breaker 12-4 was closed**. The failure of the PDA led to a C-phase **to ground arcing event, which quickly involved all phases.** The arcing led to actuation of the protective relaying, which resulted in a turbine/reactor trip. **The poor electrical connection was caused by poor conductive surfaces.** A thinned silver coating on the connections exposed copper oxides in the conductors. **This led to a high resistance connection, and overheating.** The silver layer was most likely thinned by environmental and operating conditions and/or maintenance practices.

---

Fire ID:119 | LER: (DER) 39678

Fire Characterization Type: Flaming combustion – external to component
Challenging Determination: Not Challenging

Description / Detailed Failure / Cause:

A trip of the "A" Charging Pump breaker52-1205 caused a fire in the Cable Spreading Room. **The breaker for the "A" Charging Pump failed to clear the arc and the incoming breaker** to Bus 12 (52-1202) tripped on overload**. Preliminarily, the fire appears to have occurred within the breaker compartment** on load center #12 supplying Charging Pump 55A.

---

Fire ID: 142 | LER: (DER) 42605

Fire Characterization Type: Smoldering combustion – internal to component
Challenging Determination: Challenging

Description / Detailed Failure / Cause:

There were no flames, only smoke. CO2 discharged automatically into the switchgear room

---

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Fire ID: 144 | LER: 3682006001

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Cause: **misalignment of the circuit breaker stabs** that connect the 2VSF-1A circuit breaker to the bus bars: both sides of the "C" phase stab and its associated spring clip ending up on one side of the bus bar → **high resistance connection. Subsequent starts** of 2VSF-1A **likely resulted in arcing which increased the resistance at the connection due to oxidation at the contact points.** When an attempt to start 2VSF-1A was made on October 30, the **large inrush current of the motor** at the high resistance connection **caused the spring clip to melt.** It cannot be determined if the **molten metal from the spring clip caused a fire in the bottom of the MCC which created a conductive vapor in the cabinet OR IF the clip simply vaporized, creating the conductive environment.** Nonetheless, the result was that the conductive vapor created an **arc path to ground between the bus bars and the metallic dust pan in the bottom of the MCC**, resulting in significant damage to the bus bars. The upstream circuit breaker tripped immediately, terminating the over-current event.

---

Fire ID: 146 | LER: (DER) 43189

Fire Characterization Type: Flaming combustion – external to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:
The fire is located in the Unit 3 Turbine Area Load Center cubicle.

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Fire ID: 152 | LER: (DER) 43742 + Other (Condition report w/ pictures; 452 pages)

Fire Characterization Type: Flaming combustion – external to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:
Operators located at the 2B-52 Bus reported a flash, followed by smoke and fire. Load center breaker 2B-532 tripped.
**The most probable root cause was determined to be marginal bus/stab current carrying capacity design.** The other causes listed are probable "contributing causes":

- Insufficient physical stab engagement on bus resulting in elevated stab to bus interface resistance.
- Degraded stab clip tension resulting in elevated stab to bus interface resistance.
- Dust in the inaccessible bottom pan increasing the fault potential.
- Oxidation on stabs or bus bars could increase resistance and heating

The Root Cause Analysis Team identified the following most probable failure scenario:
• Service related conditions (large loads, frequent starts, repetitive starts, age, and environmental conditions) caused a high resistance connection at MCC bus/stab interface leading to arcing at the 2B-52A5 cubicle.
**• The arcing at the connection caused a phase to ground fault at the stab/bus connection which moved to the bottom of the MCC** [Motor Control Center] **progressing to a phase to phase fault, vaporizing the bottom of each bus bar (see note below).**
**• The heat from the fault caused the MCC plastic base pan and the space heater wires in the MCC to catch on fire.**
• The pressure from the fault caused the side wire way door to open.
• The upstream MCC feeder breaker, 2B-532, then tripped open and interrupted the fault.
• The fire in the base of the MCC self extinguished, ending the event sequence

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Fire ID: 161 | LER: (DER) 45013

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

Operations personnel identified a **strong odor**. Subsequent investigation identified that the odor was coming from circuit breaker 01-EE-BKR-1J1-2S-J1. Operations personnel locally opened the circuit breaker to place it in a safe condition. 1-HV-F-37D had **tripped approximately 30 minutes prior to the event**. [1-HV-F-37D is the control rod drive mechanism associated w/ this breaker] Operation personnel then **opened the circuit breaker cabinet and a small (6-inch) [15 cm] flame was observed**. Operations personnel used a CO2 extinguisher on the internals of the circuit breaker to quickly extinguish the small fire. **The cause of the circuit breaker failure has not been identified.**

---

Fire ID: 175 | LER: (DER) 45515

Fire Characterization Type: Flaming combustion – external to component;
Challenging Determination: Challenging

Description / Detailed Failure / Cause:

The fire is in the [non-safety] 1A 7.2 kV switchgear room.

Fire ID: 180 | LER: 2612010002

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Challenging

Description / Detailed Failure / Cause:

**The feeder cable failure (<u>cable insulation failed, resulting in an arc flash and cable fire</u>)** from non-vital 4kV Bus 4 to non-vital 4kV Bus 5 initiated the sequence of events. **The failure of circuit breaker 52/24 to open and isolate 4kV Bus 4 is the root cause of the fire event,** which also resulted in a reactor trip with complications. The **circuit breaker failed to open because of a mechanical flaw in the trip circuit fuse** [EI:FU], which disabled the control power trip circuit. The **fuse was** found to be **mechanically failed,** which caused the red indication light on the front panel of the breaker cubicle to be extinguished. The initial fault on 4kv Bus 5 **also resulted in electrical fires at 4kV Bus 5 and at Breaker 52/24 on 4kV Bus 4**. The fires were extinguished by fire brigade and security personnel using dry chemical fire extinguishers.

**<u>Review of deficiencies:</u>**

**Original design called for shielded cable**; Change Number 6, Feb. 14, 1986, **changed the cable to an unshielded cable** that did not meet the requirements of L2-E-035 for insulation rating or shielding.

**The installation of the cable was contrary to the acceptable installations in the MSDS** (which specifies that installing 3 conductors of this cable in a conduit is permissible only in non-magnetic conduit. The installation at HBRSEP, Unit No. 2, was in rigid steel conduit, which is magnetic.

**Insulation level of the cable** (100% vs. 133%) and **lack of an outer jacket may have contributed to the degradation of the cable** insulation system. The same cables installed in other locations showed similar signs of degradation.

Fire ID: 187 | LER: (other)

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

A security guard noticed smoke coming from the unit 3 condensate demineralizer control panel 2253-11. Thick grey smoke required the use of breathing apparatus.



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Fire ID: 188 | LER: (other)

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:
A **lightning strike** on site caused a fire in a power control center and wooden broom handles stored in the area.

---

Fire ID: 191 | LER: (other)

Fire Characterization Type: Smoldering combustion – internal to component
Challenging Determination: Not Challenging

Description / Detailed Failure / Cause:
Smoke coming from Westinghouse breaker type DS-206

---

Fire ID: 203 | LER: (other)

Fire Characterization Type: Flaming combustion – external to component
Challenging Determination: Challenging

Description / Detailed Failure / Cause:
MCC 2341B burned at 0106
MCC 2341A burned at 0130

---

Fire ID: 206 | LER: (other)

Fire Characterization Type: Flaming combustion – internal to component
Challenging Determination: Undetermined (NC-PC)

Description / Detailed Failure / Cause:
Operator rounds discovered a fire in the recirculation motor generator field breaker. Investigation revealed the **operating extension piece for the center phase shorting bus to be missing. This allowed the field to be continuously shorted during operation**

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Fire ID: 20357 | LER: 3181995005

Fire Characterization Type: Arc/electric discharge
Challenging Determination: Potentially Challenging

Description / Detailed Failure / Cause:

The **ground fault occurred when an internal cover plate fell, contacted the electrical bus, and caused a phase-to-ground short circuit**. A control Electrician noted that he saw 'the inner cover plate start to shift, heard a loud explosion, and found himself standing on the floor.'

## Appendix C: MATLAB script used to tabulate FEDB fire event statistics

```
clc
clear all
IN=readtable('frmFireData_ElectricalPanelx1990_2011.txt','Delimiter','tab’
);
Headers=IN.Properties.VariableNames;
ni=size(IN,1);
nk=size(IN,2);
save_nc=0*ones(nk,1);


for k=14:20                              % For all nk namelist groups (i.e.,
FireDesc    BldgStart   Text161 ...)
    [UniqueIN] = unique(IN{:,k});   % Find all unique categories (e.g.,
120V, 480V, 4kV) in that namelist group
    nc=size(unique(IN{:,k}),1);      % Number of categories in the current,
k, namelist group
    save_nc(k)=nc;
    %Create a 3D array that holds nk (one for each namelist group) 2D
arrays:
    % [category | # of fire events in that category]
    for i=1:nc
        STAT{i,1,k}=UniqueIN{i};     % Populate column 1 of array k with
each category in this namelist groupp
        STAT{i,2,k}=0;               % Initialize column 2 of array k to
hold # of fire events in each category in this namelist group
    end

    for i = 1:ni
        for j = 1:nc
            count=strcmp(IN{i,k},STAT{j,1,k});      %Does item i in the
main table IN belong in category j?
            STAT{j,2,k}=STAT{j,2,k}+count;          %If so, add 1 to the
number of items in that category
%              STAT_c(j,1)=STAT_c(j,1)+count;
        end
    end
        clf
%       Preliminary plot of results
%       fig = gcf;
%       fig.PaperUnits = 'inches';
%       fig.PaperPosition = [0 0 12 5];
        pie([STAT{1:save_nc(k),2,k}],{STAT{1:save_nc(k),1,k}});
        title(Headers(k))
        print(char(Headers(k)),'-dpdf') % Create, save figure of results

end
```

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