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DEVELOPMENT OF RISK INFORMED METHODS FOR ESTIMATING RADIATION RELEASE FROM CABLE FIRES AT HIGH ENERGY PHYSICS FACILITIES

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Master thesis submitted in the Erasmus+ Study Programme

International Master of Science in Fire Safety Engineering

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Name: **Daniel Funk**

Work completed

Introduction and Objectives:	100%
Objective 1 – Literature and SME Research	100%
Objective 2 – Cable Fire Sub-Model	100%
Objective 3 – Cable Fire Rad Release Fraction	100%
Objective 4 – Pilot Case Studies	100%
Objective 5 – Sensitivity Study	100%
Conclusions	100%

NB: It was originally intended to obtain installation and configuration values for Objective 2 pilot case studies. Pilot case studies (Objective 4) were completed; however, assumed values for cable specifications and configuration details are used for the cable fire sub-model (Objective 2) pilot case studies. Although some data was obtained, COVID-19 restrictions precluded site visits to CERN for data retrieval. Furthermore, CERN staff were working remotely, making it impractical for the staff to collect the desired data. Objective 3 is not impacted because the use of non-specific data is preferred to avoid disclosure conflicts for confidential information. The assumed values for pilot studies are representative and thus do not degrade the methodology development, but observations pertaining to parameter sensitivity must be viewed within the context of this limitation.

Work not commenced

No outstanding items

Declaration

To the best of our knowledge, this form is an accurate record of the project status on May 16, 2020.

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Abstract

CERN operates the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator. The LHC was built to advance the state of knowledge in particle physics by increasing the energy of colliding particles to the TeV range. With this increase in capability comes increased fire safety challenges, including the need for more accurate assessment of fire-induced release of radioactive materials. Through normal operation of particle accelerators, some materials used in the facility structure and equipment are made radioactive through a process called proton activation. Electrical cables are susceptible to proton activation; therefore, a cable fire can potentially result in liberation of radionuclides to the environment. This thesis elevates the state of knowledge and refines methods for estimating fire-induced radiation release from burning cables through (1) development of a more accurate framework for modelling cable fire sequences and quantitatively estimating cable fire frequencies and (2) development of quantitative methods for estimating the portion of radioactive isotopes released into the smoke plume of fires involving activated electrical cables.

Improved modelling of cable fire sequences was accomplished by applying electrical engineering principles to categorise and refine cable fire sequences within a fault tree format. Ignition source frequency weighting factors are then applied to associated sequences in the fault tree to produce greater precision in the determination of cable fire risk with respect to configuration, location, operating mode, and prevailing conditions. Proof-of-concept case studies confirm that the methodology is viable for "real-world" applications and can substantially improve cost-benefit analysis for risk mitigation strategies.

Conservation of mass principles were used to quantitatively analyse fractional release of radionuclides from burning cables. Mass balance inventory of pre-fire and post-fire radionuclides allowed assessment of activity levels contained in residual char, soot, and gaseous combustion products. Proof-of-concept case studies demonstrate that fractional release calculations are viable but several key influence parameters require further study to ensure accurate application.

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Acronyms and Symbols

List of Acronyms

A	Ampere
AC	Alternating current
ALICE	A Large Ion Collider Experiment
ATLAS	A Large Toroidal LHC Apparatus
BNL	Brookhaven National Laboratories
Bq	Becquerel, derived measure of radioactivity in nucleus decays per second
C	Celsius
CERN	European Organisation for Nuclear Research (Centre européen de recherche nucléaire)
CFD	Computational Fluid Dynamics
CMS	Compact Muon Solenoid
DC	Direct current
DOE	United States Department of Energy
ET	Event tree
ETA	Event tree analysis
FDS	Fire Dynamics Simulator (NIST CFD fire analysis software)
FIRIA	Fire-Induced Radiological Integrated Assessment
FLASH-CAT	Flame Spread over Horizontal Cable Trays
FSE	Fire Safety Engineering
FT	Fault tree
FTA	Fault tree analysis
g	Grams
GeV	Giga electron volt
Gy	Gray, derived measure of ionizing radiation dose based on deposition of 1 joule of energy in 1 kilogram of material (J/kg)
HSE	Occupational Health & Safety and Environmental Protection Unit (CERN)
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electrotechnical Commission
ISO	International Organisation of Standards
J	Joules
K	Kelvin
kA	Kiloampere
kg	Kilogram

km	Kilometre
kW	Kilowatt
LHC	Large Hadron Collider
LLNL	Lawrence Livermore National Laboratories
MW	Megawatt
NEA	Nuclear Energy Agency
NEMA	National Electrical Manufacturers Association
NETA	International Electrical Testing Association
Nb-Ti	Niobium - Titanium
NRC	United States Nuclear Regulatory Commission
NUREG	Series of NRC Nuclear Regulatory technical reports
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratories
PE	Polyethylene
PRISME	Propagation d'un incendie pour des scénarios multi-locaux élémentaires (Fire Propagation in Elementary, Multi-room Scenarios)
PS	Proton Synchrotron
PVC	Polyvinyl chloride
$Risk_{Fire}$	Total fire risk, summation of risk for all fire scenarios
RG	Series of NRC Regulatory Guides
RMS	Root Mean Squared
SFPE	Society of Fire Protection Engineers
SNL	Sandia National Laboratories
SPS	Super Proton Synchrotron
Sv	Sievert, derived measure of ionizing radiation dose that represents equivalent biological effect of deposition of 1 joule of energy in 1 kilogram of human tissue (J/kg)
TeV	Tera electron volt
UPS	Uninterruptible Power Supply
V	Volts
WP	Work Package
XLPE	Cross-Linked Polyethylene

List of Symbols

A_{Si}	Activity level in Becquerel (Bq) for radioactive isotope species i
A_c	Cross sectional area in square millimetres (mm^2) of conductor material
C_i	Consequence of Scenario S_i, expressed as radioactivity in Becquerel (Bq)
I	Electrical current in amperes (A)

I_{fault}	Fault current in RMS amperes (A)
λ	Decay constant of a radioactive isotope
L	Length of electrical conductor (m) or circuit inductance (Henry)
$\dot{m}_{vap}$	Mass vaporization rate of electrical conductor during an arcing fault (g/s)
m_{vap}	Total conductor mass vaporised during an arcing fault (g)
N(t)	Activity of original radioactive isotope remaining after time t
N_o	Initial activity of a radioactive isotope
Ω	Ohms
P	Power in Watts (W), kilowatts (kW), or megawatts (MW)
ρ	Resistivity of a given material measured in ohms per unit length (Ω – m)
R	Electrical resistance measured in ohms (Ω)
S_i	Fire scenario i
$t_{1/2}$	Half-life of radioactive isotope in time (seconds, minutes, hours, years)
T_1	Maximum rated operating current of a cable (°C)
T_2	Maximum rated short circuit current of a cable (°C)
V	Electrical potential in volts (V)
V_{arc}	Voltage drop (potential difference) across an arcing fault in volts (V)
v_r	Residual char yield

1 Introduction and Objectives

The European Organisation for Nuclear Research (CERN) operates the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator [1]. Particle accelerators are used by researchers to examine the fundamental nature of matter. This is done by accelerating subatomic particles to high energy levels and then causing the particles to collide into each other. Scientists are ever in search of more powerful machines that increase the collision energy of the particles. The LHC machine was built to advance the state of knowledge in particle physics by increasing the energy of colliding particles from the GeV to TeV range [2]. As such, the design and operation represent state-of-the-art technology and push material and equipment performance requirements to new limits.

The unique facilities and inherent nature of LHC operations pose non-standard fire safety challenges – most notably combustible radioactive materials [3], [4]. A severe fire incident within the LHC tunnel or at one of its critical facilities could result in a major setback to CERN's mission. Such an event could cause: (1) significant operational disruptions, (2) costly equipment/property damage, (3) safety risks to CERN staff and fire service personnel, (4) fire-induced release of radioactive materials to the environment, and (5) exposure of the general public to undesired levels of ionizing radiation. Thus, it is important to minimize the risk of a fire-induced radiological release and mitigate repercussions to the environment and general public, within and beyond CERN's geographical boundaries [5].

1.1 FIRIA Project

Based on a growing realization that additional fire risk insights are needed to support and implement CERN's risk management goals, the CERN Occupational Health & Safety and Environmental Protection Unit (HSE) has embarked on a large-scale, multi-year project to enhance CERN's fire safety engineering (FSE) capabilities and analysis tools. [3]. This project is known as the Fire-Induced Radiological Integrated Assessment (FIRIA).

The primary goal of the project is to develop a state-of-the-art methodology and governing framework for conducting fire risk analyses at CERN facilities, including fire-induced radiological risks [4]. The FIRIA assessment framework is based on quantitative risk analysis principles and aims to align with ISO 16732-1:2012, "Fire safety engineering – fire risk assessment (Part 1: General)" [6]. Appendix A provides additional details about the FIRIA project (NB: This thesis often refers to the FIRIA Project for context. It is suggested that readers not familiar with the FIRIA Project review Appendix A).

Clearly, the level of effort necessary to address all FIRIA Project research activities goes well beyond a one-person master's thesis. Accordingly, the focus of this thesis is limited to a specific research area within the overall FIRIA Project: analytical techniques and methods for quantitatively modelling cable fire sequences and estimating radiological release from cable fires. Cable fires are of keen interest to the FIRIA Project because of their potential for significant events [5].

1.2 Thesis Purpose and Objectives

The technical challenges faced in conducting integrated fire – radiation risk assessments at high-energy physics facilities are discussed in Appendix A and Appendix B. The inherent nature of these assessments call for a detailed methodology that includes quantitative techniques for estimating potential release of radioactive nuclides. At present, no such guidance exists. Hence, the CERN FIRIA Project targets several areas of research to fill in the missing pieces, as discussed in Appendix Section A.4 [5], [7].

A full and complete understanding of this thesis requires fundamental knowledge of radiation concerns and the mechanism by which materials at particle accelerators become radioactive. Readers not familiar with radiation issues at particle accelerators are encouraged to review the radiation background information in Appendix B.

1.2.1 Purpose

The purpose of this thesis research is to:

> *Develop a framework and methods to (1) model cable fire sequences and quantitatively estimate cable fire frequencies and (2) quantitatively estimate the portion of radioactive isotopes released into the smoke plume of fires involving electrical cables that have become radioactive through accelerator operation.*

The cable fire framework represents a set of new "analytical tools" intended to fit within the overall FIRIA governing framework, which conforms to agreed-upon codes and standards [4], [6].

1.2.2 Objective

Specific objectives include:

Objective 1: Investigate existing nuclear facility (reactor and non-reactor) fire risk analysis methods, techniques, failure and reliability data, cable fire test data, and lessons learned for potential application/adaptation within the CERN FIRIA framework and methodology, as applicable to cable fires.

Objective 2: Investigate enhanced and refined modelling methods to more accurately correlate cable fire initiating event sequences to specific categories of ignition source hazards. Advances to this aspect of fire hazards analysis will afford better insights into cable fire hazard categories and associated initiating event frequencies, which can readily be applied using a fault tree format to "inform" initiating event sequences and associated probabilities in facility event tree models.

Objective 3: Investigate methods and techniques for estimating fire-induced release of radioactive isotopes (particulate and gaseous) from burning cables. To the extent feasible, develop rules/guidelines for computing radionuclide evolution via pyrolysis and combustion products, thereby providing a means to estimate the fractional amount of radionuclides evolved from cable fires with a known radioactive source term.

Objective 4: Conduct pilot case studies for the analytical methods developed under Objectives 2 and 3. These studies shall fall along the lines of "proof of concept" rather than full scope pilot studies. The efforts of this research will focus on the LHC machine and ATLAS experiment; however, the concepts and methods resulting from this thesis are envisioned to have applicability to other CERN facilities as well as other high-energy physics facilities with similar considerations.

Objective 5: Identify sources of uncertainty and conduct a qualitative parameter sensitivity assessment for the proposed methodologies. Project scope constraints preclude a full quantitative assessment of uncertainty and sensitivity.

1.3 Limitations and Assumptions

The following limitations and assumptions apply to this thesis project:

1. No live-fire testing will be conducted for the project. Existing cable fire test data will be used for parameter estimates and cable fire behaviour quantification. Recommendations for additional testing will be identified as appropriate.
2. Aerosol transport and deposition of radionuclides (once evolved from the source fire) is not within the scope of this project. The CERN FIRIA Project team in collaboration with NIST are addressing this phenomenon to improve FDS modelling of radionuclide species contained in combustion products FDS [5], [8].
3. Methods development is limited to cable fire scenarios. However, it is likely that some concepts employed for cable fires can be extended to other electrical equipment.
4. The project does not include full development of design fire scenarios, design fire curves, or CFD simulations. The modelling and methods development for cable fires is focused on ignition sources and sequences for cable fire initiation, which in turn serves as input to the design fire scenarios. The fire-induced radiation release methods are based on a "per unit" approach, which makes the method independent of fire size and duration.
5. Some information and/or data used in development of this thesis report are confidential to CERN. This information was reviewed for insights but is not included nor referenced in this report. These limitations are judged to have a negligible impact on the main objectives of this research and do not degrade the academic value of the thesis.
6. Consistent with Item 5, radiation values used in pilot case studies are not CERN specific, but rather are generic values generated by the NIST neutron activation and scattering calculator [9]. The generated radionuclide values have no direct correlation to CERN but are sufficient for proof-of-concept testing of the methods.
7. In cases where CERN-specific data is not readily available, representative values are used, e.g., cable specifications.
8. The special Nb-Ti wire used in construction of the superconducting magnets is not included in the scope of this research. The wire is encapsulated within resin and housed inside the beam outer shell. Thus, the Nb-Ti wire does not represent conventional cabling. Accordingly, the analytical methods of this thesis cannot reasonably be applied to the Nb-Ti wire [10].
9. Parameter uncertainty and sensitivity are an important part of a quantitative risk analysis. However, for this initial development effort, uncertainty and sensitivity are not addressed in detail due to project scope limitations. Additionally, as stated in Items 6 and 7, some data used for the pilot case studies is either fictitious or assumed. While this does not hamper methods development, it degrades the value of uncertainty and sensitivity studies. Future quantitative assessment of uncertainty and sensitivity will be necessary once CERN-specific input and influence parameters are established.

2 LHC Description

The CERN LHC machine, with all its associated elements, is one of the most sophisticated and complex devices ever built. Some would argue it represents the most advanced technology in existence…few would disagree. This thesis assumes a fundamental understanding of particle accelerator design and operation, specifically the LHC machine and experiments at CERN. Readers not familiar with the CERN LHC machine and experiments are encouraged to review Appendix C as a primer to the core topics addressed by this research.

Appendix C contains a high-level description of CERN's major facilities, with a focus on the LHC accelerator assembly and related experiment facilities. The intent is not to provide an exhaustive discussion about all CERN facilities and equipment, but rather to explain in basic terms the major parts of the system and how they work. A general understanding of the LHC machine and its operation are necessary to put in context the unique fire risk considerations at CERN (as addressed by the FIRIA Project). By extension, this information sets a foundation and framework for this thesis.

The LHC machine is comprised of the high-energy particle beam accelerator, supporting subsystems and equipment, and experiment facilities [1],[11]. The main beam accelerator is contained in an underground circular tunnel approximately 27 km in length and 100 m deep. The "experiments" are stand-alone facilities located at discrete locations along the beam loop. At these locations, particle collisions are made to occur in the presence of sophisticated high-energy particle physics detection and measuring equipment [11]. The term "experiment" is potentially misleading in that the physical size, complexity, and uniqueness of these individual facilities cannot be overstated. Similarly, the infrastructure and support systems for the LHC are complex and extensive.

Figure 1 shows the physical size and location of the LHC. The locations of the four major experiments (ATLAS, CMS, ALICE, and LHCb) and main CERN complex are identified on the picture. Note the LHC's circular footprint in comparison to Lake Geneva and the Geneva airport. The CERN fire department and firefighting equipment are located at the main complex. The fire department is responsible for fires at all CERN facilities. The transit time to remote facilities such as CMS can take considerable time. Further complicating fire response time is that a majority of the LHC is in France (France – Switzerland boarder depicted by a yellow line in Figure 1). Firefighters must cross the border from Switzerland to France when responding to a call out for most of the LHC facilities.

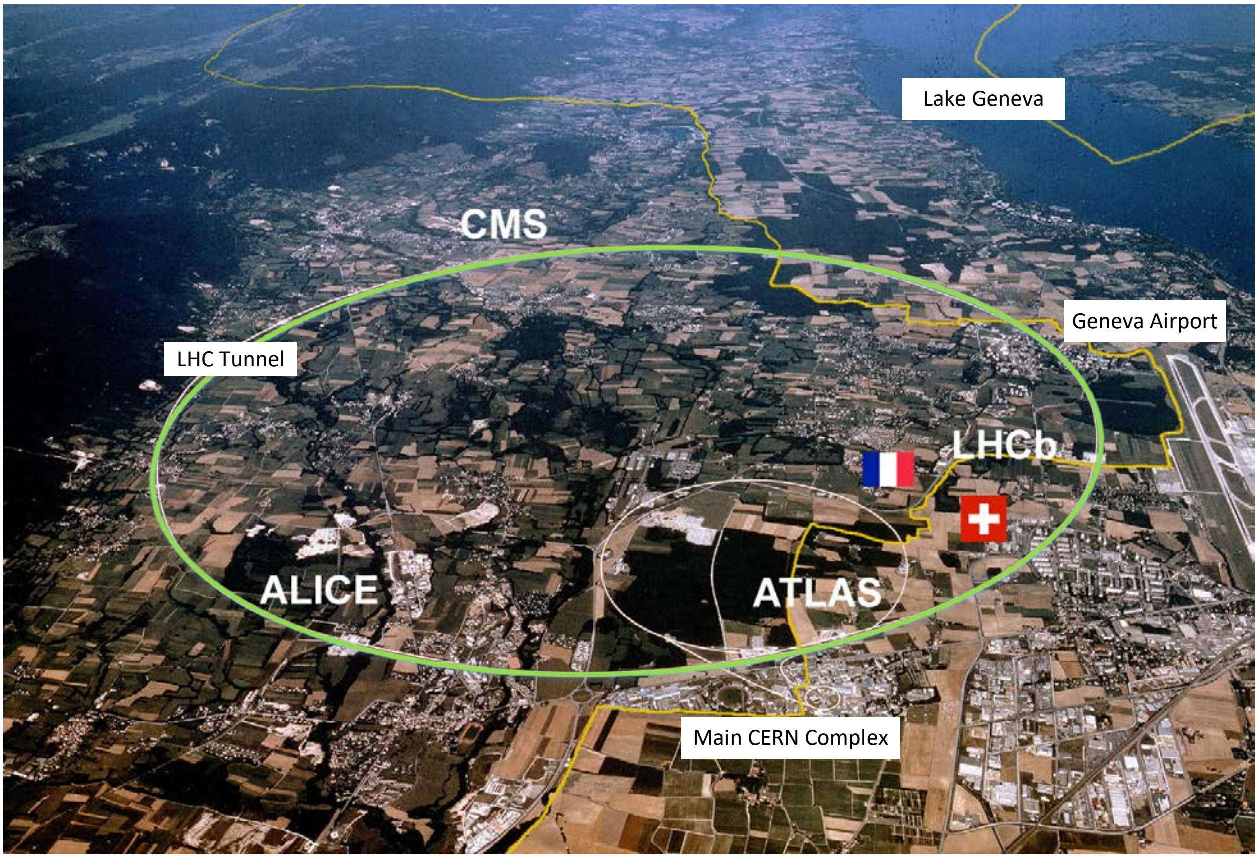


Figure 1 CERN LHC Loop and Major Experiments [12]
(as modified with annotations)

Cable fires are of particular interest to CERN [5]. The LHC beam tunnel and experiment facilities contain a massive amount of cable, with a broad range of types and sizes[1]:

- Large power cables are used throughout the LHC to support various subsystems. These subsystems are unique in design and function, but in general make use of high-quality, but traditional, industrial cables operating at 18 kV and 400 V [14].
- Low voltage control and control power cables are used throughout the installation for various control, safety, and monitoring functions.
- Small and delicate instrument cables are used extensively in the experiment facilities to support custom particle detectors and associated equipment for collection of a massive amount of data.

Cable fires can conceivably include any of the above cables.

The superconducting magnets are constructed from special Niobium-Titanium (Nb-Ti) wire. The magnets are operated in a superconducting mode in a nearly perfect vacuum under cryogenic conditions [2], [10]. As noted in Section 1.3, the Nb-Ti wire is outside the scope of this thesis because of its unique construction and operating conditions. The wire does not represent a typical cable fire hazard.

[1] A 2007 thesis project estimated fire risk of electrical equipment at CERN. This project identified over 200 cable types in the LHC tunnel (excluding the experiments) with an estimated total mass of about 2,200,000 kg (conductor and insulation) [13].

3 Research and Methodology Development

The purpose of this thesis is to develop a framework for cable fire sequences / frequencies and supporting methods for quantitatively estimating fractional evolution of radionuclides from fires involving activated electrical cables. The research strategy to accomplish the project goals is embodied in the specific thesis objectives listed in Section 1.2.1. Accordingly, the research approach is best described by explaining the concepts and strategy associated with each of the enabling objectives.

3.1 Objective 1: Nuclear Facility Fire Research

As discussed in Section 1 and Appendix A, the CERN FIRIA Project team faces several technical challenges in their pursuit of a site-wide general methodology for conducting quantitative fire-induced radiological risk assessments. The premise behind this objective is that existing nuclear facilities have likely faced the same or similar challenges as those currently faced by CERN. CERN can benefit from judicious application of existing relevant information that might not be in mainstream fire safety guidance documents.

3.1.1 State of Knowledge for Quantitative Fire Risk Analysis

Historically, CERN has conducted limited investigation into fire-induced radiation release; however, in application, its fire safety practices fall in line with traditional prescriptive methods [5]. These prescriptive methods are recognized as insufficient to provide the risk insights desired by CERN [4], hence the formation of the FIRIA Project team. Additionally, the risk associated with fire-induced radiological release has not been explicitly considered in the past; fire and radiation hazards have been treated independently. An integrated approach is needed to fully address the fire-induced radiological release hazard.

Conventional risk analysis standards and guidelines do not address the unique conditions at CERN, in particular, the LHC and associated experiment facilities. Additionally, rigorous full-scope fire risk analysis is not commonly performed by the fire safety engineering community. Numerous available standards address fire risk analysis and performance-based design. These standards typically contain a general framework and process geared toward conventional fire safety problems but offer little for special facilities. It is further observed that conventional fire risk guidance documents contain little detailed direction in the way of quantitative fire risk analysis; this part of the problem is left up to the user. This observation is not a criticism of the existing standards, but rather an acknowledgement that the state-of-knowledge for quantitative fire risk analysis is relatively immature and well-vetted best practices are virtually non-existent.

In lieu of starting from ground level, this thesis proposes that fire risk analysis work conducted by nuclear power plants [15], [16] and other non-reactor nuclear facilities may provide useful information that can be adopted for use at CERN. Although not identical, these facilities have similarities to CERN facilities, as well as similar fire risk and radiological concerns.

The commercial nuclear power industry has invested several hundred million Euros into the development of fire risk analysis methods over the past 20 years [17]. This effort was driven by regulatory agencies because of growing concerns about fire risks at nuclear power plants. Early in the nuclear industry's fire risk improvement efforts, cable fires emerged as a top concern. A significant knowledge gap existed with respect to cable fire behaviour, which effectively precluded application of quantitative methods to cable fire risk analysis. To fill the knowledge void, an international effort began in 2001 to characterise fire-induced cable failures. These efforts have produced a wealth of detailed cable fire test data, as discussed in the following sections.

3.1.2 Research Effort

The research effort into nuclear facility information will include two parts:

Part 1: Discussions with present and past nuclear industry subject matter experts (SMEs) to gain insights into potentially applicable materials and avenues of research. It is thought that these experts will help steer the research in more fruitful directions and facilitate efficient investigation. Discussions with SMEs is intended to be informal and unstructured, as the goal is to obtain general insights and background perspective. Use of a formal survey or structured questionnaire is not necessary to accomplish the intended goal.

Part 2: Collection of nuclear facility reference materials and data with potential for application/adaptation within the CERN FIRIA framework and methodology. Collection of information shall deliberately be broad in scope so that relevant documents and experience are not inadvertently screened out because of narrow key word searches. Targeted information includes fire risk analysis methods, analytical modelling techniques, best practices and guidelines, electrical failure and reliability data, fire event probabilities and frequencies, fire-induced radiological accidents, cable fire test data, cable burning behaviour, academic and institutional research efforts, pitfalls and lessons learned, and electrical fault characterisation. Of high priority is information that supports quantitative analysis methods for cable fire probability and fire-induced radiological accidents.

The strategy for literature and data collection will follow a structured process involving:

- Detailed search of NRC and DOE document databases, which are selectable by topic and key word searches
- Relevant electrical documents are known to the author so additional searches on this topic are limited to industry and academic papers based on key word searches associated with electrical fires
- Relevant CERN information shall be obtained through liaison with the CERN FIRIA Project team
- Follow-up on SME suggestions to locate and screen sources of data
- General key word searches for specific topics, such as metal out-diffusion, char yield, and soot constituents

The organisations listed in Table 1 represent a substantial portion of the collective knowledge and experience pertaining to the technical areas of interest for this thesis. Communication with subject matter experts will focus on these organisations. As informed by the insights gained in Part 1, a focused literature and data search will be performed. In most cases, the collected information will be within the public domain. However, some cable fire test data is anticipated to have limitations on disclosure. In these cases, mutually agreed upon methods for including the information will be established such that distribution of the thesis report carries no limitations.

Table 1 Nuclear Organisation Contact List

Organisation	Short Title	Location
Brookhaven National Laboratories	BNL	USA
Commercial nuclear power plant utilities	---	Worldwide
Electric Power Research Institute	EPRI	USA
International Atomic Energy Agency	IAEA	Austria
National Institute of Standards and Testing	NIST	USA
Nuclear Energy Agency, Organisation for Economic Cooperation and Development	NEA OECD	France
Nuclear Energy Institute	NEI	USA
Nuclear industry consultancies	---	Worldwide
Nuclear Risk Research Center	NRRC	USA
Oak Ridge National laboratories (ORNL)	ORNL	USA
Sandia National Laboratories (SNL)	SNL	USA
Universities – nuclear safety research	---	USA, Japan, Sweden
US Department of Energy	DOE	USA
US Nuclear Regulatory Commission	NRC	USA

3.2 Objective 2: Modelling of Cable Fire Sequences

The primary goal of this thesis relates directly to Objective 2 – improve modelling techniques and frequency estimates for cable fire sequences. These improvements will allow more accurate correlation between initiating event probabilities and specific categories of cable fires, which in turn can be applied within fault tree (FT) and event tree (ET) formats. This area of research is a high priority for the CERN FIRIA Project because it directly influences the ability to accurately estimate the risk of radiological release for fires involving electrical cables [5], [7].

3.2.1 State of Knowledge for Fire Probabilistic Risk Analysis

Current fire risk analysis practice typically defaults to conservative bounding assumptions with regard to electrical failures and fire. This approach is understandable because satisfactory results for common applications can generally be achieved by lump sum treatment of electrical failures. However, some experts are taking notice of the relatively primitive way in which electrical failures are being handled in fire safety analysis. Dr. Vytenis Babrauskas presented a paper in 2001 addressing electrical faults as ignition sources [18]. He makes the following observation in the paper:

> *"It is surprising how little systematic research has been done to elucidate and quantify the mechanisms whereby electric wiring faults lead to structure ignitions. Almost all of the experimental papers that could be found studied problems only of a*

very narrow scope. In addition, a number of them (mostly not reviewed here) have approached the topic by attempting to prove that certain modes of ignition cannot happen. This, of course, is hardly good scientific methodology, but is an easy trap to fall into, when it is realized that failures of highly reliable devices are involved [18]."

It has been nearly 20 years since this paper was issued and little has changed regarding treatment of electrical failures in fire safety analysis[2]. One might ask why so few advancements have taken place. At face value, the answer appears to be that no major driving force exists to fund R&D in this area of fire protection. There are, however, certain special industries that can benefit from refinements to fire risk analysis methods for modelling of electrical failures – CERN is one such case. The stated goals of the FIRIA Project cannot be achieved unless the new integrated fire risk methodology includes a means of calculating more realistic values for fire-induced radiological release. From this perspective, cable fires are of keen interest to the FIRIA Project [5].

The commercial nuclear power industry faced similar problems in conducting fire probabilistic risk analysis (PRA) at reactor facilities. Original fire PRA work relied on bounding conservative assumptions for cable fire impacts. This typical approach was cost effective; however, the lack of resolution between impacts and specific scenarios resulted in gross overestimates of risk (measured in frequency of core damage per reactor operating year). The industry was forced to regroup and develop new methods and analytical tools for fire-induced circuit failures. CERN's cable fire concern is different than that of the nuclear power industry. CERN is interested in radiological release from burning cables and the nuclear industry is concerned primarily with cable failure modes that impact safe shutdown of the reactor. Regardless, the technical underpinnings of the two problems are similar and the nuclear power knowledge base for cable fires represents a strong baseline from which to pursue advanced fire risk analysis methods.

3.2.2 Technical Basis for Development of Cable Fire Sub-Model

This section presents the approach, technical basis, and logical reasoning for the line of investigation used to satisfy Objective 2.

3.2.2.1 Electrical System Design and Operation

Design and operation of electrical systems and circuits is a mature technology:

- Decades of experience exists for electrical system design, operation, performance, protection, and failure
- Design and analysis tools are prevalent, and these tools are in common use
- Electrical system design and operation is broadly covered by universal electrical codes, standards, and guidance documents
- Construction and performance of electrical equipment and cables are highly standardized

Given the high state of knowledge for electrical system design and performance characteristics, electrical engineers can accurately predict safe operating limits for electrical circuits and design proper protection against hazardous conditions. This brings us back to Babrauskas's statement: *"It is surprising how little systematic research has been done to elucidate and quantify the*

[2] This observation is based on the thesis author's direct experience relating to electrical fire risk analysis for the past two decades.

mechanisms whereby electric wiring faults lead to structure ignition… [18]". It is indeed surprising; the mechanisms for electrical failure are well known and post-event analysis of electrical events (including fire) are frequently traced back to violation of a basic design or operating parameter. So why are electrical fire events treated in such a cursory manner when it is possible to provide much better insights through better modelling? The answer appears to be twofold:

1. As professional practices, electrical engineers do electrical engineering and fire safety engineers do fire safety. How often does one see an electrical engineer on a fire safety analysis project? How often is a fire safety engineer consulted in the design and placement of electrical distribution equipment? The cross-discipline knowledge does not extend much past the fact that the electrical engineer and fire safety engineer both know that electrical failures can cause fires. Therefore, this becomes the handoff point.
2. The lump-sum treatment of electrical failures, albeit not highly accurate, is usually adequate, as discussed in Section 3.2.1.

In summary, standard engineering design and operating principles can be used to better characterise the initiating event sequences and probabilities for cable fires. However, within the broad application of fire safety engineering, this information is rarely used in performance-based analysis. Certain special applications can benefit from more precise fire risk modelling methods, and these methods do not need to be overly burdensome, assuming relevant electrical information is readily available.

3.2.2.2 Cable Fire Categories

Methodology development will proceed under an assumption that cable fires can be classified into three fundamental groups, and these three fundamental groups can be further sub-divided based on specific electrical design and configuration characteristics. Basic electrical engineering principles support the groupings.

One can envision hundreds of cable fire scenarios, which is not all that helpful. However, the task is made much easier by logically grouping cable fires into one of three basic categories [18], [19], and these three main categories have a limited number of second-tier branches that dictate the behaviour of the fire sequences.

External Exposure Fire: The cable or group of cables is ignited by an external ignition source. The fire origin can be any location along the cable.

Self-Ignited Cable Fire: The cable fire begins as a result of self-ignition of the cable insulation. The fire origin can be at any location along the cable, including multiple simultaneous locations.

Terminal Equipment Fire: A fire begins at a cable's termination point due to electrical failure. The fire can propagate from the terminal equipment along cables connected to the equipment.

An argument can be made that the terminal equipment fire category can be subsumed into the other categories. This is possible but not desirable from a practical implementation perspective. External exposure fires and self-ignited cable fires can start at any location along the cables' routing. The origin of a cable termination fire can be pinpointed and often probability values for these failures are easier to determine.

3.2.2.3 Electrical Parameters of Interest

There are many ways to categorise electrical circuits, systems, and equipment. To avoid failure through data overload, this project will focus on a few key parameters, the correlation of which to fire risk is well understood and readily quantified. The electrical system attributes shown in Table 2 are candidates for investigation as relevant variables in cable fire sequences.

The feasibility of incorporating the various electrical attributes will depend to a large extent on the availability of information. Facility walkdowns to determine electrical equipment design attributes are often inefficient and ineffective [15], [16]. It is important to reemphasise that the objective is to define sequences that lead to a cable fire and estimate the frequency of those sequences. This thesis does not include any aspects of fire modelling to determine fire growth or spread once a cable fire has started. However, the nature of the sequences themselves will assist in design fire development.

Table 2 Electrical System Parameters of Interest for Cable Fire Sequences

Parameter	State/Class/Condition	Discussion
Circuit operating state	Energised Deenergised Intermittent	Deenergised circuits are not vulnerable to self-ignited cable fires.
System voltage	Low voltage: up to 1000 V Medium voltage: 1000 V to 35 kV High voltage: 35 kV to 230 kV Extra high voltage: above 230 kV	Voltage level influences the type and rate of electrical failures due to the intensity of the voltage gradient. Voltage rating is an important cable parameter.
Available energy	Power transmission level Available fault current Stored energy	The propensity for electrical fault damage and vigorous arcing faults is correlated to available energy of the circuit under normal and abnormal conditions.
Circuit classification	Signal Control Control power Power	The circuit application class generally correlates to voltage level and available energy, which in turn correlate to damage potential of electrical faults.
Cable material	Conductor Copper alloy Aluminum alloy Special Insulation / jacket Thermoset Thermoplastic Silicone rubber Other	Conductor material affects cable damage limits and arcing fault behaviour. Insulation and jacket material affect cable damage levels, failure modes, burning characteristics, ignition temperature, and fire spread rates.
Overcurrent protection	Design ratings Overload protection Short circuit protection	Cable overcurrent protection directly affects the propensity for self-ignited cable fires through insulation overheating and arcing faults.
Maintenance and testing	Hot-spot testing (connections) Cable integrity testing Protective device testing	Lack of periodic maintenance and testing for electrical protection components is a contributor to electrical fires.

Parameter	State/Class/Condition	Discussion
	Interrupting device maintenance	
Cable installed environment	Temperature Moisture Radiation	High temperatures, high moisture, and high radiation exposure reduce cable life.

3.3 Objective 3: Radioactive Release from Cable Fires

The basic fire risk analysis and fire modelling processes called for by the FIRIA methodology are challenging because of the complex nature of the LHC and experiment facilities. However, there are no new fire science principles involved – the challenge is implementation. Integrating fire-induced radiological release into the fire risk assessment methodology adds a new dimension to the problem. As separate technical disciplines, fire and radiation have been studied for many decades. As an integrated "cause-effect" mechanism, fire-induced radiological release is not well understood.

Objective 3 aims to develop a better understanding of the portion of radionuclides that will be released during a cable fire, assuming activated cable materials with known isotopes and activation levels.

3.3.1 State of Knowledge for Fire-Induced Radioactive Release

As noted above, the knowledge level is quite high for fire (including cable fires) and nuclear physics (radiation) as independent topics. However, the knowledge level regarding the combination is low. The current process at CERN is to assume that 100% of the radioactive content of burning materials is released to atmosphere during a fire. Preliminary research indicates that this same bounding assumption is made by other nuclear facilities when calculating the potential radiological release from fires involving low-level radioactive waste and other combustible materials [20]. A completely different analytical process is used for high-level radioactive materials in nuclear reactor fuel and other applications.

Discussions with nuclear experts reveals that fire-induced radiological release has likely undergone significant study at nuclear weapons research and production facilities; however, this information remains classified and is not available.

3.3.2 Technical Basis for Approach to Estimating Radiation Release

This section presents the approach, technical basis, and logical reasoning for the line of investigation used to satisfy Objective 3. The low state of knowledge for this phenomenon and the lack of specific test data imply that modest improvements should be targeted. Given that the current practice is to assume 100% radiological release of the source term, any technically justified methods that allow relaxation from this assumption are welcome.

Cables include polymer materials for the insulation and metal alloys for the conductor. Activation can occur in both the polymers and the metals, as discussed in Appendix Section B.1. On this basis, the line of investigation is centred on two principles:

1. When cables burn there is a residual char left behind. Therefore, not all materials are converted to combustion products, pyrolysis gases, or soot. On this basis, it is presumed that

some fraction of the original radionuclides remain in the residual char layer and are not evolved as smoke.

2. Burning cables might or might not include arcing faults while burning (the propensity for arcing is a function of circuit status, system voltage, energy levels and circuit fault protection):
   - If a cable is vulnerable to arcing faults when burning begins, radioactive isotopes released as a result of metal vaporization of the conductor should be considered [21], [22].
   - If a cable is not vulnerable to arcing faults when burning begins, radioactive isotopes released from conductor vaporization need not be considered (i.e., the fire is not hot enough to vaporise the metal conductor). However, temperature-induced diffusion of metal atoms should be considered [9].

Research will focus on cable testing performed to characterise cable fire behaviour. Although most testing has concentrated on heat release rate (HRR) and flame spread, available data will be reviewed for any ancillary information that can be used to estimate the amount and chemical composition of char left behind when the cable is fully burned. Additionally, the data will be reviewed to assess the degree to which specific insulation types influences the fractional release.

The electrical engineering principles are sound for differentiation between burning cables with and without arcing faults. The high rate of conductor vaporised under certain conditions is well supported by testing and analysis [21]. However, the overall significance of this factor to the radiological release is not known, nor is the practicality of such assessments.

Finally, it is anticipated that investigation into this aspect of fire-induced radiological release will yield as many questions as it answers. It is hoped that these questions will provide insights that allow for more directed research and testing.

3.4 Objective 4: Cable Fire Scenario Pilot Studies

The purpose of Objective 4 is to conduct limited-scope pilot studies for the methodologies developed under Objectives 2 and 3. These studies are not intended to be full-scope pilot case studies, but rather proof-of-concept assessments.

Several cases are selected for the proof-of-concept trials:

- Frequency assessments for various cable fire scenarios representative of the LHC tunnel and ATLAS main cavern (Objective 2 cases)
- Radionuclide release fraction estimates for typical cable configurations involving different types of cables (Objective 3 cases)

These cases are representative of key locations of interest with respect to fire-induced radiological release and are representative of areas where cable fires are a dominant concern.

Reasonable efforts are made to obtain actual data for the many input parameters needed to support the pilot studies. For cases where data is not readily available, representative values will be used. The impact of using assumed values for some parameters is judged to have minimal effect on the outcome of this research because the goal is methods development and not evaluation of a specific case. However, care will be needed in assessing sensitivity studies.

As noted in Section 1.3, actual radiological values for CERN are not used for the pilot cases, but instead rely on typical isotopes for the materials involved, as determined by the NIST activity calculator [9]. Here again, it has been judged that use of reasonable but non-exact values does not invalidate the trial studies with respect to methodology evaluation.

The proof-of-concept pilot trials will focus on the criteria shown in Table 3. It is acknowledged that the criteria are qualitative and not quantitative. Qualitative assessment is considered appropriate for concepts in the incubation phase.

Table 3 Assessment Criteria for Proof-of-Concept Trials

Parameter	Description
Technical validity and fidelity	▪ Are the new methods traceable to accepted scientific and engineering principles? ▪ Do the models reliably generate reasonable outputs over the range of likely inputs?
Practicality and usability for production work	▪ Are the methods/models deployable in a production environment? ▪ Will they work under real world conditions where design input will not be perfect and user experience levels will vary?
Return on investment	▪ Does the increase in resolution and accuracy afforded by the new methods and models outweigh the level of effort required to conduct and maintain the higher resolution analyses?

The methodologies developed for modelling cable fire sequences (Objective 2) and determining fractional release of radionuclides from cable fires (Objective 3) have been developed following a systematic approach based on widely accepted scientific and engineering principles. However, scientific research has taught us that first-time experiments are often most valuable for the mistakes that are discovered rather than the actual results. Accordingly, the trial pilot cases will be equally interested in the parts of the methodology that do not work as in those that do work.

3.5 Objective 5: Parameter Sensitivity Analysis

Objective 5 will include a general assessment of sources of uncertainty and the importance of key parameters. Uncertainty and parameter sensitivity play a significant role in assessing and refining the new methods and models for assessing fire-induced radiological release for cable fires. In many ways, the sensitivity analysis serves to validate the usefulness and practicality of the methods/models.

The purpose of Objective 5 is to gain insights into sources of uncertainty and the sensitivity for the numerous input variables that influence the frequency of cable fire sequences and the radiation release fraction from cable fires. This thesis will not attempt an exhaustive sensitivity and uncertainty study on all variables. As a proof-of-concept research effort, the results presented here represent the beginning stages of the R&D cycle. Before engaging in detailed sensitivity and uncertainty studies, additional trial cases should be conducted using CERN-specific inputs and influence parameters to verify and validate that the recommended methodologies are viable and satisfy the objectives of the FIRIA Project.

4 Literature and Data Research Results

In accordance with Objective 1, a rigorous literature and data search was conducted as outlined in Section 3.1. The premise behind this research effort is that existing nuclear facilities (reactor and non-reactor) have faced fire safety challenges similar to those CERN is currently addressing via the FIRIA Project. It is therefore likely that CERN can benefit from prior research, testing, and application experience gained by these other nuclear facilities. Of specific interest is the significant effort undertaken by the international nuclear power community to improve fire probabilistic risk analysis (PRA) methods.

Recall that the research effort includes two parts:

Part 1: Interviews with past and current SMEs.

Part 2: Identification and collection of information and test data having potential applicability to CERN.

This section is intended to provide a high-level summary of the SME interviews and literature search results – what information was useful and potentially adaptable to CERN and what information was judged to be irrelevant. Sections 5 and 6 provide details on how the relevant information is incorporated or adopted into the main developmental efforts for this thesis (Objectives 2 and 3).

4.1 Subject Matter Expert Interviews

Discussions with nuclear and fire safety subject matter experts (18 individuals) proved invaluable. Most experts had experience that spanned several decades and included different industries. Highlights of the interviews include:

- Collectively, the discussions with SMEs steered the literature and test research effort toward the documents and testing most relevant to the thesis topics. This guidance greatly improved the overall efficiency of the literature research effort.
- In several instances, the SMEs identified older vintage (circa 1970s – 1980s) US NRC and national laboratory research documents that addressed obscure aspects of cable material performance during fire (i.e., char residue).
- US NRC experts who directed much of the nuclear power industry cable fire testing provided detailed insights into the various test series, and in some cases, provided guidance on how to interpret the data. These insights provided a more in-depth understanding of the relevance of the test data to the thesis topics.
- Experts with US DOE experience explained that sought-after information regarding fire-induced radionuclide release was most likely documented as part of US DOE nuclear weapons processing facility accident studies. However, this information remains classified and not available to the general public.

4.2 Cable Fire Test Data

A significant amount of cable fire test data was obtained as part of the thesis research effort. However, this test data was less relevant than anticipated:

- The OECD-NEA conducted substantial cable fire tests as part of the PRISME program (several phases) [23]. Unfortunately, the tests were focused on macro parameters of cable fires, including cable ignition times, flame spread rates, toxic gases, and heat release rates. This data is certainly beneficial for cable fire modelling but has little direct applicability to the parameters of interest for this thesis effort – primarily residual char yields, soot constituents, soot yields, and cable fire ignition sources.
- Cable fire research and testing conducted by US DOE national laboratories under sponsorship from the US NRC was more useful [21], [24]–[26]. Numerous tests involved characterisation of the cable materials, including residual char and soot yields. However, as with OECD-NEA much of the testing focused on ignition temperatures, flame spread, and heat release rate. NIST personnel participated in almost all of the recent cable fire tests.
- Lund University cable fire testing was performed for CERN [27], [28]. These tests were useful in characterising some aspects of burning cable materials. Since the cables tested were CERN-specific samples, the results are considered directly applicable to this thesis.
- US NRC research into cabinet fire behaviour was used to guide development of termination fire sequences [29]–[32].

4.3 Fire Risk Analysis Methods

The numerous guidance documents developed by the nuclear power industry over the past two decades were instrumental in supporting development of a sub-framework model for cable fires:

- The general guideline for conducting fire PRA at nuclear power plants (NUREG/CR-6850) [15], [16], [33] presents a comprehensive framework for quantitative risk analysis. This thesis has made use of several concepts presented in the guide, including fire compartment breakdown, categorisation of ignition sources, zone of influence concepts, HEAF events, and practical fault tree development.
- The US NRC and EPRI have devoted significant effort to characterisation of ignition source frequencies [34]. These values are adopted for the assessment of cable fire sequences developed as part of this thesis.
- Numerous supporting documents have been developed to provide practical guidance based on lessons learned over 20 years of implementation. Many of the "best practice" methods are relevant to CERN due to the large scale and complexity of the LHC facilities.

4.4 Electrical System Fault Protection

A key part of this thesis effort includes integration of electrical system design, fault behaviour, and overcurrent protection performance. Development of the self-ignited cable fire sequences in the cable fire sub-model draw heavily from well-documented electrical engineering principles contained in long-standing IEEE standards, IEEE electrical protection guidelines, and IEEE short circuit testing (direct faults and arcing faults) [35]–[39].

5 Cable Fire Modelling Methods

This section presents a new and refined approach to modelling cable fire sequences and frequencies (Objective 2). The new methods are developed in support of CERN's FIRIA Project goals for realistic analysis of fire-induced radiological release. However, they are considered transferable to other high-energy physics facilities having similar concerns. Development of the new methodology follows a systematic process that leverages three primary elements:

- Electrical fault behaviour is well understood within the electrical engineering community and this knowledge provides a sound technical foundation from which to build more accurate and higher resolution cable fire sequences.
- The nuclear power industry has over the past 20 years made significant technical advancements in quantitative fire risk analysis methods. Many of the underlying principles and lessons learned from the nuclear industry's work are adaptable to the cable fire challenges confronting CERN.
- The nuclear power industry has sponsored a substantial amount of laboratory experiments and full-scope live-fire cable tests. The results offer insights into cable fire behaviour and electrical circuit performance characteristics that shed light on several aspects of the fire-induced radiological release problem.

Making use of the information mentioned above, the methodology development will follow the major steps shown in Figure 2.

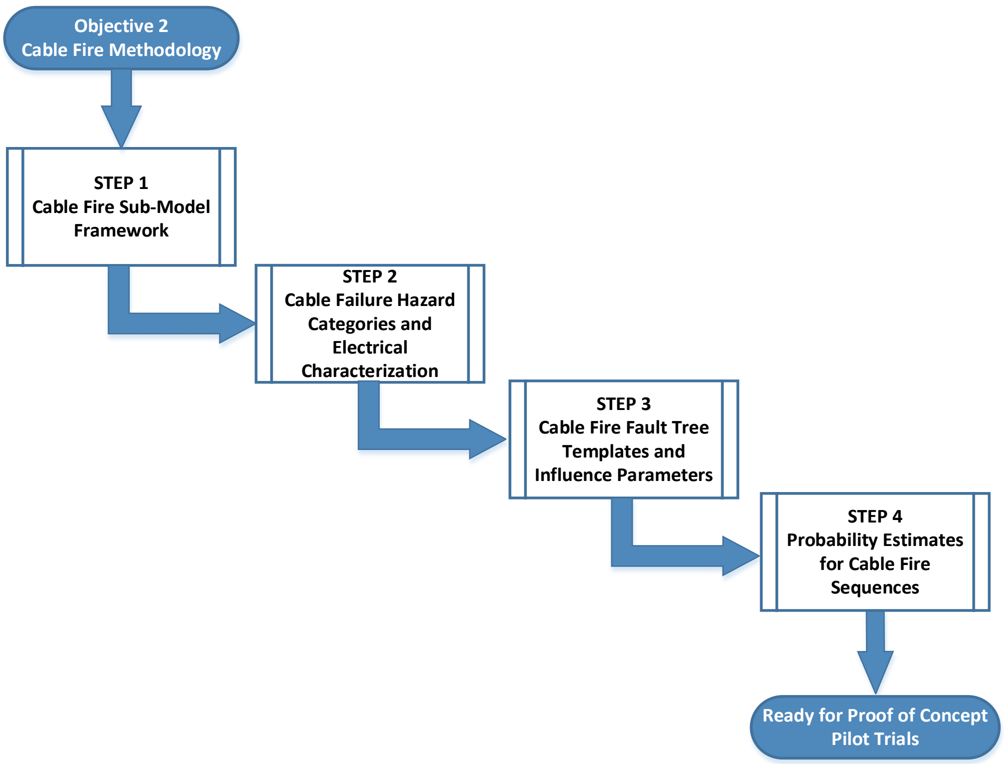


Figure 2 Cable Fire Methods Development – Key Steps

5.1 Cable Fire Sub-Model Framework

The cable fire sub-model must function as a seamless "plug-in" module to the overall FIRIA methodology framework. As a first step, this framework must be defined.

5.1.1 FIRIA Overall Methodology

The overall FIRIA framework is built around an event tree (ET) analysis process in which fire risk is represented as a function of defined fire scenarios (or scenario groups), each having an assigned frequency.

Risk is formally defined as: "*The potential for realization of unwanted adverse consequences, considering scenarios and their associated frequencies or probabilities and associated consequences* [40]". Risk analysis differs from other performance-based fire analysis methods in that it considers both frequency and consequence, whereas other methods focus on the hazard consequence itself and do not explicitly assign a frequency/probability to the scenarios[3].

The overall fire risk for radiological release is mathematically expressed as a summation of the individual scenario or scenario group risks [40], [41]:

$$Risk_{FIRE} = \sum_{i}^{n} Risk(S_i) = \sum_{i}^{n} P_i \times C_i$$

Where: $\mathrm{Risk_{FIRE}}$ is the total fire risk for the defined analysis boundary

$\mathrm{Risk(S_i)}$ is the fire risk for each fire scenario $\mathrm{S_i}$,with a total of n scenarios

$\mathrm{P_i}$ is the probability of occurrence for Scenario $\mathrm{S_i}$

$\mathrm{C_i}$ is the consequence of Scenario $\mathrm{S_i}$, which for radiological release is the amount of radionuclides released to atmosphere expressed in Becquerel (Bq)

5.1.2 Compartmentation

The most effective method to discretise the fire scenarios depends on the nature of the hazards and the physical configuration of the structure of interest. Based on the unique characteristics of the LHC (including experiments and support facilities), a global system-based breakdown is not recommended as the primary categorisation for scenarios. CERN facilities are better represented by physical breakdowns (i.e., location). The reasons for this are many:

- The facilities differ in vintage, construction, systems, and equipment. Blending data as a crude cutset across all facilities will give nominal values but these values most likely would not be representative for a given facility.
- Merging data across facilities will mask the main benefit of risk analysis – identifying which specific locations/factors are the main contributors to fire risk and fire-induced radiological release.
- CERN is concerned with traditional fire safety goals (evacuation, business continuity, property loss); however, of special interest is radiological release. Radiological release varies significantly for different locations within the LHC tunnel and experiments.

[3] This thesis assumes a fundamental understanding of hazard and risk analysis. Basic hazards, risk, and performance-based design concepts will not be covered. Numerous standards and texts cover these topics well.

Therefore, using physical location as the main delimiter for scenarios aligns best with the overall project objectives.

- System and equipment level problems are readily tracked through fire event reporting. This allows location to remain the primary binning category without a loss of reliability/failure information.
- Nuclear power experience indicates that quantitative cable fire analysis is only effective when conducted on a compartment basis in which ignition sources can be counted and binned.

Examples related to cable fires are helpful in visualising the rationale for using physical location and compartmentation as the primary categorisation factor for fire scenarios:

Example 1: A specific room at ATLAS might have many electrical ignition sources. This room will have a much higher frequency of cable fire than a room containing no electrical equipment (cases in which the cables simply pass through the room). Treating cable fires uniformly across the entire ATLAS facility masks this difference.

Example 2: Equipment type, cable types, and radiation levels are different for different sections of the tunnel. In particular, cable activation levels throughout the LHC tunnel differ significantly. Treating the tunnel as a single entity (i.e., viewing the LHC tunnel as one element) significantly reduces the inherent value of the fire risk analysis. This problem is exasperated by assuming a worst-case activation level for all locations, making the overall risk estimate two steps removed from actual conditions at any given location.

5.1.3 FIRIA Framework and Cable-Fire Sub-Model

Based on the fundamental FIRIA process and location-based ETA, the FIRIA framework for ETA is presumed to be as represented by Figure 3. The figure shows where the cable fire sub-model fits within the overall scheme. The cable fire sub-model is a fault tree that "informs" the governing event tree with a probability value at the point shown. This probability value adds to the other scenario probabilities to give a compartment fire probability (moving backwards in the ET). The cable fire probability value also serves as the starting point for proceeding with a further breakdown of the scenario based on event factors (moving forward in the ET).

Note the following regarding the figure:

- The ET is intended to be representative only and does not necessarily reflect the exact breakdown for facilities, compartments, and scenarios.
- Lower-tier compartmentation is only shown for the LHC tunnel. Other branches will have their own compartment breakdown structure as appropriate for the design and partitioning of the structure.
- The diagram highlights that the cable fire sub-model is to be fully captured as a fault tree such that its integration into the FIRIA methodology is seamless and surgical.

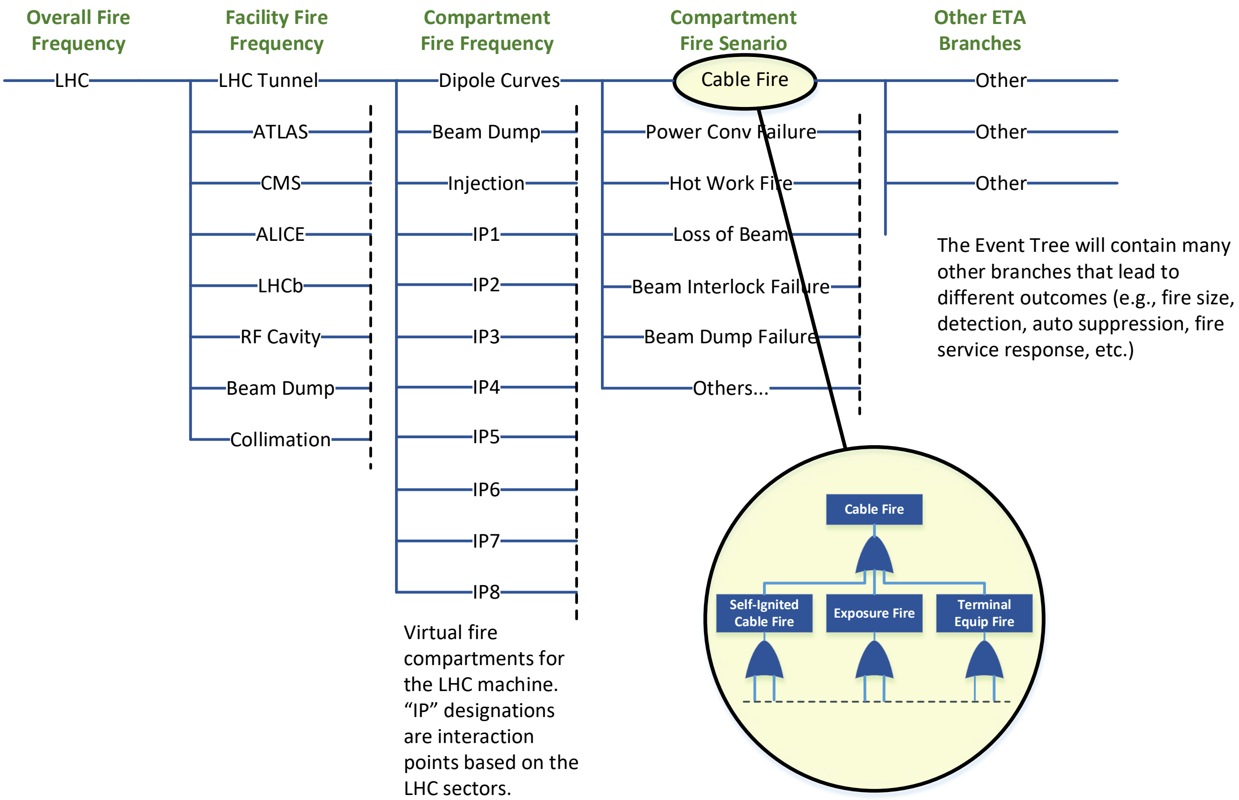


Figure 3 Fire Event Tree and Cable Fire Sub-Model – Top Tier Representation

5.1.4 Virtual Compartmentation

The location-based analysis is most effective for highly compartmented facilities. Nuclear power plants fall into this category because redundant safety systems are generally located in different fire compartments. Conversely, some CERN facilities have limited compartmentation because of unique design functions (e.g., LHC tunnel, experiment main caverns). Although not optimal, a compartmentation scheme can still be used for these facilities.

It is proposed that facilities with minimal compartmentation make use of a "virtual compartmentation" scheme. The virtual scheme concept is to logically divide the physical compartment into virtual compartments. Although the virtualized compartments are not divided by rated fire barriers, the superimposed boundaries provide a means to analytically identify locations of higher risk. The concept of virtual compartmentation is shown on Figure 3 – the LHC tunnel has been divided into compartments that align with the tunnel arrangement. Observe that the dipole sections are represented as a single, consolidated virtual location. This assumes the dipole sections are essentially the same configuration. They could also be represented as separate locations based on the LHC sections. Virtual compartmentation should be mindful of consequence as well as other geometric factors (activity level of cables for the purposes of this project).

The experiment main caverns can be virtualised as well. Platforms along the sides lend themselves to logical partitioning and the main machine sections can be divided into circular regions based on equipment groups and activation levels (which will reduce radially).

The concept of virtual compartmentation is not without its drawbacks. The analysis must include a means of estimating the likelihood of a postulated fire migrating into an adjacent virtual compartment. Such cases are much easier to address when rated fire barriers can be credited;

however, for CERN applications, this will not generally be the case. The pilot cases to be conducted under Objective 4 will exercise the virtual compartment concept.

5.2 Cable Fire Hazard Categories

This section presents the technical evaluation of cable fire hazards and the recommended top echelon fault tree events and gates. These elements represent the basic framework for the cable fire sub-model. The methods development process for Objective 2 (Section 3.2.2.2) puts forth the concept that cable fires can be binned into one of three primary categories [18], [19]:

- External Exposure Cable Fire
- Self-Ignited Cable Fire
- Terminal Equipment Fire

It is further proposed that each of these primary categories has a limited number of second-tier groupings needed to characterise cable fire sequences. Each of the primary cable fire categories and their respective second-tier groups are explained in the following sections. Other methods are certainly possible for categorising cable fires. However, it is argued that the suggested breakdown is derived from electrical engineering first-principle concepts and is thus technically robust regardless of specific application.

5.2.1 External Exposure Cable Fire

An "External Exposure Cable Fire" is defined within the context of this thesis as: *A cable or group of cables that are ignited by an external ignition source*. Key characteristics of an external exposure cable fire are:

- The fire origin can be at any location along the cables' length, as defined by the possible ignition sources.
- Ignition source hazards can be classified as fixed or transient.
- A cable fire is only possible if the ignition source (or primary fuel package) has the capability to cause sustained burning of the cables. Typical ignition sources can be characterised and categorised for analysis purposes.
- A cable can be energised or de-energised at time of ignition. For energised cables, secondary ignitions along the cable route should be considered.
- Ignition of cable materials can occur due to flame impingement, radiation, or hot gas layer.

Figure 4 illustrates an external exposure cable fire for a cable routed from a main power panel to a smaller distribution panel. The illustration depicts a pool fire, but the fire could be from any ignition source. Although the illustration implies that the cable is damaged by direct flame impingement, the cable failure can also be initiated by radiation, or soak time in the hot gas layer. Different cable insulation materials have different thresholds for ignitability.

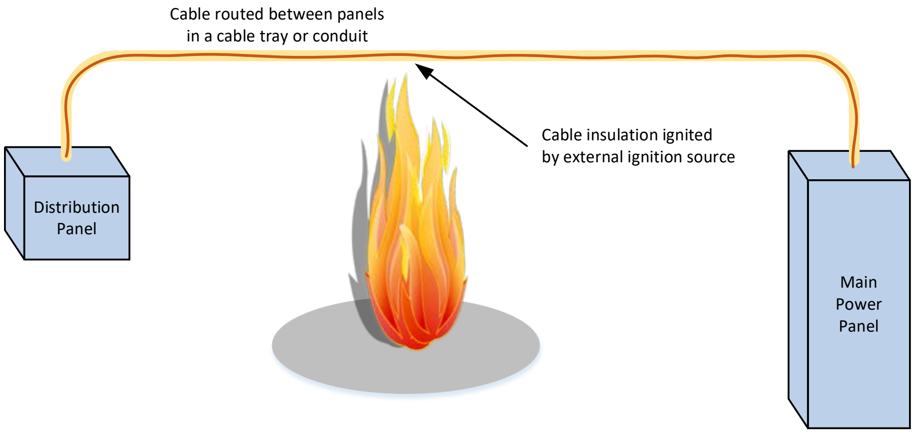


Figure 4 External Exposure Cable Fire

5.2.1.1 Fixed and Transient Fire Hazards

Exposure fires can be caused by "Fixed Ignition Hazards" or "Transient Ignition Hazards." Fixed hazards are a permanent part of the facility (e.g., power panels, electric motors, stored flammable gases, cables). Transient hazards are non-permanent hazards or activities (pallet of plastic parts, portable test equipment, maintenance activity, hot work).

5.2.1.2 Cable Ignition Thresholds

Criteria must be established to assess if an exposure fire has the potential to ignite cables. Numerous test regimens have been conducted by NRC and OECD to investigate this issue. Results vary and, as expected, many variables appear to influence the results. After much discussion, the nuclear industry agreed upon criteria that represent a typical set of conditions that represent loss of cable function. These same values are used for ignition threshold based on consensus that the values represent a conservative lower limit for all cable materials within the polymer class (i.e., thermoset or thermoplastic) [42]. For a given cable type, higher limits for self-ignition may be justified, but generally the benefit is negligible because of the exponential relationship between fault current and temperature excursion. The criteria are shown in Table 4.

Table 4 Cable Damage Threshold Criteria [42]

Cable Type	Radiant Heating	Surrounding Temperature
Thermoplastic	6 kW/m^2	205°C
Thermoset	11 kW/m^2	330°C

These criteria are used in conjunction with Zone of influence (ZOI) assessments to determine if target cables are ignited by ignition sources of concern. This process is analogous to the design fire development step in which assessments are made regarding ignition of different fuel packages.

5.2.1.3 Ignition Source Zone of Influence (ZOI)

The possibility of an external exposure cable fire depends on (1) the probability of the ignition source (fixed or transient) and (2) whether the ignition source (or primary fuel package) can produce a fire capable of igniting the cables of interest. Herein lies a subtle but important point – the likelihood of an external exposure cable fire is not simply the frequency of the ignition source, but rather it is the frequency of the ignition source AND the likelihood the postulated ignition source / initial fire has the capability to ignite nearby cables (i.e., the cables are viewed as a separate fuel package).

Original nuclear plant analyses for ignition of secondary fuel packages (cables) were inconsistent and subjective. To address this problem, the industry developed a simplified approach based on "zone of influence". ZOI is a concept in which a set of rules is established for typical ignition sources to represent the probable limits (i.e., the zone) of damage for a given ignition source category. Cables outside the ZOI for a given ignition source are treated as "not ignited" due to the direct effects of the ignition source.

Considerable research and testing have been done by the nuclear industry to develop and refine the damage capability of various generic ignition sources [16], [29]–[31], [34] . Nuclear plant ignition sources are not identical to those at CERN. However, significant overlap exists for electrical ignition sources (electrical equipment), and thus the ZOI approach is considered technically viable at CERN – albeit not blind application but reasoned adaptation.

The ZOI approach offers a means to greatly simplify design fire development, while also bringing consistency and repeatability to this qualitative process. A customized, full scope design fire development could be done for each scenario, but such an effort would be prohibitively resource intensive and most likely would have consistency issues similar to those experienced by the nuclear power industry during their initial efforts in fire PRA. Application of ZOI analysis is addressed in detail in Section 5.5.

5.2.1.4 Secondary Fires

A final topic to be addressed is the potential for an external exposure fire to cause a self-ignited cable fire at a location remote from the original fire (i.e., a potential fire at any location along the affected cable's route). These cases are termed "secondary fires" because they are initiated by the first fire and can produce a second fire at a different location. The failure mechanism that precipitates a secondary fire is insulation overheating, as discussed in Section 5.2.2. Secondary fires are a concern because simultaneous fires at separate locations is confounding for diagnosis and extremely challenging for firefighters. Secondary fires might seem highly unlikely; however, their occurrence is not infrequent. The most significant fire at a US nuclear plant in the past 10 years was caused by a secondary fire [43].

5.2.2 Self-Ignited Cable Fire

A "Self-Ignited Cable Fire" is defined within the context of this thesis as: A cable that is ignited as a result of abnormal current flow in the cable caused by an electrical fault in the cable or the circuit to which the cable is connected. Key characteristics of a self-ignited cable fire are:

- Electrical faults can manifest as direct short circuits, arcing faults, or a combination of both. The type of fault directly influences the circuit response and susceptibility to self-ignition.
- Two distinctly different failure mechanisms can result in cable self-ignition [18]:
    - Insulation Overheating – This failure mode occurs when resistive heating losses from electrical current flowing through the cable conductor exceed the ability of the cable to dissipate the heat. Ultimately, the cable insulation temperature reaches its failure point. This condition can result from a short circuit, overload, design deficiency, or circuit protection failure.

- Arcing Fault – This failure mechanism is caused by a loss of insulation integrity that results in airgap arcing when a voltage (electrical potential) difference is present. Arcing through air can produce extremely high local temperatures and explosive energy release.

- The fire origin for self-ignited cable fires can be at any location along the cable route, including multiple simultaneous locations.
- Self-ignited cable fires are possible only when a cable is energised. Therefore, equipment and circuits that are not in service are not susceptible to this failure mode.
- The risk of self-ignited cable fires can be managed through proper circuit design, appropriate fault protection, and testing/maintenance of circuit protection equipment and devices [35], [36].
- Cable insulation materials have different temperature withstand abilities [35], [37]. Accordingly, less capable materials are more susceptible to this failure mode. Conductor materials are also a factor, as they have different resistivity characteristics.
- The type of electrical circuit and its particular characteristics in which a given cable is installed influence significantly the risk of a self-ignited cable fire. These factors are discussed in Section 5.3.

5.2.2.1 Insulation Overheating

Except for superconducting materials, all electrically conducting materials have an intrinsic resistance to electrical current flow, characterised by the materials' resistivity. For typical conductor materials, resistivity values are extremely low. Resistivity (ρ) is a material property and is expressed as:

$$\rho = \frac{R \times A}{L} \quad \text{with units of } \Omega - \text{metre} \qquad [44]$$

Where: ρ is resistivity of a given material

R is the resistance of a specimen, specified in ohms (Ω) and calculated by Voltage/Current

A is the cross-sectional area of the specimen, specified in square metres (m^2)

L is the length of the specimen, specified in metres (m)

The inherent resistivity of a cable conductor results in heat production when current flows through the cable. This phenomenon is commonly referred to as "resistive losses" or "ohmic heating". The amount of heat produced in a cable is readily determined using basic electrical principles:

$$\mathrm{P} = \mathrm{V} \cdot \mathrm{I} \quad \text{and} \quad \mathrm{R} = \frac{V}{I}, \quad \text{thus } \mathrm{P} = I^2 \cdot \mathrm{R} \qquad [44], [45]$$

Where: P is power measured in Watts (W)

V is voltage, specified in Volts (V)

I is electrical current, specified in Amperes (A)

Combining these equations gives:

$$\mathrm{P} = I^2 \cdot \mathrm{R} = I^2 \left(\frac{\rho \cdot L}{A}\right) \qquad [44], [45]$$

Based on the above equation for resistive heating in an electrical circuit, the following observations with respect to cables are evident:

- The heat production in the cable occurs uniformly over the entire length of the cable
- By convention, cable specifications generally provide cable resistance as a per unit length quantity
- The longer a cable, the greater the overall resistance
- The bigger the cable (larger cross-sectional area), the lower the overall resistance and the lower the per unit heating
- Short circuit current can be many orders of magnitude greater than normal current, which – due to the squared function – can cause cables to overheat in seconds

A simple example helps illustrate insulation overheating. Assume a 25 mm^2 copper cable of length 60 m has a 90°C continuous temperature rating and is supplying a normal load current of 40 A. Now presume a short circuit occurs at the load end of the cable and this fault produces a fault current (I_F) of 12,000 A, which is a typical value for an industrial 400 V system. The per unit resistance of 25 mm^2 cable is about 685.6 $(10)^{-6}$ Ω/m, thus:

Heating Losses (Normal Conditions):

$$\mathrm{P} = \mathrm{I}^2 \cdot \mathrm{R} = 40^2 \cdot 685.6(10^{-6}) \cdot 60\ \mathrm{m} = 65.8\ \text{W or about 1.1 W/m}$$

Heating Losses (Fault Conditions):

$$\mathrm{P} = \mathrm{I}^2 \cdot \mathrm{R} = 12{,}000^2 \cdot 685.6(10^{-6}) \cdot 60\ \mathrm{m} = 5{,}923\ \mathrm{kW\ or\ 98.7\ kW/m}$$

It is obvious that cable heating under fault conditions is intense and extremely rapid; conductor temperature exceeds the insulation limit quickly. To guard against this condition, electrical codes mandate overcurrent protective devices (fuses, circuit breakers) be installed to detect faults and actuate prior to an unacceptable temperature excursion in the cable.

Figure 5 depicts the cable overheating concern. A fault occurs at the load, which allows a high fault current to flow. The high magnitude fault current dramatically increases the heat generation within the cable, which in turn rapidly raises the internal cable temperature to a level that causes insulation failure. Note that the heat production in the cable is uniform over the entire length of cable between power source and fault location. Thus, insulation failure can occur at any location along the cable and, as noted previously, failure can occur at multiple locations. The figure arbitrarily shows fire breakout at two locations, but it is emphasised that fire can erupt at many locations simultaneously. The inability to pinpoint the exact fire location resulting from this failure mode makes fire risk analysis difficult for long cable runs. Due to the location ambiguity and possibility of multiple fires in multiple fire compartments, the nuclear power industry places a high priority on risk management for this failure mode. The cable fire sub-model resulting from this thesis work will incorporate a similar philosophy.

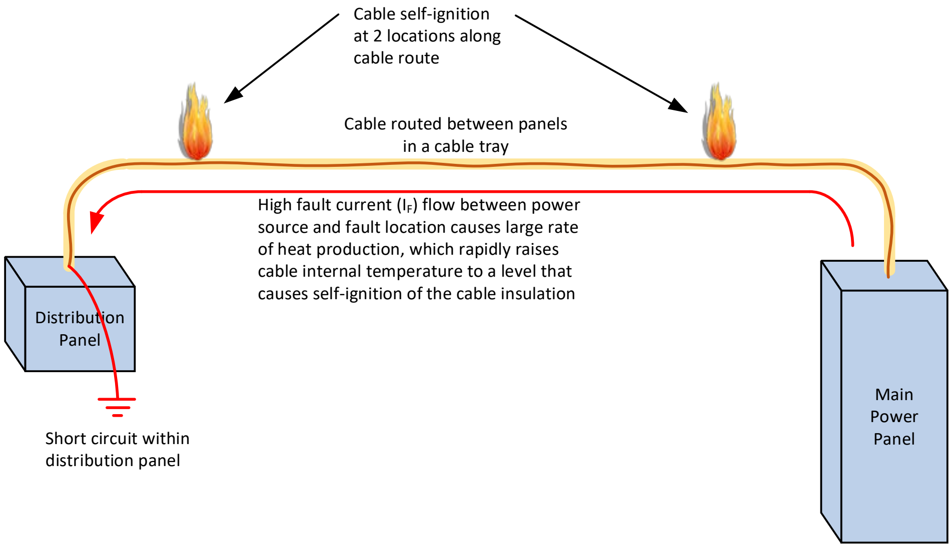


Figure 5 Self-Ignited Cable Fire – Insulation Overheating

The above example and discussion have focused on a short circuit as the initiating event that leads to an insulation overheating failure. Other conditions can also cause cable insulation overheating [35]:

- Inadequately sized cable for the load such that normal current draw from the load exceeds the cable rating
- Modifications that add loads to distribution panels without confirming the supply cable can handle the additional load without exceeding its ratings
- Improper settings or inadequately sized overcurrent protective device
- Overfilling cable trays such that the cables are not able to dissipate normal heat loads
- Inadequate maintenance and testing of protective devices
- An exposure fire that causes a short circuit at the fire location

Fortunately, this failure mode is well understood and rigorously covered by electrical design requirements. Problems most often occur when fundamental design standards are violated. The longstanding method of confirming adequate cable protection is through an electrical coordination study. The primary analytical tool for this study is "Time-Current Plots." Time-current plots are logarithmic graphs of time and current that depict damage thresholds for equipment (including cables) in relation to the tripping characteristics for a circuit's protective devices. The objective is that the protective device tripping characteristics are "coordinated" so that the device actuates before damage occurs to the protected equipment.

Figure 6 shows a typical coordination plot. Current is along the horizontal axis and time is along the vertical axis. The plot shows damage curves for two cables and one transformer. The other curves are the circuit's protective device tripping characteristics. The plot shows that the protective devices (adjustable circuit breakers in this case) will trip before the cable damage thresholds are reached for any fault current up to the maximum possible fault current for the circuit under review.

Standard equations are used to generate the cable damage curves. The equation for copper conductor cables is:

$$\left[\frac{I}{A}\right]^2 \cdot \mathrm{t} = .0297 \text{ Log} \left[\frac{T_2 + 234}{T_1 + 234}\right] \qquad [35], [37]$$

Where: I is short circuit current in amperes (A)

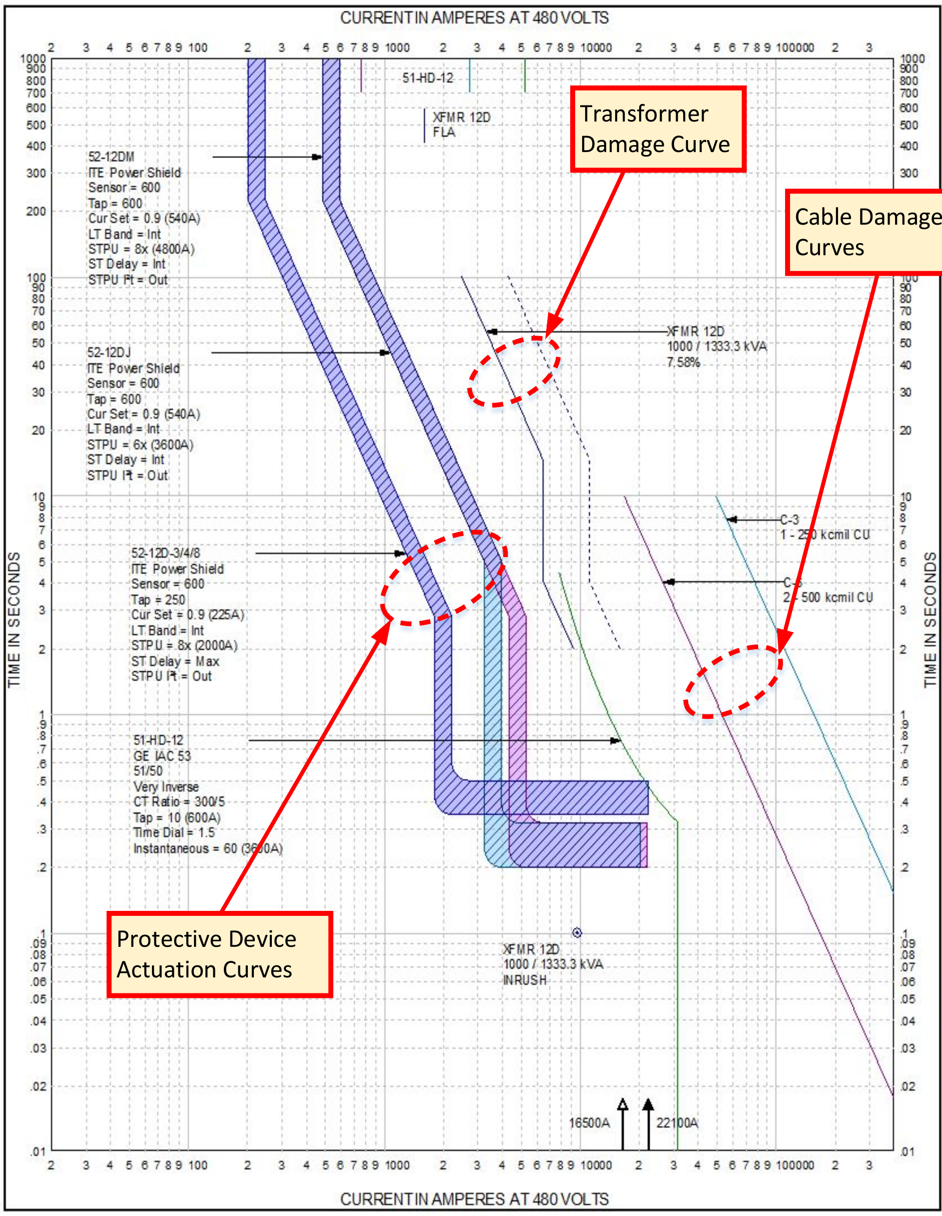
A is conductor area in cmils

t is time in seconds of short circuit condition

T_2 is cable maximum rated short circuit temperature in Celsius

T_1 is cable maximum rated operating temperature in Celsius

The formula for Aluminium conductor is slightly different. By convention, the maximum rated short circuit temperature is typically conservatively set to either 150°C or 250°C [37], which represents the onset of permanent damage. However, other temperature values can be used. For example, the actual self-ignition point for the cable insulation material can be used. However, in most cases experience shows that using self-ignition temperature in lieu of the onset to damage temperature (as provided by the cable manufacturer) does not appreciably change the outcome because of the logarithmic characteristics.



This typical time-current plot shows the relationship between equipment damage curves (transformer and cables) and the electrical protective device actuation characteristics.

Current is along the horizontal axis and time is along the vertical axis. The plot shows damage curves for two cables and one transformer. The other curves are the circuit's protective device tripping characteristics. The plot shows that, for any value of fault current, the protective devices (adjustable circuit breakers in this case) will actuate before the cable damage thresholds are reached.

Figure 6 Typical Time-Current Coordination Plot

5.2.2.2 Arcing Faults

The arcing fault hazard and insulation overheating hazard share common initiating events but manifest themselves in quite a different manner. The insulation overheating concern is a distributed problem along the entire cable length, whereas the arcing fault concern is a localized phenomenon.

An arcing fault occurs when an electrical arc is drawn across an airgap due to a voltage difference. The mathematical relationship supporting the concept of arcing is shown by the following equation:

$$\mathrm{v}(t) = \mathrm{L} \cdot {di}/{dt} \qquad [44], [45]$$

The equation shows that voltage in an inductive circuit is a function of the rate of change of current times the circuit inductance (L). An instantaneous change in the current quantity $(\mathrm{di}/\mathrm{dt})$ would require infinite voltage. This of course cannot occur in a real-world system, but voltage will increase. Depending on the voltage gradient, air pressure, and airgap distance, the voltage transient can create an arc. This arc might be momentary (as in a static discharge), intermittent (on and off cycle), or sustained. The arcs of concern from a fire ignition source perspective are intermittent and sustained arcs in high energy systems.

In many instances, an arc has negligible energy and thus does not have the capacity to ignite cable materials in the absence of another ignition source. However, high energy electrical power systems can produce large and highly damaging arcs, referred to as high energy arcing faults (HEAF) [21]. HEAFs have received substantial attention in the electrical industry over the past decade due to the many personnel injuries resulting from HEAF events [36], [46]. HEAFs have also been a source of concern in the nuclear power industry due to their potential to cause immediate and catastrophic damage [21]. Although HEAFs can initiate in cables, a vast majority of HEAF events are associated with equipment failure or connection point failure.

With respect to cables, an arc can result when an insulation breakdown occurs. The insulation breakdown allows unstable parasitic current paths to develop. When a conduction path ceases to exist, electrical principles dictate that current flow cannot stop instantaneously. Thus, system voltage undergoes a transient excursion in an attempt to maintain the current flow. The rapid voltage transient creates an electrical voltage gradient sufficient to ionize the air between the live conductor and other surface (usually a grounded surface). An arc can also occur in a cable if the air gap between the cable conductor and another conducting medium is sufficiently small that the voltage gradient breaks down the air in the gap and conduction occurs in the form of an arc.

Figure 7 depicts a high energy arcing fault (HEAF) caused by an insulation failure in the cable. Note that an abnormally high current flows, but only while the arc exists. HEAFs are primarily a transient phenomenon. Circuit protective devices are designed to detect the abnormal current flow and rapidly clear the fault. However, the explosive nature of arcing faults can initiate a fire even with proper fault protection. If protection fails, the extreme violence of a HEAF quickly vaporises the conductor and/or deranges the equipment. The consequences are severe and usually involve explosion damage and a subsequent fire.

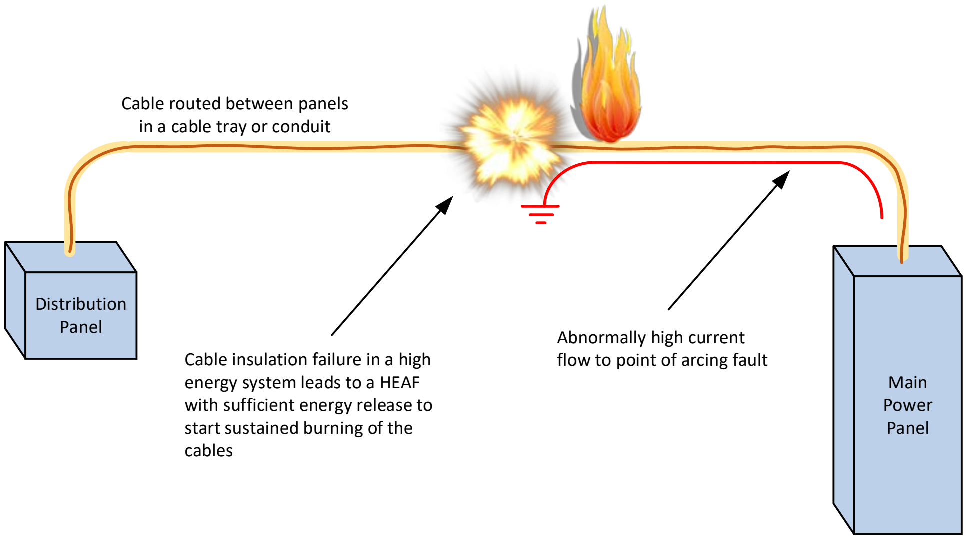


Figure 7 Self-Ignited Cable Fire – Arcing Fault

Arcing faults are primarily associated with equipment or cable termination points, as noted previously. These cases are classified as Cable Termination Fires and are addressed in 5.2.3. Arcing faults along a cable route do occur but are much less common. Possible causes of cable arcing faults are:

- Cable degradation due to aging, high temperature environment, damp environment, ionizing radiation, or a combination of these factors
- Mechanical damage to insulation material as part of construction or other work activity
- Violation of cable bending radius during insulation
- Cable insulation failure caused by an exposure fire

The precise behaviour of cable faults is dynamic and depends on many factors. A fault can include both insulation overheating and arcing in combination.

5.2.3 Terminal Equipment Fire

Within the context of this thesis, a "Terminal Equipment Cable Fire" is defined as a cable or group of cables that are ignited by a fire at the terminal equipment for the cable(s). Key characteristics of a terminal equipment cable fire are:

- Unlike an exposure fire or self-ignited cable fire, the point of origin is known for a terminal equipment cable fire.
- It is possible but not desirable to treat terminal equipment cable fires as external exposure fires or self-ignited cable fires because the probability values and behaviour are different at termination points.
- Termination point failures involve electrical equipment (motors, power panels, heaters, junction boxes, instrument cabinets, power supplies, batteries, etc.). The initiating event for the fire will vary depending on the type of equipment.
- A cable can be energised or de-energised at the time of ignition. For energised cables, secondary ignition along the cable route should be considered.
- Cable ignition can be due to fire propagation, flame impingement, radiation, or arcing fault.

Figure 8 shows two examples of a cable termination fire – a fire originating at an electric motor and a fire originating inside an electrical power panel. The conditions are essentially the same regardless of the equipment involved. The equipment catches fire due to some sort of failure – usually an electrical failure, but not always. For example, the motor failure could be caused by an overheated bearing. Regardless of the cause, the fire ignites the cable (or group of cables) and continues to propagate along the cable.

Many instances of cable termination fires involve electrical panels, boxes, or cabinets. For these cases, the analysis focuses on two considerations:

- The probability of failure for the equipment
- The likelihood that a fire inside a panel or cabinet can propagate to outside the cabinet

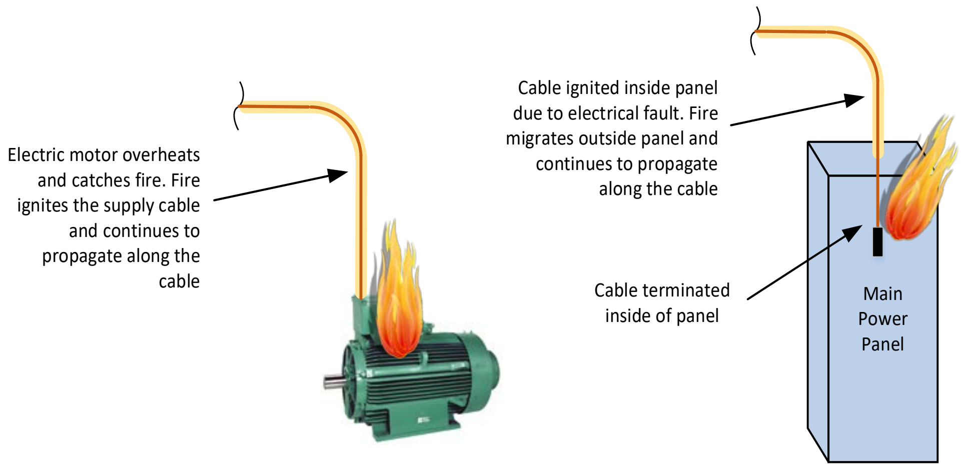


Figure 8 Terminal Equipment Cable Fire (with fire propagation)

5.3 Electrical Parameter Characterisation

This section presents a technical evaluation of the electrical parameters thought to influence cable fire sequences (see Table 2). The assessment provides a technical basis for including (or not including) a given parameter in the model. Some parameters might be worthy of inclusion from an analytical perspective, but practical considerations and/or marginal incremental benefit might limit real-world application. Such cases will be identified.

5.3.1 Circuit Operating State

A simplistic approach to circuit operating state is adequate for the purposes of this study. Cables are considered to carry the same operating state as the circuit to which they belong. Three operating states are of interest:

Energised (On)	The circuit is in service and is electrically energised; electrical voltage and/or current are present
De-energised (Off)	The circuit is not in service and not energised; no electrical voltage or current are present
Intermittent (On/Off)	The circuit operates intermittently based on a controlling parameter, condition, or configuration; for example, an air compressor motor will start and stop as necessary to keep an air receiver within a set pressure band

The importance of operating state to the cable fire risk analysis is that:

- De-energised circuits are not vulnerable to self-ignited cable fires
- De-energised equipment does not pose an electrical failure hazard with respect to external exposure fires or cable termination fires

LHC dipole magnets provide an example. During shutdown periods the magnets are powered down. In this state, the power converters are off, the non-superconducting lead cables carry no current, and the super-conducting magnets are de-energised. The fire risk associated with this system is much lower in this state than when energised.

It is not practical to track operating state for the thousands of individual circuits in the CERN complex. However, the state of most electrical equipment is driven by the LHC operating mode. Hence, the cable fire sub-model will include as a variable the LHC overall operating mode, as defined by CERN procedures [47]. Operating modes are classified as Accelerator Modes and Beam Modes. Each category has numerous sub-modes. It is not considered practical nor beneficial to run separate fire risk analyses for each sub-mode. Thus, the sub-modes are rolled up into three general modes, as shown in Table 5. NB: As discussed in 6.2.2, the “Start-up” and “Operational” modes are lumped together and treated as a single mode.

Table 5 LHC Operating Modes [47]

Operating Mode	Description
Shutdown	▪ Beam is off ▪ Magnets are cold ▪ Vacuum, cryogenic, other support systems off ▪ Machine accessible after waiting period
Startup	▪ Beam is off ▪ Encompasses many accelerator sub-modes associated with support system startup and machine checkout
Operational	▪ Beam is on ▪ Magnets, vacuum, cryogenic, other support systems in service ▪ Encompasses many beam sub-modes, including normal and abnormal conditions

5.3.2 Circuit Classification

In practice, it is common to use four general circuit classifications (see Table 6). These classifications are driven by function, but inherently characterise the circuit with respect to voltage, current, and energy. Consequently, circuit classification is a useful fire risk parameter since it aggregates the key circuit parameters (i.e., operating voltage, available current capacity, and energy levels). Table 6 lists and describes the commonly used circuit classifications.

Table 6 also comments on the fire risk associated with each class of circuit. As explained, high energy power circuits and equipment are the greatest concern and will be included in the cable fire sub-model. Control power circuits will also be included in the model as potential ignition sources, but their relative risk potential is considerably lower than power distribution circuits. In general, signal circuits and control circuits can be treated as a negligible ignition source risk. It must be kept in mind that the above argument applies to cables only and not to equipment. Signal and control electrical cabinets are treated as ignition sources.

Table 6 General Circuit Classification

Classification	Description	Fire Risk
Signal	▪ Measuring, recording, computing ▪ Analog and digital circuits ▪ Very low voltage AC or DC (5 V – 50 V) ▪ Very low current (typically milliamperes) ▪ Low energy levels	▪ Negligible risk of cable self-ignition due to low energy ▪ Rarely considered a viable ignition source
Control	▪ Analog and digital circuits ▪ Very low voltage AC or DC (5 V – 50 V) or control voltage (100 V – 220 V) ▪ Often intermittently energised ▪ Very low to low current and energy levels	▪ Negligible risk of cable self-ignition for very low voltage, low energy circuits ▪ Low risk of cable self-ignition for conventional circuits ▪ Some older style 110 V or 220 V control circuits carry enough energy to pose an ignition source concern, but most new control circuits are digital or operate at low voltage with limited energy potential ▪ Battery backed systems more hazardous because of high stored energy potential
Control power	▪ AC or DC voltage ▪ Conventional voltage levels (100 V – 220 V) ▪ Low to medium energy levels ▪ Medium current levels ▪ DC systems almost always have UPS backup with batteries	▪ Potential for self-ignition must be considered ▪ Intermittent arcing faults possible, but sustained faults are rare ▪ Main concern is insulation overheating associated with large power source or battery system
Power	▪ AC power distribution systems ▪ Broad category – includes facility, distribution, and transmission systems ▪ Low, medium, and high voltage levels (220 V – 400 kV) ▪ Medium to high current and energy levels	▪ Primary category of concern for self-ignited cable fires ▪ Highly damaging HEAF concern ▪ Firefighting live electrical fires involving large power distribution equipment carries inherent challenges

5.3.3 System Voltage

The electrical power industry has established through codes and standards the nominal breakdown of electrical power distribution system voltage. The nominal categories typically used in Europe are defined by IEC Standard 60038 [48]; these categories are shown in Table 7. Except for the main substations, CERN electrical systems include only low and medium voltage systems.

The primary power distribution system to LHC facilities operates at 18 kV. Local power transformers step down voltage to 400 V [14], which is the nominal service voltage at the facilities. Accordingly, the cable fire sub-model focuses on fire risk from low voltage systems.

Table 7 Electrical System Voltage Classification [48]

Classification	Description
Low voltage	Up to 1,000 V
Medium voltage	1,000 V up to 35,000 V
High voltage	35,000 V up to 230,000 V
Extra high voltage	Above 230,000 V

The low voltage category designation can be misleading. High energy power circuits operating at 400 V and above can produce highly damaging arcing faults and can suffer major cable insulation overheating events. In general, circuit classification is a better gage of fire risk potential than voltage alone because it is the combination of voltage and energy level that define the fire risk, as discussed in Section 5.3.2. For this reason, voltage will not be a stand-alone parameter in the cable fire sub-model, with one exception.

Voltage will be used as a delimiting parameter for arcing faults in power circuits. General industry consensus is that voltages less than 240 V are not able to sustain an arc through multiple cycles of the AC waveform, which means arc energy is held to low levels because the arcing time is very short [36], [38], [46], [49], [50]. The idea behind a sustained arc in an AC system is that an arc momentarily extinguishes as voltage across the arc location cycles. If voltage recovery reaches a certain threshold level, the arc restrikes thereby sustaining the event. If the voltage is not of sufficient magnitude to cause restrike, the arc does not sustain itself.

Although systems below 240 V have caused fires, it is generally not because of arcing faults. Based on the electrical principles discussed above and the electrical industry practice of discounting voltages lower than 240 V as an arcing fault concern for personnel, arcing faults will not be considered a viable ignition source for circuits operating at voltages of 240 V or lower [22], [36], [46].

In contrast, 400 V power systems have demonstrated the ability to sustain arcing faults and deposit substantial energy into the arc [21], [22], [38]. Due to the high damage and fire potential of HEAF events within the 400 V to 500 V range, electrical codes often require specific fault detection sensors for arcing faults.

5.3.4 Available Energy

Available energy from a system is a key factor in determining the fire risk potential of a circuit. As was the case with voltage, circuit energy capacity is best captured within the circuit type category. A circuit with low energy potential is not able to sustain voltage during electrical faults. As current increases, the voltage collapses to a level controlled by the power source. Therefore, total available energy that can be driven into a faulted circuit is limited by the power source's power rating. As such, it is readily apparent that signal and control circuits, supplied by small DC power supplies, pose a minimal fire risk. Conversely, a large power transfer that can supply 20,000 A of fault current with minimal voltage collapse poses a significant risk. These concepts are incorporated into the cable fire sub-model via the circuit classification parameter.

5.3.5 Cable Materials

Cable design and materials play a significant role in cable fire risk, including ignition temperature, propensity to propagate flame, and combustion product yields. A wealth of information and fire test data is available for cables and this project will make use of much of it; however, this thesis is necessarily constrained as to the depth to which this topic can be addressed. The focus here is on the relevant functional characteristics of ignition potential; other aspects of the FIRIA Project address flame spread and propagation, cable heat release rate (HRR), and combustion product yields.

Except for certain special high temperature cables, general industrial cables can be grouped based on two insulation categories and two conductor categories:

Insulation Types: Thermoset and Thermoplastic

Conductor Types: Copper and Aluminium

5.3.5.1 Cable Insulation

Table 8 identifies typical insulation properties of interest.

Table 8 Cable Insulation [37], [42]

Characteristic	Thermoset	Thermoplastic
Damage Temperature	250°C	150°C
Failure Temperature	330°C	205°C
Failure Heat Flux	11 kW/m^2	6 kW/m^2
Operating Temperature	90°C	75/60°C

Notes:

1. Operating temperatures are from customary electrical engineering and cable specifications. These temperatures represent a temperature at which a cable can operate continuously without any decrease in cable life.
2. The damage temperatures are from customary electrical engineering and cable specifications. These temperatures represent a temperature at which cable life can be degraded.
3. Failure temperatures are from nuclear industry testing and represent the point of immediate cable failure. These temperatures are also taken as the threshold of self-ignition.

Thermoset insulation materials are typically associated with better temperature withstand and flammability characteristics in comparison to thermoplastic materials. Thermoset materials are polymers that become irreversibly hardened as part of the manufacturing process. Thermoplastic materials are also polymer materials but differ from thermoset materials in that they become pliable and melt at elevated temperatures. This characteristic is evident during a cable fire – thermoplastic insulation catches fire, melts, and drips away from the cable conductor. Thermoset insulation catches fire at a higher temperature and, while burning, it does not appreciably change its original shape, even after completely burning (the insulation becomes a charred shell around the cable conductor).

Thermoset cables are superior to thermoplastic cables from a fire protection perspective. They are less likely to be ignited by a fire and are less likely to undergo self-ignition under fault conditions. Additionally, thermoset cables propagate fire at a lower rate and do not drip hot flaming materials, which can start secondary fires. Thermoplastic cable is used pervasively in general purpose applications that do not require high performance. It is less expensive, easier to work with, and less prone to physical damage. Cable manufacturers often include additives to the insulation and jacket material to reduce flammability, minimise toxicity and acidic content of smoke, increase electrical insulating properties, resist moisture intrusion, and increase aging and radiation resilience.

5.3.5.2 Cable Conductor

Table 9 identifies conductor properties of interest.

Table 9 Cable Conductor [51], [52]

Characteristic	Copper	Aluminum
Specific Resistivity	1.678 $(10)^{-8}$ Ω m	2.796 $(10)^{-8}$ Ω-m
Conductivity	5.96 $(10)^{7}$ S/m	3.58 $(10)^{7}$ S/m
Melting Temperature	1083°C	660°C
Thermal Conductivity	392 W/m-K	240 W/m-K

Copper has better electrical properties than aluminium; however, aluminium is considerably less expensive and thus it is popular in general purpose applications. Copper is about 65% more conductive than aluminium. Therefore, it performs better than aluminium under both normal and abnormal current flow. Temperature conductivity for copper is also greater.

CERN LHC cable specifications call for copper conductor, high quality insulation materials (thermoset – typically XLPE or EPR), and robust thermal and radiation aging properties. In some instances, special fire-resistant cable is used. The use of high-quality cable reduces the vulnerability to fire for all three categories of cable fires. The use of high-quality cable also mitigates the consequence of a cable fire because of slower flame propagation rates and reduced smoke production. The use of high-quality cable will be taken into consideration during the development of fire scenarios.

5.3.6 Overcurrent Protection

Overcurrent protection is a key factor is assessing cable reaction to fire. Previous sections have explained the types of circuits that are vulnerable to self-ignited cable fires, including both insulation overheating and arcing fault failures. Proper overcurrent protection is critically important to minimising cable fire risk [35], [36], [53]. Recall that both external exposure fires and termination fires can initiate a self-ignited cable fire for energised circuits. Hence, overcurrent protection can influence the probability and consequence for all three categories of cable fires.

Section 5.2.2 discusses the electrical principles that lead to insulation overheating and arcing faults. This section expands on these principles and explains electrical engineering objectives in developing overcurrent protection schemes. A foundational element of electrical circuit design is protection against fault conditions. It might be a ¼ ampere fuse in a small 12 VDC control circuit or large SF_6 circuit breaker for a 400 kV switching station, costing 2M €. In either case, the function is the same:

1. Detect abnormal current flow and remove the faulted portion of the circuit from service as rapidly as possible

2. Avoid disruption of service by undesired actuation during normal and expected transient conditions
3. Coordinate with other protective devices in the circuit such that the device closest to the fault actuates first

Following applicable codes and standards [35], [36], [46], [53], electrical engineers develop an electrical protection scheme for facilities and equipment. The universally accepted means of developing and documenting the protection scheme is a “coordination and protection study”. The coordination and protection study is a compilation of time-current characteristic plots that reflect the design engineer’s decision on selection of overcurrent protective device type, size, and settings for all circuits in a system. Figure 6 introduced time-current plots and explains how cable damage curves are plotted. Although the time-current plots are multifaceted, the focus here is on the protection of cables. A properly designed system will include:

1. Overload protection against low-level overcurrent conditions that can eventually raise cable temperature above its rated temperature limit
2. Short circuit protection over the full range of available fault current, including ground faults, line-to-line faults, and arcing faults
3. Backup or redundant short circuit protection that clears a faulted circuit in the event the primary protection fails

Figure 9 is a typical time-current plot that demonstrates the above design criteria:

- The small one-line diagram shows the branch circuit devices
- The cable to be protected is from the transformer (SUB 11) to the distribution switchgear (SUB 11 BUS). The cable damage curve is labelled as a C-TX11
- The circuit protective devices include a primary fuse (S&C SMD-50) and multifunction overcurrent relay (MAIN Basler BE1-851)
- The multicurrent relay provides ground fault and arc fault protection (Neutral curve) and line-to-line protection (Phase curve)
- The multifunction relay will clear before the upstream main fuse
- The main fuse provides backup overcurrent protection for the cable if the relay fails

The cable fire sub-model fault tree will include logic gates to capture the overcurrent protection features, including primary and backup protection. Provided this protection exists and is properly maintained and tested, the contribution to cable fire likelihood and consequence of self-ignited cable fires and secondary fires can be greatly reduced.

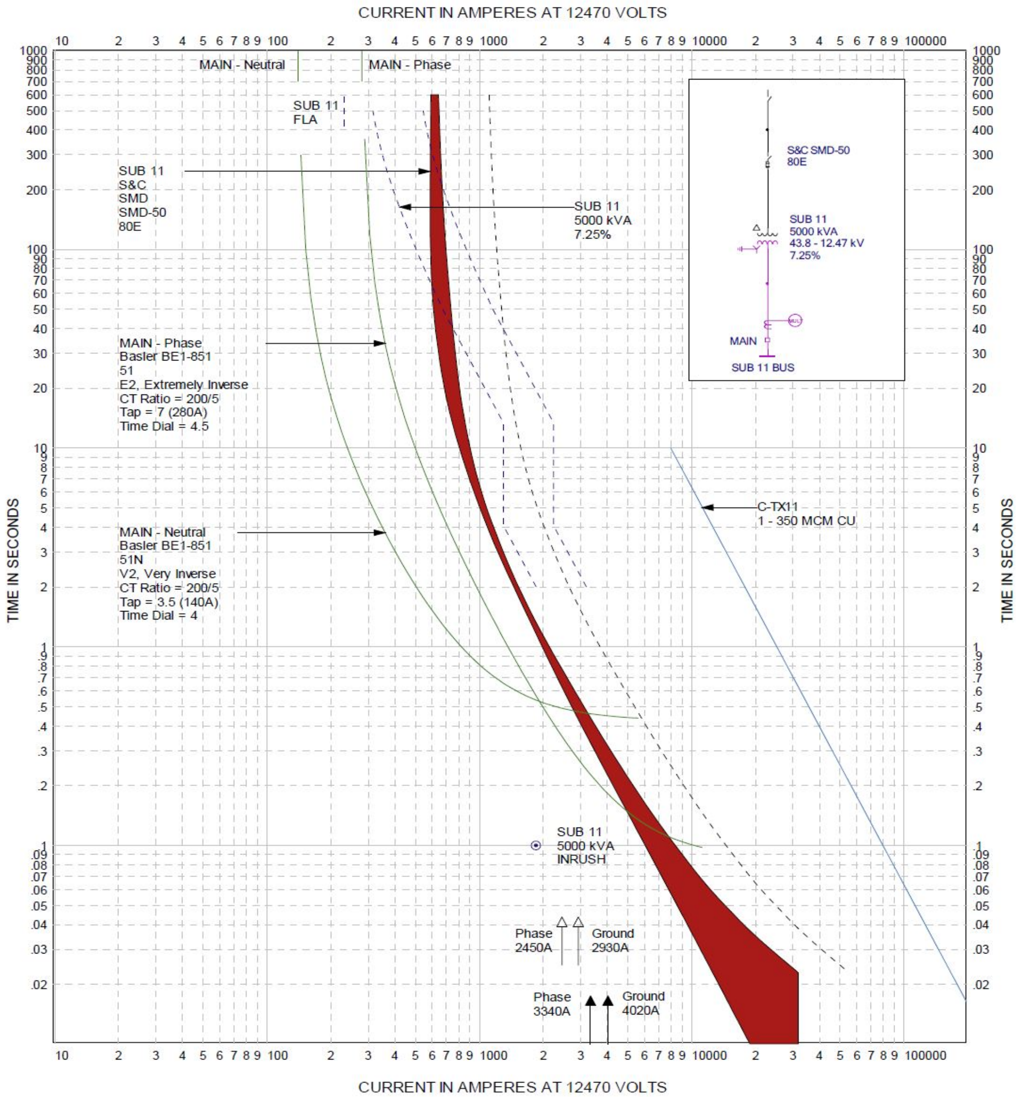


Figure 9 Coordination Study Time-Current Plot

5.3.7 Equipment Monitoring, Testing, and Maintenance

Previous sections discuss the relevance of cable characteristics and overcurrent protection to cable fire risk. As with all equipment, cable, circuit breakers, and overcurrent devices require monitoring, testing, and maintenance to ensure continued functionality. Industry experience demonstrates a high correlation of electrical fires to inadequate design conditions or failure of overcurrent protection equipment. In many instances, improper or lack of maintenance and testing is the root cause. The nuclear power industry tracked HEAF initiated fires for over 20 years; over 60% of the failures were attributed to a design mistake, improper maintenance, or failure to test [34]. The most severe fire at a nuclear plant in recent times was due to a combination of cable failure, inadequate maintenance of circuit breakers, and human error. The event resulted in secondary fires in separate fire compartments and challenged the automatic nuclear safety emergency cooling system. Events of this nature in more traditional industries might not be as consequential, but the correlation between electrical failures and inadequate maintenance is remarkably high.

A run-to-failure strategy is justified for equipment that is normally in service and performing an active function, such as a motor or machine. If the device quits working, the failure is immediately noticed. Circuit protective devices are fundamentally different. These devices sit idle for years and then are expected to respond perfectly within milliseconds to detect and clear a severe electrical fault. The mechanical and electrical stresses under a severe short circuit on a high energy power system are tremendous. The only means of ensuring these devices are able to respond as intended is through periodic testing and maintenance.

Manufactures provide recommendations for maintenance and testing for their equipment. There are also codes and standards which apply. Protective device maintenance and testing often centre around guidance from the International Electrical Testing Association (NETA) [54] and National Electrical Manufacturers Association (NEMA) [55]. Inadequately maintained protective devices correlates to increased fire risk [36], [54].

5.3.7.1 Circuit Breakers & Relays

Circuit breakers and overcurrent sensing devices in particular require periodic servicing [54]. A failure to conduct necessary periodic maintenance and testing progressively degrades the health of an electrical power system and its ability to safely isolate a faulted circuit.

Small moulded-case circuit breakers have lubrication on the tripping mechanisms. This lubricant can harden over time, which slows or prevents the tripping mechanism function. Larger power circuit breakers contain delicate linkages for the many operating parts. These linkages and other mechanical parts require periodic adjustment and lubrication to ensure tripping times remain within specification [55].

Overcurrent relays (electrical and mechanical) and fault sensors are delicate instruments that are subject to drift over time. These devices require periodic calibration to ensure proper response to a fault condition [54], [55].

5.3.7.2 Cable Monitoring

A consideration for cable is service life under prevailing conditions. Cable aging is a well understood phenomenon that has been studied extensively. Natural aging, chronic high temperature and moist environments, average operating load, number of through faults seen, and ionizing radiation act to slowly degrade cable insulation characteristics over time. CERN LHC is a relatively new facility and environmental effects are most likely negligible. However, over time aging will result in an increase in the frequency of cable failures. CERN appears to have an active cable aging management program. Cable aging and environmental degradation is unlikely to be an important factor in fire risk at LHC.

5.4 Cable Fire Fault Tree Template

This section presents one possible sub-model fault tree arrangement. The fault tree branches can and should be modified to accommodate different hazards that will be present in different compartments. Figure 10 shows the top-tier structure of the cable fire fault tree. Note that each facility and compartment can have separate inputs, thus the top gates are labelled with the facility and compartment identifiers. The likelihood of a cable fire can be represented as three distinct branches in the fault tree, with each branch being one of the main cable fire hazard categories, as described in Section 5.2. These categories are treated as independent events, although this is not strictly true due to secondary fire possibilities. Each main hazard category is sub-divided into two distinguishable sequences based on the ignition source hazard.

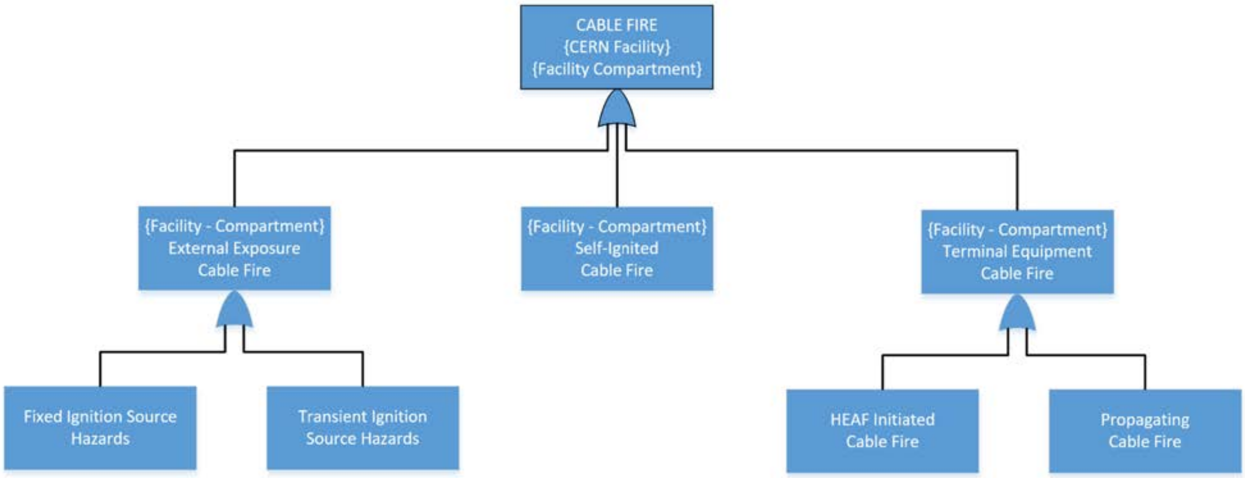


Figure 10 Cable Fire Fault Tree Top-Tier Framework

5.4.1 External Fire Hazard Fault Tree Branch

Figure 11 shows the fully developed fault tree for external fire hazards. The Bin 1 to Bin 4 gates represent the ignition frequency due to fixed ignition sources, with each bin representing a separate category of equipment/hazard. Although four bins are shown in the figure, the actual bins to be modelled are determined by the different fixed ignition sources in the compartment under review. Fire failure probabilities are established for each bin based on failure frequency data for the characterised ignition source. Each equipment bin is paired with a ZOI factor to represent the likelihood that a given external fire ignition source will ignite cables nearby (i.e., the cables are within the ignition source's ZOI). The transient ignition source hazards are based on typical concerns, but other specific hazards can be included as appropriate.

5.4.2 Self-Ignited Cable Fire Hazard Fault Tree Branch

Figure 12 shows the fully developed self-ignited cable fire fault tree. For the reasons discussed in Section 5.3, separate branches are created for low voltage control power, 400 V power, and 18 kV power. Each of these branches uses a different style of equipment for fault protection and interruption. Additionally, each category has different fault behaviour and energy levels. Both primary and backup overcurrent protection are considered since both should, by design, minimise the chance of cable overheating and limit the energy deposited during an arcing fault. Sustained arcing faults along a cable route are rare and are not considered a significant contributor to self-ignited cable fires since most arcing faults occur within equipment or at connection points. Available date does not distinguish between arcing faults and insulation overheating for self-ignited cable fires.

5.4.3 Terminal Equipment Cable Fire Hazard Fault Tree Branch

Figure 13 shows the fully developed fault tree for terminal equipment fire hazards. Separate branches are created for HEAF events and propagation. The two branches are quite different and help distinguish between general electrical cabinets and power distribution enclosures.

In developing terminal equipment fault tree branches care must be taken to distinguish propagating faults from exposure fire hazards. As shown in the previous illustrations, they are separate mechanisms for a cable fire. Fire propagation along a cable from inside an electrical enclosure to outside the enclosure is generally considered preventable by proper electrical penetration seals at the equipment/cabinet entrance.

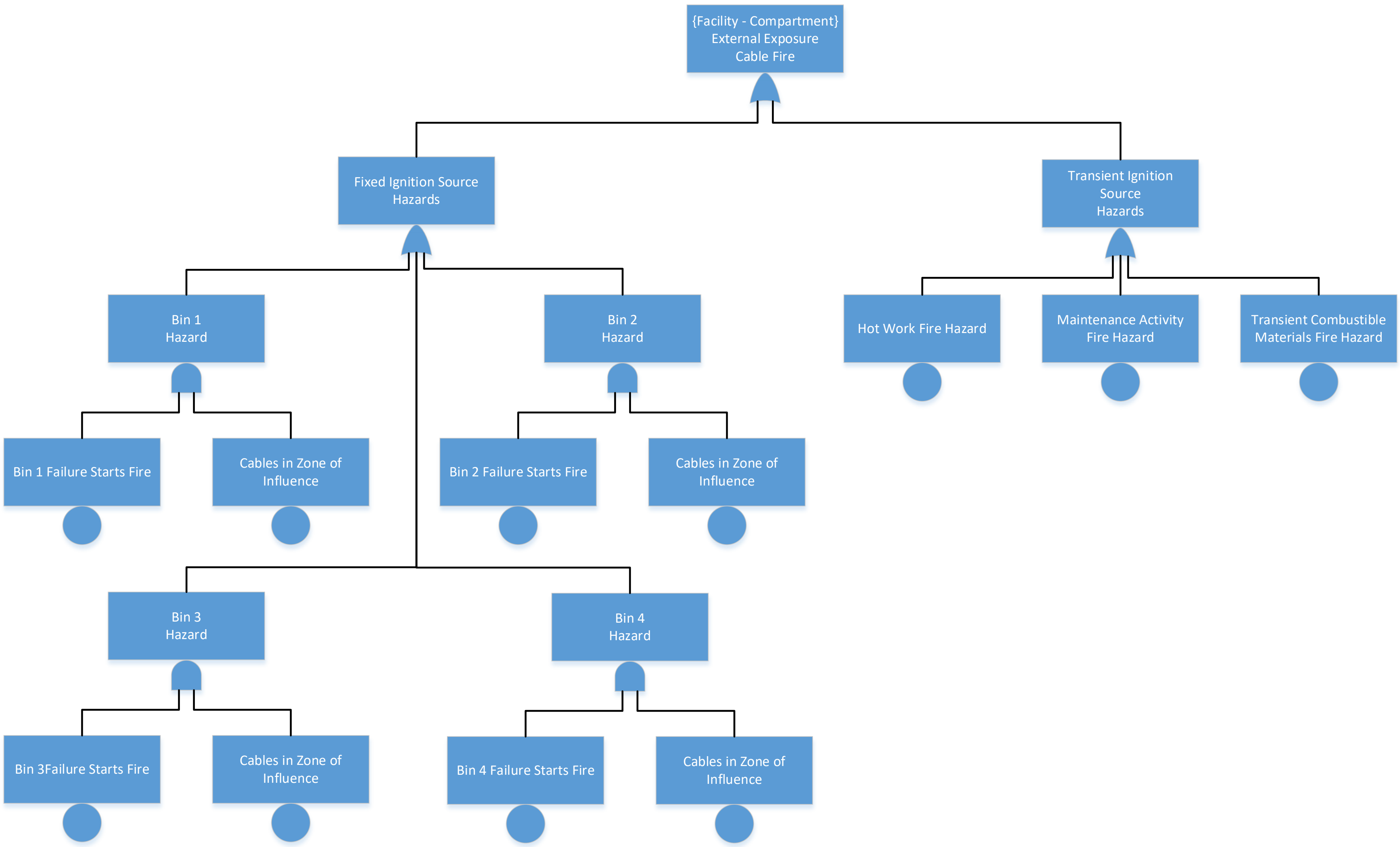


Figure 11   Fixed and Transient Ignition Fire Hazard Fault Tree Branches

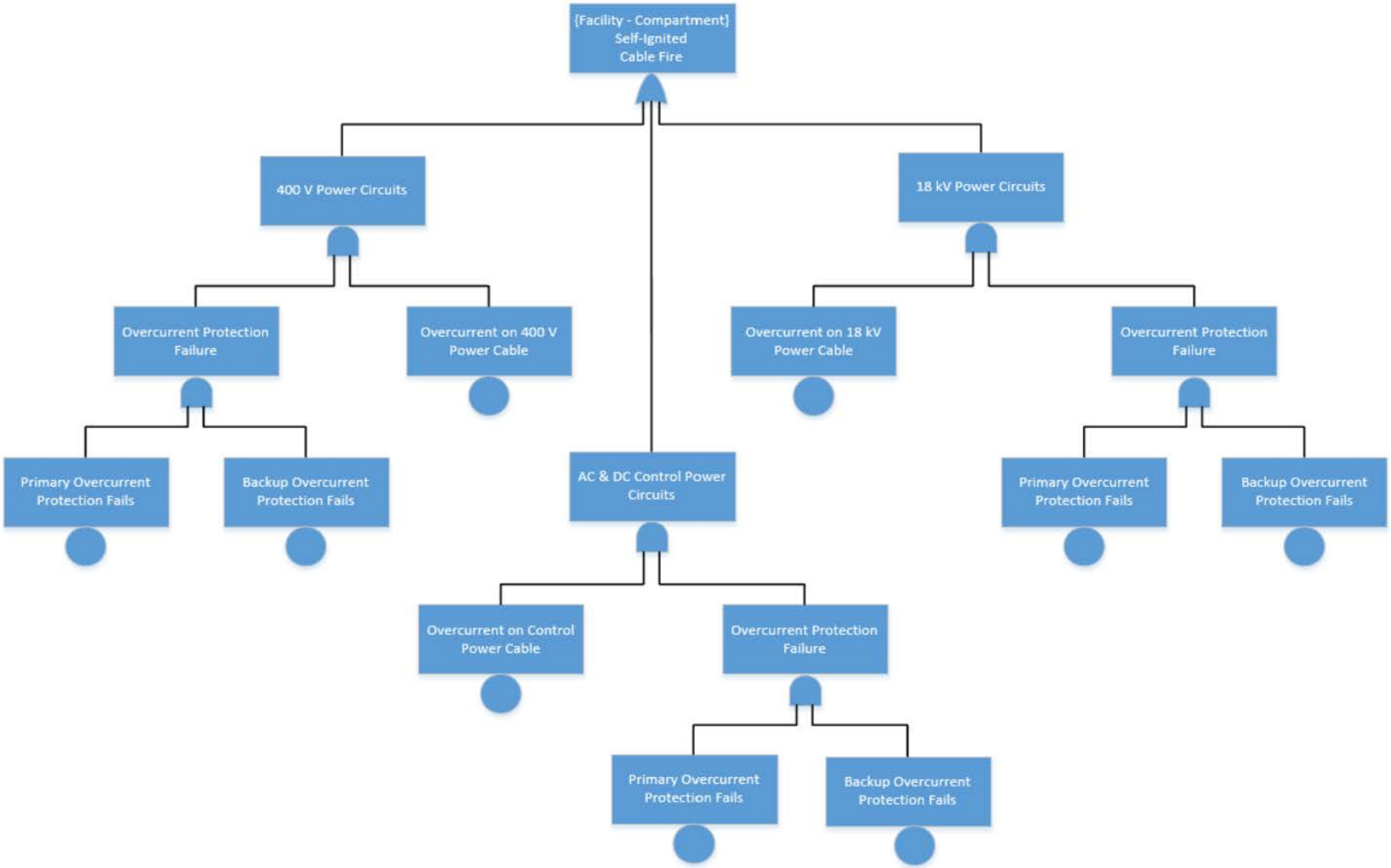


Figure 12 Self-Ignited Fire Hazard Fault Tree Branches

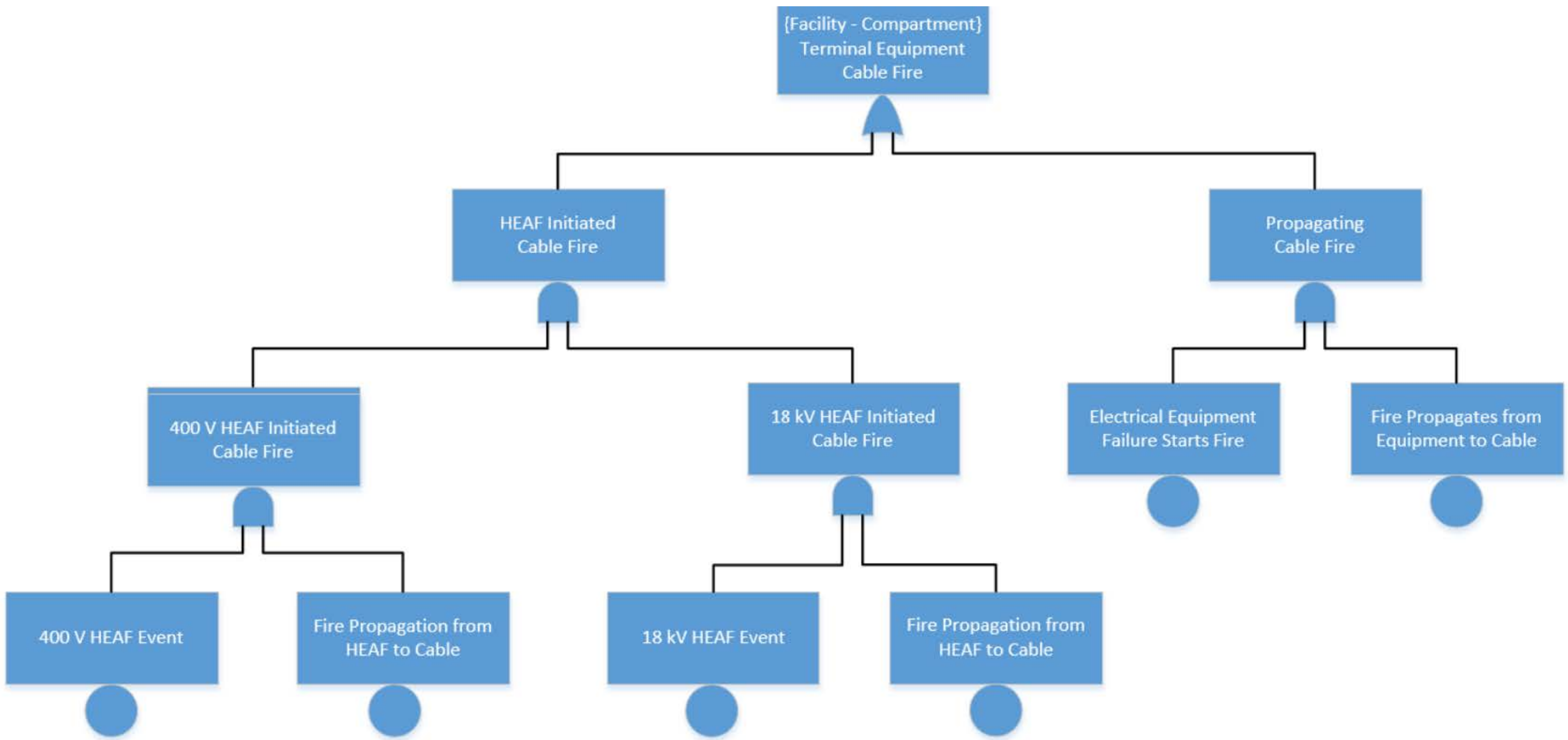


Figure 13 Terminal Equipment HEAF and Propagation Fire Hazard Fault Tree Branches

5.5 Probability Estimates for Cable Fire Sequences

Before proceeding with the calculation of cable fire sequence probabilities, it is appropriate to review what is and what is not included in the fault trees. Referring back to Figure 3, the cable fire fault tree provides a probability for inclusion into the event tree. The probability is assigned to the cable fire scenario within a specific compartment for a given facility (NB: The fault tree is illustrative only and does not capture other important aspects of the design fire scenario. For example, the event tree might also include probability of detection, probability of automatic or manual suppression, fire department response, fire HRR, flame spread, ventilation, etc.). Estimating the probability of a cable fire does not obviate the need to define a design fire curve for the scenario and to conduct a full analysis to determine consequences.

5.5.1 Cable Fire Analysis Methodology

The fault tree logic structure inherently combines the individual basic event input probabilities to compute an overall cable fire frequency for the given scenario. Therefore, the main effort involves determining the fault tree basic event frequencies. The proposed process for calculating the basic event frequencies is based on the methodology presented in NUREG/CR-6850 [16], [33], [34] and related lower-tier guidance documents. The methodology is based on a rigorous accounting of potential fire hazards within defined fire compartments (including virtual compartments) and avoids site-wide uniform distribution of risk. In this way, the overall analysis maintains a quantitative approach several levels deep and thereby avoids masking true risk areas.

An example is helpful in depicting this concept. Assume data shows the likelihood of a self-ignited cable fire for ATLAS is 3.5 E-3/year. This information can be represented as a site-wide value and the fire hazards assessment completed accordingly. However, this general approach does not offer any specific insights as to which locations within ATLAS actually carry this risk. If instead the analysis is conducted on a compartment level and facility walkdowns determine the nature of circuits routed in each area (i.e., power, control, instrumentation), specific frequency values can be assigned as appropriate. This more refined approach provides quantitative probability values for the different compartments, allowing clear distinction between areas containing mostly instrument cables versus areas with a high load of large power cables. One might say that this is obvious, which it is on an individual basis. However, the benefits of this rigorous approach become evident when trying to assimilate and analyse all possible combinations of cable ignition hazards and target cables, as dispersed over the entire facility. The example case portrays the two fundamental elements upon which the NUREG/CR-6850 method [16] is based:

<u>Defined Compartments</u>: The hazards analysis (cable fire risk for the purposes of this research) is conducted on a compartment-by-compartment basis. Hence, the fire frequencies and fire risk are computed for each compartment. Since the LHC tunnel and experiment main caverns do not contain compartments easily defined by structural boundaries, this study will use the concept of virtual compartments, as introduced in Section 5.1.4. It is acknowledged that use of virtual compartmentation is not ideal compared to fire rated barriers. However, the approach will yield better insights compared to treating these locations as single areas.

<u>Weighted Assignment of Frequency</u>: The compartmentation process is advantageous. However, the true value of compartmentation is leveraging weighting factors for the compartment ignition source fire hazards. This is accomplished by binning the various fire hazards within each

compartment and assigning an ignition source fire frequency in the fault tree based on the single failure probability for the bin times the number of ignition sources in the compartment. For example, assume that the scenario of interest is the virtual compartment for a dipole magnet section of the LHC tunnel. Further assume that it has been determined that the LHC tunnel has a total of 490 electrical cabinets, of which 22 are located in the defined virtual compartment. If the facility fire frequency for electrical cabinet fires is 2.2E-1/year, then the individual fire frequency for each cabinet is:

2.2E-1 / 490 = 4.49E-4/year

and the probability value for this hazard bin in the fault tree is:

4.49E-4/year x 22 = 9.88E-3/year

The NUREG/CR-6850 [16] process can appear overwhelming. However, with the hazard bins predefined and facility level fire probabilities available for each bin, fire hazard walkdowns can be accomplished in a relatively short period of time. The resources expended on focused walkdowns greatly streamline the follow-on fire scenario development effort and set the stage for true quantitative fire risk analysis.

5.5.2 Ignition Source Fire Hazard Frequencies

Ideally, CERN-specific fire frequency values are applied in the fault tree. Unfortunately, CERN fire event data and equipment failure data has not historically been collected in a manner that supports failure frequency estimations. Consequently, other data must be used to begin with. It is envisioned that the FIRIA Project will include actions to revise data collection of fire events and failures such that this data can progressively replace the generic data. An update plan such as annual Bayesian updates is one possible option.

In lieu of using general industry fire and reliability data, this thesis will focus on data obtained for nuclear power plants. Ignition source frequency data for the various ignition source bins is provided in NUREG/CR-2169 [34]. This data is judged to be the best substitute for CERN specific data due to similarities in equipment, operating conditions, and facility management. Appendix D provides a listing of ignition source frequencies and an explanation of the “binning” process developed by the nuclear power industry. The adoptability of this process to CERN has many advantages. It is a well vetted process and incorporates many lessons learned over the past two decades.

The cable fire fault tree sub-model developed for Objective 2 is an advancement beyond the current practice in the nuclear power industry. The more advanced model contains functionality related to circuit overcurrent protection, which is not covered by traditional ignition source frequency data. Other information sources are used for electrical equipment reliability values.

5.5.3 Implementation of Cable Fire Sub-Model Methodology

Previous sections have presented the theoretical basis for the cable fire sub-model and explained the basic concepts of virtual compartmentation and weighted ignition source inputs. This section consolidates the various pieces of the cable fire sub-model framework and provides the basic steps in applying the methodology to “real world” cases.

Three pilot case examples are included in Appendix F to demonstrate practical application of the methodology. The values for bin count are assumed values and the frequency data is taken from the baseline frequencies established in Appendix D. The pilot cases are:

Case 1: LHC tunnel dipole magnet section (curved section of beam) with Beam On operating mode.

Case 2: Same as Case 1 but with Long-Term Shutdown operating mode.

Case 3: ATLAS experiment inner detector zone (instrument cables only). The pilot case is done for Long-Term Shutdown operating mode.

The analysis is best done using a spreadsheet or database to manage and manipulate the data. The steps are outlined below using Pilot Case 1 as a working example. All frequency values are on a per year basis.

Step 1: Fire Hazards Walkdown

A facility fire hazards walkdown is a normal and customary part of a fire hazards analysis. In addition to the traditional information collected, it is necessary to develop an inventory of the number of items for each defined ignition source bin category. It is also necessary to identify the cable "targets". This is most efficiently accomplished by tracking cable trays rather than individual cables. The target cable information is later compared to the zone of influence for the identified ignition sources to assess whether an ignition source is likely to ignite the cables. Experience shows that maintaining this information in an orderly manner in a database or spreadsheet is advantageous.

Step 2: Walkdown Data Compilation and Boundary Conditions

This step involves compiling data and framing the assessment, including:

- Facility and compartment (spatially define virtual compartments)
- Operating mode (e.g., Beam On, Short-Term Cooldown, Long-Term Shutdown)
- Inventory of ignition sources and target cables
- Determining functional state for the various ignition sources and cable targets based on operating mode (non-energised electrical equipment and panels are excluded as ignition sources and non-energised cables are excluded from self-ignited cable fire sequences).
- Compute individual ignition source frequencies based on bin count and baseline site frequency (given in events/year)

Figure 14 shows the walkdown and fire event frequency data for Pilot Case 1.

CABLE FIRE IGNITION SOURCE & TARGET INVENTORY	
Scenario Description	
Facility	LHC tunnel
Compartment	LHC tunnel, dipole magnet section
Operating Mode	Beam On
Walkdown Source Reference	EDMS 23xxxx
Frequency Basis Reference	EDMS 23xxxx

Ignition Source Inventory		
Item	Bin ID	Energized
B-042	Battery	Y
B-066	Battery	Y
EC-0292	Electrical Cabinet	Y
EC-0658	Electrical Cabinet	Y
EC-0623	Electrical Cabinet	Y
EC-0244	Electrical Cabinet	Y
JB-0376	Junction Box	Y
JB-0378	Junction Box	Y
CP-056	Electrical Cabinet	Y
PP-065	Power Panel (LV)	Y
ME-22	Electric Motor	Y
ME-24	Electric Motor	Y
	Welding/Cutting	N
	Transients	Y
	Maintenance Activity	N

Ignition Source Frequency (Events/year)			
Bin ID	Bin Count	$Freq_{base}$	$Freq_{ind}$
Battery	25	1.96E-05	7.84E-07
Elec Cab	280	3.00E-02	1.07E-04
Junction Box	190	3.61E-03	1.90E-05
Power Pnl (LV)	90	1.52E-04	1.69E-06
Elec Mtr	95	5.43E-03	5.72E-05
Weld/Cut	48	2.77E-04	5.77E-06
Transients	48	4.28E-03	8.91E-05
Maintenance	48	4.28E-03	8.91E-05

Targets			
Raceway	Type	Function	Energized
P134	Tray	Power	Y
P276	Tray	Power	Y
C038	Tray	Control	Y
S005	Tray	Signal	Y
P228	Conduit	Power	Y
S066	Conduit	Signal	Y

Figure 14 Compartment Ignition Source, Target, and Frequency Identification

Step 3: Zone of Influence (ZOI) Matrix

Based on the identified ignition sources and cable targets, build a zone of influence matrix. The ZOI matrix is essentially a determination of fuel package vulnerability to the ignition sources, which is an essential part of any design fire curve development. At this stage of the analysis, the ZOI is generally viewed in isolation and does not include suppression or other mitigating actions; the objective is to determine if a given ignition source HRR, proximity, and flaming characteristics are such that it is likely to ignite the target cables.

A probability distribution can be used for the ZOI factor; however, a simple Yes/No (1 or 0) approach is more feasible at this point, as shown in Figure 15. Note that metal conduits are normally treated as "excluded" targets (P228 and S066 in this example). The "consolidated" column identifies if the ignition source affects any of the targets and is set to Yes (1) if one or more targets are within its ZOI. This determines if the ignition source is included as a potential concern for external cable fires. The Yes/No counting determines if an ignition source can cause a cable fire. Which and how many targets are affected is captured as a consequence of the fire. NUREG/CR-2178, Vol 2 [30] and NUREG-2230 [31] provide HRR values and ZOI recommendations for electrical cabinets, electric motors, transformers, and control boards.

ZONE OF INFLUENCE MATRIX							
IS/Target	P134	P276	C038	S005	P228	S066	Consolidated
B-042	0	0	0	0	0	0	0
B-066	0	0	0	0	0	0	0
EC-0292	1	1	1	1	0	0	1
EC-0658	1	1	1	1	0	0	1
EC-0623	1	1	0	0	0	0	1
EC-0244	1	1	0	0	0	0	1
JB-0376	0	0	0	1	0	0	1
JB-0378	0	0	0	1	0	0	1
CP-056	0	1	1	0	0	0	1
PP-065	1	1	0	0	0	0	1
ME-22	0	0	0	0	0	0	0
ME-24	0	0	0	0	0	0	0
Weld/Cut	1	1	1	1	0	0	1
Transients	1	1	1	1	0	0	1
Maintenance	1	1	1	1	0	0	1

Figure 15 Zone of Influence Assessment

Step 4: External Cable Fire Calculation

Based on bin count, individual frequency, and ZOI factor, the external fire frequency for the compartment is calculated, as shown on Figure 16. Notice that the bin counting serves as the ignition source weighting factor.

Observe that transient ignition source hazards (welding/cutting, transient combustibles, and maintenance activities) do not have a "bin count" in the traditional sense because they are human related and are not fixed at a certain location. For this reason, the customary approach is to equally divide the overall facility baseline frequency between the defined fire compartments (actual or virtual). It is reasonable that the baseline frequency could be allotted such that certain compartments are more heavily weighted than others, provided that a basis exists for an unequal distribution.

Since the LHC is in operation in this pilot case study, no welding/cutting or maintenance activities are occurring in the LHC tunnel. Therefore, these frequencies are set to zero. The transient combustible frequency count is set to 5% to account for any flammable materials inadvertently left in the tunnel prior to start up. This 5% is based on the compartment individual frequency and was selected based on judgment; operating experience may show that a different value is more appropriate. It might also be the case that different compartments have a different value.

Note that for Pilot Case 2 the LHC operating mode is Long-Term Shutdown. In this case, the frequencies for all transient ignition sources are set to 100% of the individual compartment value. Also consider that LHC locations in which transient ignition sources can occur during operation should also use 100% of the individual values. The tunnel is a special case since it is completely inaccessible during operation.

EXTERNAL CABLE FIRE					
Bin ID	Count	$Freq_{ind}$	$Freq_{comp}$	ZOI	Bin Totals
Battery	2	7.84E-07	1.57E-06	0	0.00
Electrical Cabinet	5	1.07E-04	5.36E-04	1	5.36E-04
Junction Box	2	1.90E-05	3.80E-05	1	3.80E-05
Power Panel (LV)	1	1.69E-06	1.69E-06	1	1.69E-06
Electric Motor	2	5.72E-05	1.14E-04	0	0.00
Welding/Cutting	0	5.77E-06	0.00	1	0.00
Transients	0.05	8.91E-05	4.45E-06	1	4.45E-06
Maintenance Activity	0	8.91E-05	0.00	1	0.00
				TOTAL	**5.80E-04**

Figure 16 External Cable Fire Analysis

Step 5: Self-Ignited Cable Fire Calculation

The self-ignited cable fire assessment is shown in Figure 17. The fraction listed accounts for approximate percentage of total facility cable of each category that is contained in the compartment. The total quantity reflects the estimated total combustible fuel load for the entire LHC machine for the given category (NB: in this example, the values of 7% and 5% are arbitrarily assigned because neither the total amount of cable nor the fraction of cable within a tunnel dipole section are known). Calculating fuel load for each compartment is a normal expectation for building the design fire curve for the compartment. Notice in this case the 18 kV fraction is set to zero because it is assumed that no 18 kV circuits are located in the LHC tunnel.

SELF-IGNITED CABLE FIRES							
Circuit Class	Fraction	Energized	$Freq_{site}$	$Freq_{comp}$	$\lambda_{breaker}$	$\lambda_{protection}$	SI Totals
Control Power	7%	Y	4.22E-04	2.95E-05	4.08E-01	1.66E-01	4.91E-06
400 V Power	5%	Y	1.20E-02	6.00E-04	1.53E-01	2.34E-02	1.40E-05
18 kV Power	0%	N/A	1.35E-01	0.00	5.10E-02	2.60E-03	0.00
						TOTAL	**1.90E-05**

Figure 17 Self-Ignited Cable Fire Analysis

Step 6: Termination Equipment Fire Calculation

Figure 18 shows the analysis for HEAF and propagation cable fires. The ignition source frequencies are the same as those used for exposure fires, except the mechanism for starting a cable fire is propagation from the ignition source, which is quite different than an exposure fire. Refer to Appendix D for guidance on assigning propagation factors. Note that the frequency for propagation fires is on the same order of magnitude as exposure fires; however, in most cases the consequences are much lower.

TERMINATION FIRE - HEAF					
HEAF EQ ID	Energized	Volt Class	$Freq_{ind}$	Prop Factor	$Freq_{comp}$
PP-065	Y	400 V	1.69E-06	7.00E-01	1.18E-06
				TOTAL	**1.18E-06**

TERMINATION FIRE - PROPAGATION			
IS/Target	$Freq_{ind}$	Prop Factor	$Freq_{comp}$
B-042	7.84E-07	0	0.00
B-066	7.84E-07	0	0.00
EC-0292	1.07E-04	0	0.00
EC-0658	1.07E-04	0	0.00
EC-0623	1.07E-04	0	0.00
EC-0244	1.07E-04	1	1.07E-04
JB-0376	1.90E-05	0	0.00
JB-0378	1.90E-05	0	0.00
CP-056	1.07E-04	1	1.07E-04
ME-22	5.72E-05	0	0.00
ME-24	5.72E-05	1	5.72E-05
		TOTAL	**2.71E-04**

Figure 18 Terminal Equipment Cable Fire Analysis

Step 7: Compartment Level Cable Fire Fault Tree

Figure 19 shows the top-tier fault tree for Pilot Case 1. Notice that electrical cabinet fires dominate the fire risk contribution – this is normal for locations with minimal HEAF concerns and no other high risk, non-electrical ignition sources. Case 2 will show the difference for shutdown conditions when much of the electrical equipment is deenergised and transient concerns become prevalent.

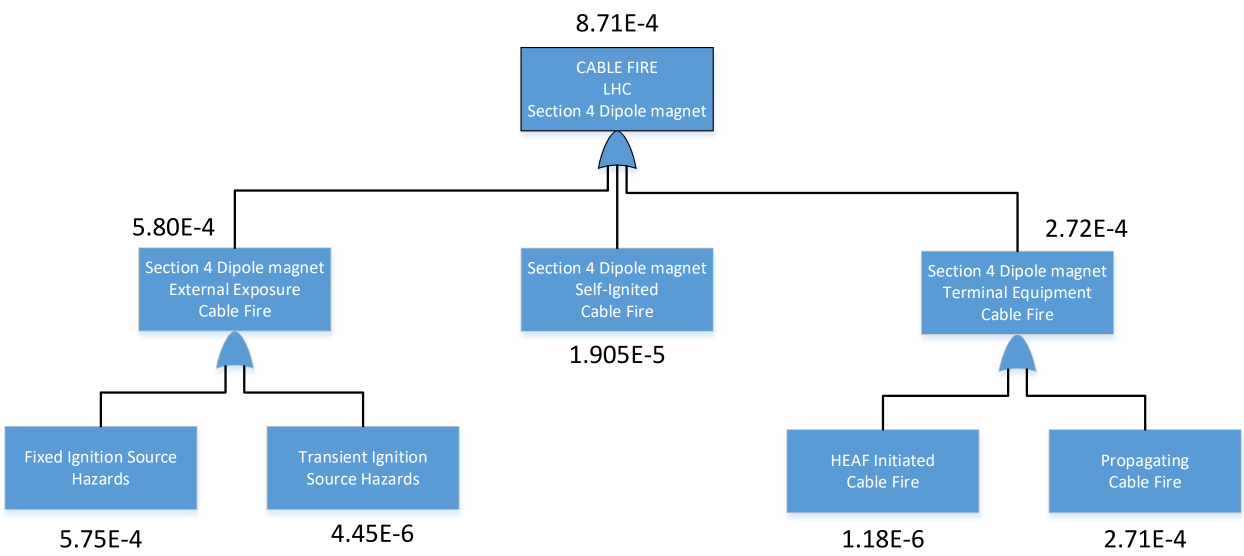


Figure 19 Top Gates of Fault Tree for Pilot Case 1

If the eight dipole sections of the tunnel are essentially the same, the total cable fire risk for the dipole curve sections is 8 x 8.71E-4 = 6.97E-3.

6 Radioactive Release Fraction

This section presents an approach for estimating the portion of radioactive nuclides released[4] during a fire involving activated cables (Objective 3). The most important factor in assessing radionuclide release distils down to balancing the combustion chemical equation. Combustion changes the form of matter but does not alter the amount of each element present before and after burning [40], [56]. Therefore, the pre-fire inventory of radionuclides must equal the post-fire radionuclides evolved as smoke plus the radionuclides left behind as carbonaceous char. The smoke will contain gaseous combustion molecules and particulates (soot). Since some fraction of the soot is lost through deposition and the soot can contain various radioactive isotopes, it is also desirable to estimate the fraction of radionuclides released as soot in lieu of gas. It is important to note that only the out-diffused fraction of the metal conductor radioactive isotopes is included in the radionuclide balance; a majority of the activity associated with the metal conductors is unaffected by the fire and thus remain in place. Another important consideration is that radioactive isotopes do not impact chemical processes. Hence, the burning reaction is blind to the isotopes associated with the fuel elements. Based on combustion chemistry and assuming that radionuclides are distributed uniformly in the cable materials:

$$\sum_{S_i} A_{S_i}\,(Pre\ Fire) = \sum_{S_i} A_{S_i}\,(Post\ Fire)$$

$$\sum_{S_i} A_{S_i}\,(Pre\ Fire) = \sum_{S_i} A_{S_i}\,(smoke) + \sum_{S_i} A_{S_i}\,(char)$$

$$\sum_{S_i} A_{S_i}\,(Pre\ Fire) = \sum_{S_i} A_{S_i}\left(smoke_{gas}\right) + \sum_{S_i} A_{S_i}\,(smoke_{soot}) + \sum_{S_i} A_{S_i}\,(char\ rresidue)$$

Where: $\mathrm{A_{S_i}}$ is the activity level of radionuclide species $\mathrm{S_i}$ in Becquerels (Bq)

The proposed method assumes activated cable materials of known isotopes and activation levels. The methodology is developed in support of CERN's FIRIA Project goals for realistic analysis of fire-induced radiological release [7]; however, the conceptual process is considered transferable to other high-energy physics facilities having similar concerns. Section 3.3 provides relevant background information, including problem statement, objective, current state of knowledge, and technical development approach.

The proposed method for estimating fractional release of radionuclides is based on several driving factors:

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[4] As a point of clarification, the terms "radioactive release" and "radionuclide release" within the context of this thesis refer to the amount of radioactivity that is evolved with the smoke plume of burning cable, i.e., the amount of radionuclides (isotope and activity level) that are contained in the smoke plume of burning cable. This definition is not to be confused with radioactive release associated with outdoor dispersion estimates.

- The current state of knowledge for fire-induced radiological release is low. Current practice is to invoke bounding, conservative assumptions [20], which are at odds with both quantitative risk analysis concepts [40], [41] and CERN's desire for realistic estimates [7]. No directly applicable, publicly available research pertaining to radionuclide release during fire events was identified by the literature search or discussions with subject matter experts (SMEs)[5].
- The proposed method for determining fractional radionuclide release is based on fire chemistry and estimating the mass percentage of residual carbonaceous char material left after burning. Limited data is available for burning cables; however, the available research demonstrates a wide variation depending on the exact cable configuration, size, conductor count, and material content [24]–[26], [40]. Hence, the proposed method is not considered viable for full implementation at CERN until verification testing is conducted to confirm carbonaceous char content and mass percentage for representative cables.
- The proposed method assumes the radionuclides of concern and their activation levels for specific cables at specific locations are known. The method should not be universally applied without confirmation of input data for the specific scenario under consideration.
- The proposed method serves to estimate the fractional amount of activated materials that are released into the smoke plume as part of the burning process. The transport and deposition of the radionuclides within the smoke plume are addressed by other FIRIA Project tasks.

The following sections outline the methodology and provide suggested values for the influence factors or identify where further research is needed to determine technically defensible influence factors. Fundamental concepts and background information pertaining to radiation concerns, analysis approach, and positioning of this sub-model within the overall FIRIA Project framework are addressed in Appendix A, and will not be repeated here.

Figure 20 shows the major steps for completing Objective 3. For perspective, Figure 30 (refer to Appendix A) illustrates the overall flow chart and "work packages" for the FIRIA Project working structure.

[5] Discussions with SMEs having past experience at non-reactor nuclear facilities revealed that radioactive release estimates for fire events were studied for certain nuclear weapons production facilities; however, this information remains classified and not available to the general public.

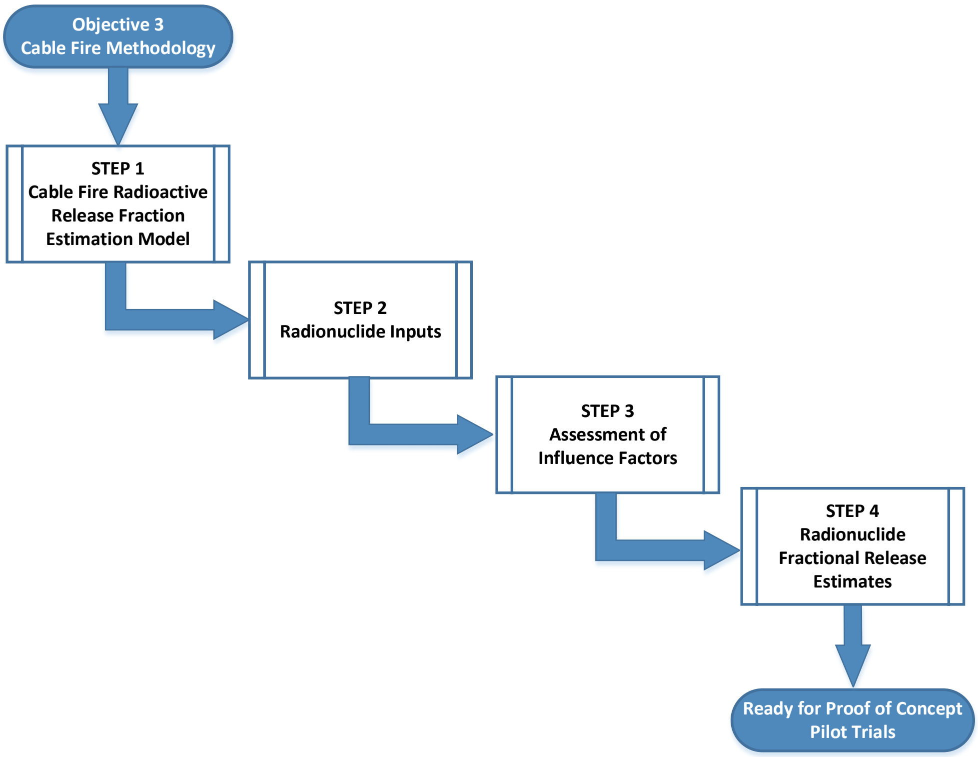

Figure 20 Estimation Method for Radionuclide Release from Cable Fires – Key Steps

6.1 Cable Fire Radiological Release Fraction Estimation Method

In the absence of available research for this topic, the goals for this development effort are modest. The intent is to pull together several disjointed pieces of information from different technical disciplines (nuclear physics, electrical engineering, and fire science) and apply fundamental principles to obtain a first order estimate of radiation release from burning radioactive materials associated with cables.

The methodology consists of a simple input-output model, with various influence factors applied to determine the fractional release estimates. To be clear, this primitive model is intended as a starting point that can be further refined and enhanced through future research and testing. The radionuclide release estimation model framework is shown in Table 10.

Table 10 Radionuclide Release Estimation Framework

Item	Parameter
Inputs	Scenario description Location Cable description & characterisation ▪ Insulation & jacket materials ▪ Conductor material ▪ Material mass fractions Elemental mass fractions Radionuclide species & activation levels Cumulative operating cycles (irradiation baseline) Operating mode adjustments (activity inventory) ▪ Beam On ▪ Short-Term Cooldown

Item	Parameter
	▪ Long-Term Shutdown
Influence Factors	Cable fault mode ▪ Arcing fault ▪ Non-arcing fault Temperature-induced metal diffusion factors Combustion product characterisation ▪ Residual carbonaceous char o Mass fraction (yield) o Constituents ▪ Soot production o Yield o Constituents ▪ Gas production o Yield o Constituents
Outputs	Fractional release estimates (mass & activation) ▪ Residual char ▪ Gaseous ▪ Soot ▪ Metal

6.2 Radionuclide Release Model Input Parameters

This section identifies and discusses the minimum input parameters needed to estimate cable fire radiological release fractions.

6.2.1 Isotopes of Concern and Activation Levels

The most basic input are the isotopes of interest and the activation level for each isotope. This information is generally provided by radiation protection specialists. Isotope characterisation is most often obtained using a two-step process involving computer modelling [57]. First, the radiation field to which the cables are exposed is determined. The irradiation sources are high energy protons lost from the beam tubes and stray radiation. The second step is to determine the specific elements of the cable materials that are expected to become activated and their associated activation levels. CERN uses the FLUKA and ActiWiz software to conduct radiological characterisation studies [57], [58].

Applicability of activation data should clearly state the cable types to which the data applies. Cable materials vary significantly and thus it is not appropriate to use a simple generic set of values for all cables. Activation levels are specified in Bq/g or Bq/kg. Thus, the overall radiation released by a fire depends on the projected cable fuel load for a given design fire scenario.

6.2.2 Operating Mode Adjustments

The activation level of materials is a function of cumulative exposure, operating mode, and cooldown time. With each operating cycle, the cables undergo an additional radiation dose; hence, the activation levels after 10 cycles will be substantially greater than after a single cycle. Additionally, operational status (beam on or beam off) and the time since shutdown affect the isotopes of concern and activation levels. Accounting for these predictable variations will yield more representative activation levels for quantitative radiological release risk.

6.2.2.1 Cumulative Operating Cycle Integrated Activation Levels

For a worst-case analysis, the activation levels at LHC end-of-life can be used (i.e., maximum number of projected operating-shutdown cycles). This approach is certainly bounding, but not consistent with the concept of quantitative risk analysis [40], [41]. To obtain realistic values, the FIRIA methodology should consider a means of scaling the baseline activation levels as a function of the number of operating - cooldown cycles.

6.2.2.2 Operating Modes

Activation levels will change predictably through a given operating-shutdown cycle. The overall risk analysis will be more accurate if the activation levels are discretised based on operating status and time since shutdown. In this manner, radioactive decay during shutdown periods is included in the analysis, which will produce more accurate time-weighted consequence values. The LHC machine has many defined operating modes and sub-modes; however, in creating discrete bins for calculation of activation levels, practicality must be considered. It is suggested that three mode-based states be established, as shown in Table 11 (NB: the CERN "start-up" and "operating" modes are captured in the "Beam On" category shown in the table since distinguishing these modes for the purpose of this thesis is not required).

Table 11 Operating Modes for Activation Level Assessment

Mode	Description
Beam On	This mode covers any mode and sub-mode in which the beam is ON or in process of startup. A single set of activation levels can be established based on conditions at end-of run.
Short-Term Cooldown (0-1 month)	This mode covers a time frame of one month from time of shutdown. Worst-case or average activation levels can be used. Activation levels of short-lived isotopes will be changing significantly during this period.
Long-Term Shutdown (>1 month)	This mode covers the timeframe from one-month after shutdown until restart. After one month, short-lived isotopes will have undergone significant decay.

6.2.3 Cable Type

Cable insulation and conductor materials affect the fractional radionuclide release in several ways:

1. Different insulation and conductor materials will yield different radionuclides of concern as a result of proton activation and stray radiation [9]. It is important to apply the proper values for the specific materials of interest. Insulation additives can make a notable difference and should be assessed as part of defining the insulation constituents.
2. Different insulating materials exhibit substantially different decomposition and burning characteristics [24]–[26], [40], [56], which affect the soot yield and amount of carbonaceous

char residue. In this first-order model, cable insulation type is a key influence factor because of the variation in residual char remaining after the insulation burns [24], [25], [40].

3. Different conductor materials (e.g., copper or aluminium) have different vaporisation characteristics during arcing faults [21], which affects the amount of metal material included in the smoke plume.

6.2.4 Location

Location of the cables with respect to the beam tubes is the final input parameter. Location is taken into consideration by FLUKA and ActiWiz calculations [57], so this variable is inherently incorporated in the activation values provided by the Radiation Protection Group. Location is of greater interest for the LHC tunnel and experiment caverns close to the beam.

6.3 Influence Factors

Influence factors are applied to radionuclide activation levels to account for electrical fault conditions, materials, residual char fraction, and soot yield.

6.3.1 Cable Fault Mode

All three cable fire categories involve burning of cable insulation materials. However, electrical failures that involve arcing faults should consider dispersal of vaporised conductor metals.

6.3.1.1 Non-Arcing Faults

If the cable fire sequence does not involve arcing faults, then radionuclides associated with the conductor materials do not need to be considered. Under extreme conditions, the fire conditions might result in melting of conductor materials. However, the materials will not be vaporised.

6.3.1.2 Arcing Faults

If the cable fire sequence includes arcing faults, then vaporization of conductor materials should be considered. The amount of material vaporised depends on the conductor type and duration of the arcing fault [22].

Consistent with the suggested cable fire model presented in Section 5, only potentially sustained arcing faults on 400 V and 18 kV power circuits are considered. Non-sustained arcing faults of a few cycles on low voltage circuits (less than 240 V) vaporise a negligible amount of metal [22] [36] [46]. Conversely, sustained arcing faults can vaporise a significant amount of metal conductor. The conductor vaporisation rate for copper can be estimated by the following empirically derived relationships:

Copper Conductor 50 kW / s → 1/20 in^3 [22]

Converting this relationship to mass loss in SI units as a function of arc energy yields:

$$\dot{m}_{vap}\left(\frac{g}{s}\right) = \frac{7.341}{50} \times \text{Arc Energy}\ (kW) = 0.1468 \cdot V_{arc} \cdot I_{fault}$$

$$m_{vap}(g) = \dot{m}_{vap} \cdot t_{arc}$$

Where: $\dot{m}_{vap}$ is rate of copper vaporisation in g/s

m_{vap} is total amount of copper vaporised for arcing time t_{arc} in seconds

V_{arc} is arc voltage in volts (NB: not system voltage, but voltage drop across arc)

I_{fault} is arcing fault current in kiloamperes RMS

A few examples help with perspective for which cases should be considered in the analysis.

Example 1: 400 V power system develops an arcing fault that is cleared by primary overcurrent protection with a 0.5 s intentional delay (delay is for coordination with other overcurrent devices).

$V_{arc} = 140 \text{ V}$ with $I_{fault} = 6{,}000 \text{ A} = 6 \text{ kA}$

$m_{vap} = 0.1468 \cdot 140 \text{ V} \cdot 6 \text{ kA} \cdot 0.5 \text{ s} = 61.7 \text{ g vaporised}$

Example 2: Same as Case 1 except the fault is rapidly cleared by instantaneous overcurrent protection within 0.0167 s (one cycle at 60 Hz).

$V_{arc} = 140 \text{ V}$ with $I_{fault} = 6{,}000 \text{ A} = 6 \text{ kA}$

$m_{vap} = 0.1468 \cdot 140 \text{ V} \cdot 6 \text{ kA} \cdot 0.0167 \text{ s} = 2.1 \text{ g vaporised}$

Example 3: 18 kV power system develops an arcing fault that persists for 3 seconds before being cleared by backup overcurrent protection (case assumes primary overcurrent fails).

$V_{arc} = 150 \text{ V}$ with $I_{fault} = 22{,}000 \text{ A} = 22 \text{ kA}$

$m_{vap} = 0.1468 \cdot 150\text{V} \cdot 22 \text{ kA} \cdot 3 \text{ s} = 1{,}453 \text{ g} \approx 1.5 \text{ kg vaporised}$

Example 2 is representative of normal protective device operation and represents a case that can be considered negligible.

Testing shows that arc voltage generally falls within a narrow range (approximately 100 V to 150 V) regardless of system voltage [22], [38], [39], [49], [50], [59]; therefore, the arc voltage in Examples 1, 2, and 3 is nearly the same value. For this reason, fault current on 400 V systems is generally substantially lower than the maximum available fault current. At 18 kV, the fault current remains near its maximum value because the arc voltage is a small fraction of the overall system voltage. The values shown in the three example cases are representative of typical systems.

The three examples demonstrate a significant difference in terms of amount of material vaporised. Based on the amount of vaporised materials, it is recommended that conductor materials only be included in cable fire sequences that involve HEAF events of sustained duration. Rapidly cleared arcing faults are expected to produce a negligible amount of radioactive conductor material. Additionally, vaporised conductor materials form metal oxides that tend to cool and deposit on surrounding surfaces [21]. It is possible that smoke transport and deposition factors will demonstrate a rapid decrease in metal radionuclides in the smoke plume, but it is also possible that some isotopes are released in an aerosol form and do not solidify.

Example 4 is not for cable HEAF events per se. Rather, this case presents results obtained from HEAF testing for low and medium voltage switchgear that was conducted under a joint international agreement [21]. The tests show the potential amount of bus bar vaporised for worst-case HEAF events at power cable terminal equipment.

Example 4: Test results for arcing fault energies measured during HEAF arc fault testing of typical power distribution system terminal equipment. This testing assumed worst case conditions in which overcurrent protection fails [21]:

6.9 kV Switchgear: 20 MJ to 75 MJ → $m_{vap} \approx 3 - 11$ kg vaporised

480 V Load centre: 7 MJ – 36 MJ → $m_{vap} \approx 1 - 5.3$ kg vaporised

6.3.2 Temperature-Induced Metal Diffusion

Research has identified the potential for out-diffusion of metal elements into the insulation material of cables [5]. Existing research is limited and thus CERN is sponsoring ongoing R&D pursuant to characterisation and modelling of the out-diffusion phenomenon. Figure 21 shows a generic example for metal diffusion from copper conductor as a function of time and temperature. The out-diffusion phenomenon is a potential concern at high temperatures associated with burning.

The data plotted in the sample diffusion curves is a generic representation of out-diffusion. Actual values will depend on the specific isotopes, conductor size, temperature, and time. The 1% diffusion level shown in the graph applies to small computer or digital signal wires. For typical field cables, the nominal out-diffusion is expected to range from approximately 0.01% to 1.0% based on copper conductor at 800°C for 30 minutes (refer to Figure 21).

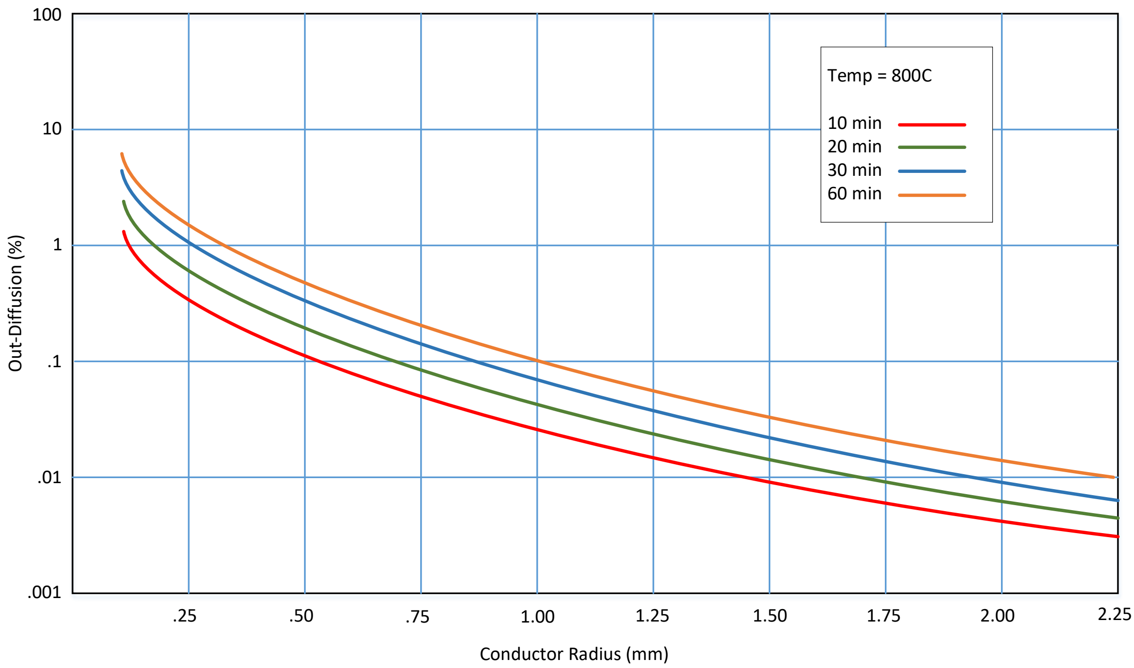

Figure 21 Generic Temperature-Induced Out-diffusion of Cable Conductor Materials

The behaviour of diffused metal isotopes has not been well characterised with respect to fire. Hence, the amount of diffused material that is evolved in the smoke plume and the amount that remains in the residual char is not known. The temperatures involved are not high enough to cause vaporisation of the diffused metal molecules. Therefore, the only plausible methods of entrainment in the smoke is by carryover of the metal molecules as constituents of soot particles, metal oxides, or free metal. One can envision that it is possible for plume buoyant forces and air entrainment to sweep away small airborne metal molecules. However, the question that remains is what micro-dynamics at the surface of the burning cables would cause the metal molecules to be entrained in the pyrolysis gases being evolved from the cable surface. These metals do not directly participate in the combustion chemistry and flame temperature is not hot enough to vaporise the metal particles.

For the purpose of this thesis, it is assumed that 50% of the activated metal particles are swept away as particulate airborne radionuclides (soot and/or metal oxides) and 50% remain in the residual char (presumably at the conductor-insulation interface. CERN's current research into the out-diffusion phenomenon should provide a better understanding of this process in the future.

6.3.3 Estimation of Residual Char Yield

Cable insulating materials consist of a wide variety of synthetic polymers. These materials leave behind a carbonaceous char when burned [24], [25], [40], [56]. Conceptually, if the chemical composition and amount of the remaining char can be quantified, conservation of mass dictates that the balance of the original material must be presumed released during the burning process [60]. The char remaining as residue after burning is called the char yield (ν_r) [24], [25].

For the first-order approximations targeted by this thesis, a basic approach is proposed for estimating the type and amount of material remaining as char after burning. Any radionuclides not accounted for in the residual char are presumed released as combustion products, pyrolysis gases, or soot through the pyrolysis and combustion reactions. Recall that isotopes bound in the metal conductor are assumed to remain in place and are therefore not included in the radionuclide inventory balance (i.e., only the out-diffused fraction of conductor isotopes are included in the analysis). It might also be the case that some insulation or jacket materials are not burned because they are buried in the middle of a large cable bundle and lack access to oxygen. It difficult to put quantitative values on the potential for unburned fuel, so it is conservatively assumed that that all combustible materials of the cable are consumed by the burning process.

6.3.3.1 Cable Materials and Fire Test Data

It has been discussed that most cable insulating materials are either a thermoset or thermoplastic material. CERN cable specifications require high quality cable, which generally means use of thermoset materials. However, cable manufacturers' formulas vary widely and often include additives to enhance performance for a variety of attributes. Desired enhancements include reduced flaming and smoking, radiation resilience, moisture and aging resilience, oil and chemical resilience, flexibility, abrasion toughness, and size reduction.

Ideally, assessing radionuclides released from burning cables would be as easy as measuring the amount of all constituents contained in the smoke of a representative test sample and then comparing these values to the radioactive elements of the original specimen. In practice, this type of testing is generally limited to a few species that are of concern for tenability (e.g., CO, CO_2, HCL HCN). Although detailed research has been conducted on decomposition of polymers, data interpretation difficulties, combined with the complex chemistry involved, limits the usefulness of the research and test data [26], [40], [56].

With respect to the specific goals of Objective 3, conventional fire test methods are not designed to track all species evolved during a fire, which limits the usefulness of these tests for direct calculation of the various radionuclides of interest [24], [27], [40], [60]. Common practice for material fire tests is to measure oxygen, carbon dioxide, carbon monoxide, and soot. This information along with a limited amount of test data regarding residual char is used to develop recommended fractions of char material.

Even this simplistic approach has limitations. The chemistry and phenomenon of residual char formation does not appear to be as well studied as soot formation. Furthermore, available information makes clear the profound effect that geometry and burning conditions have on the nature and amount of remaining char[24], [25], [40]. For example, a single cable with direct flame exposure and ample supply of oxygen will produce a much different result than a group of 50 cables in a tightly packed cable tray. In the latter case, inner cables will not be exposed to direct flame and will have poor access to oxygen.

6.3.3.2 Thermoset Cable Insulation

The Society of Fire Protection Engineers (SFPE) Handbook [40] emerges as one of the best available references for a comprehensive overview of residual char from burning polymers. Thermoset materials are addressed in detail and the following relevant information is gleaned from the discussion:

- The decomposition of thermoset materials leaves behind carbonaceous char; however, the exact structure of material can vary considerably based on the burning conditions.
- The char material is predominantly black carbon.
- Char layer can serve as a barrier to prevent release of underlying materials, but there is no way to quantify this phenomenon.
- Based on experimentation, char yield varies between 41% - 47% (for certain polymers).

From the literature search, residual char yield measurements are recorded in only a few of the cable fire tests. Table 12 provides a summary of the available test data and information regarding residual char for thermoset materials. Appendix E contains the source tables and charts from which this information is taken.

Table 12 Thermoset Cable – Residual Yield ($\boldsymbol{\nu_r}$)

Source	Char (%)	Comments	Reference
SFPE - 2016	41% - 47%	SFPE Handbook, 5th Edition, pp 243	[40]
NRC - 1987	29.5% -48.3%	NUREG/CR-4679, Vol 1, Table 1	[26]
NRC - 2012	1% - 72%	NUREG/CR-7010, Vol 1, Table 7-1	[24], see note
NRC - 2012	22% - 52%	NUREG/CR-7010, Vol 2, Table 4.1	[25]

Note: The 1% value from Reference [24] appears as an outlier in the data. Without speculation to the exact circumstance, this value is not considered representative of thermoset performance.

The table shows a large range of potential char yields for thermoset materials. The influences of test configuration, heat source, and oxygen availability are evident. The most recent NRC testing notes: "*For thermosets, approximately 75% of the non-metallic mass was consumed by fire* [24]" and recommends a value of ν_r = 25%. This value is used in the FLASH-CAT model as the default value [24].

6.3.3.3 Thermoplastic Cable Insulation

Available data for char yield of thermoplastic materials indicates yields lower than those obtained for thermoset materials [24]–[26]. The most recent NRC testing notes that: "*For thermoplastic cables, it was observed that virtually all of the non-metallic components (jacket, insulators, filling) were consumed by fire* [24]" and recommends a value of v_r = 0%. This value is used in the FLASH-CAT model [24]. However, the second phase of the NRC testing shows an average residual char of 17% [25]. Appendix E contains the source tables and charts from which this information is taken. Based on available information, setting v_r = 0% appears highly conservative. It is recommended that a v_r = 5% be used for thermoplastic materials.

6.3.3.4 Halogenated Cable Materials

The SFPE Handbook [40] indicates that halogenated species (Florine and Chlorine) disrupt the normal combustion process and quantification of residue is difficult. However, the 1987 NRC testing [26] offers some interesting insights:

- Thermoplastic cable with no halogenated jacket has residual char yield of 0.1% - 3.9%. However, materials containing halogenated jackets had residual char yields of 20.8% - 48.3%.
- Residual char yield for thermoset cables with halogenated jacket materials did not appear to differ considerably from non-halogenated cases.

Additional research on the impact of cable additives on residual char yield is needed to establish technically sound modelling recommendations. Until additional information becomes available, it is recommended that the baseline values established for thermoset and thermoplastic be used for cables containing halogenated compounds.

6.3.4 Cable Fire Soot and Gaseous Yields

Ideal stochiometric combustion produces water vapor (H_2O) and carbon dioxide (CO_2). However, actual combustion is not stochiometric and consequently, incomplete combustion yields other species [56], [60]. These species vary based on the fuel type, availability of oxygen, and temperature. Combustion products for burning hydrocarbons generally include carbon monoxide (CO), soot (carbonaceous particles), unburned pyrolysis species, and smaller quantities of other toxic chemicals (hydrogen cyanide [CHN], hydrochloric acid [HCl], hydrogen sulphide [H_2S]) [40], [56]. The pyrolysis and combustion of polymers is much more complicated than what is traditionally modelled in fire analyses. A broad range of intermediate combustion products are produced, and the final soot and gaseous products can include numerous gases and particulates. Figure 45 and Figure 46 in Appendix E show results of a study to document chemical structures produced by high temperature breakdown of PVC and PE [26].

Of interest for this project is the amount of soot produced in relation to the amount of gaseous products produced. Soot is comprised of carbonaceous particles, of which a certain fraction will be lost to deposition during smoke transport from the fire to outside atmosphere. The gas combustion products are presumed to remain in a gaseous state and thus are not subject to deposition, including the water vapor. It is also possible that some isotopes might attach to the gaseous combustion particles.

The carbonaceous soot particles can have several forms and include different elements; however, the mass fraction is predominantly black carbon (C)[6] [27]. For the purposes of this analysis, the soot particles are assumed to be comprised primarily of polycyclic aromatic hydrocarbons (PAHs) [40]. Thus, the basic building blocks are assumed to be aromatic rings (C_6-H_6). Future cable fire testing may be appropriate to characterise more precisely the chemical constituents of soot from specific CERN cable types under defined burning regimens.

Modelling of soot formation and subsequent deposition is complicated and subject to numerous influence factors. This aspect of radiation release is being addressed by the FIRIA Project Aerosol WP team. Refinement of the aerosol model and combustion species includes estimation of soot yield. Therefore, the final modelling methods for soot yield characterisation will come from the Aerosol WP team. However, to better our understanding of the radionuclide release fractions within the scope of Objective 3, it is desirable to estimate the soot yield.

Considerable information is available on soot production and reasonable bounds can be placed on soot yield for cable materials. Appendix E contains results from several cable fire tests that measured soot yield. Since the Lund cable fire tests [27] are conducted with CERN-specific cables, these soot yield values are taken as the best performance indicator of typical CERN cables. From the Lund test data, a nominal soot yield value of 0.05 g/g is selected as representative for the purpose of methods development.

6.4 Summary of Radionuclide Release Modelling Concepts

The previous sections provide a technical basis for conducting the fractional radionuclide release estimates. The fractional release of radionuclides during burning serve as the source term for smoke transport and deposition modelling. The important concepts guiding the analysis are:

1. Radiation release is based on balancing the pre-fire and post-fire radionuclide inventory in accordance with the following equation:

$$\sum_{S_i} A_{S_i}\,(Pre\ Fire) = \sum_{S_i} A_{S_i}\left(smoke_{gas}\right) + \sum_{S_i} A_{S_i}\,(smoke_{soot}) + \sum_{S_i} A_{S_i}\,(char\ residue)$$

2. Calculations are performed for a specific set of inputs, to include:
   - Radionuclide species and activity levels for a specific cable type (insulation and conductor materials)
   - Defined location and operating mode (i.e., Beam On, Short-Term Cooldown, and Long-Term Shutdown)
3. All polymer materials (insulation, jacket, filler, additives) are included in the assessment.
4. Only the out-diffused portion of the metal conductor is included in the radionuclide inventory balance. Isotopes bound in the cable conductor (non-burnable) are assumed to remain in place.
5. Conductor materials (metals) are considered based on certain factors:
   - Vaporisation of conductor is considered only for HEAF cable fire sequences.

[6] The Lund test data includes measurement of total mass yield and black carbon yield. As expected, the values do not match precisely. Refer to Reference [27] for a detailed discussion.

- Metal diffusion is included for copper conductor based on assumed 50% release during burning of materials (not validated by test).
- Recent NRC testing [24] [25] observes that about 75% of thermoset materials are consumed in the fire and a larger fraction of thermoplastic materials are consumed in the fire. The default FLASH-CAT values are based on this assessment. Residual char is assumed to be predominantly black carbon.

  Until such time that future testing of CERN-specific cables is conducted, the recommended char yields (v_r) for radionuclide release are:

  Thermoset materials: v_r = 25%

  Thermoplastic materials: v_r = 5%

  NB: The FLASH-CAT model default value for thermoplastic is v_r = 0%.

6. The mass fraction of carbon not contained in the residual char is released into the smoke plume as combustion product gasses or soot. A soot yield of 0.05 g/g is used to determine the radionuclide fraction evolved as soot; the soot is presumed to be comprised primarily of aromatic rings (C_6-H_6) [27], [28].
7. Radioactivity of conductor metals derived from diffusion is identified separately and is assumed to exist in a particulate form of some sort. The diffusion amount is determined graphically and is a function of conductor size.
8. It is not necessary to know the individual fractions of the gaseous combustion products to estimate the radionuclide release. However, the split fraction of gases will be required if condensation and deposition of water vapor, acids, or other gasses is to be included in the smoke transport and deposition modelling.

6.5 Calculation of Radionuclide Release Fractions

Outputs from the radiation release calculation include the following information, which can be used as input to the smoke transport and deposition model:

- Fraction of carbon (C) radionuclide activation levels remaining as residual char
- Fraction of carbon (C) and hydrogen (H) radionuclide activation levels released in the smoke as soot (particulates)
- Fraction of hydrogen (H) radionuclide activation levels released in the smoke as water vapor
- Fraction of carbon (C) radionuclide activation levels released in the smoke as gas
- Fraction of chlorine (Cl) or sulphur (S) radionuclide activation levels released in the smoke as gas
- Fraction of diffusion metallic radionuclides and associated activation levels released in the smoke as particulates
- Amount of metallic radionuclides and associated activation levels released in the smoke as particulates due to arcing faults

Adapting the concepts for estimating radionuclide release to "real-world" applications requires manipulation and consolidation of input values. In practice, it is not feasible to work each calculation on an individual cable basis using the baseline activity levels expressed in units of Bq/g. The suggested approach is to:

- Identify “target” cable trays (trays impacted by the fire scenario) by field walkdown or drawings
- Determine cable construction and specifications for conductor, insulation, and jacket materials, most importantly mass fractions
- Convert the material mass fractions to elemental mass fractions based on molecular weights, expressed in kg/m
- Consolidate the elemental mass fractions of all cables
- Obtain/calculate the activity levels for the radionuclides of interest for the operating modes of interest, expressed as Bq/kg
- Calculate the “per unit length” activity levels for the radionuclides of interest based on the activity level per unit mass and elemental mass per unit length

The total radioactivity release is determined by the design fire scenario, which specifies the amount of cable burned, i.e., length of cable tray involved in the fire.

These calculations are best accomplished in spreadsheet format. Appendix G provides three pilot case examples:

Case 1: Two target cable trays with multiple cables located in the LHC tunnel dipole section. One tray contains smaller control and instrument cables and the other tray contains larger power cables. The cable materials are thermoset insulation with a thermoset jacket. No arcing faults are present. The fire scenario is an exposure fire that involves both cable trays.

Case 2: One cable tray containing three power cables located in the LHC tunnel dipole section. The cable materials are PE insulation and PVC jacket (thermoplastic). The fire scenario is a self-ignited cable fire from a modest size HEAF event (4.2 MW at 400 V) that causes ignition of all three cables in the tray. The radioactivity levels include the vaporised conductor contribution from the arcing fault.

Case 3: One instrument cable wireway containing eight multi-conductor instrument signal cables located in the ATLAS Experiment inner detector area. The cable materials are thermoset insulation with a thermoset jacket. Instrument cables are not subject to arcing faults. The fire scenario is a termination fire that results in propagation from a burning enclosure into the cable tray.

Figure 22 shows the input data parameters for Case 1. Figure 25 through Figure 25 show results for all three operating modes. Activity levels are specified on a per unit length basis (Bq/m), which will be converted to total activity release (Bq) based on the design fire determination of how much cable tray is involved in the fire. Appendix G contains calculation details for all three cases.

> **NB: The radionuclide data for these examples was generated from the NIST activation calculator** [9]**, with arbitrarily assigned activation levels. Therefore, the numeric results should not be construed as representative of actual LHC radiation levels. However, the objective here is to confirm viability of the methodology, so the actual numeric results are not of great significance.**

RADIONUCLIDE RELEASE FRACTION - CASE 1	
Scenario Description	
Location	LHC tunnel, Dipole curve
Fire Category	Exposure fire
Targets	Tray P220
	Tray C330
Cable Description	
Tray C330	Cable 1: 7 cond, 2.5 mm^2, XLPE/XLPE
Tray C330	Cable 2: 7 cond, 2.5 mm^2, XLPE/XLPE
Tray C330	Cable 3: 19 cond, 0.5 mm^2, XLPE/XLPE
Tray P220	Cable 4: 3 cond triplex, 50 mm^2, XLPE/XLPE
Tray P220	Cable 5: 3 cond triplex, 50 mm^2, XLPE/XLPE
Operation Mode	
Irradiation Basis	12 years (6 mo ON / 6 mo OFF)
Modes	Beam On
	Short-term Cooldown (0 - 1 mo): 10 days
	Long-term Shutdown (> 1 mo): 120 days
Influence Factors	
Arcing Faults	No
Conductor Diffusion	Chart @ T=800 C, t=30 min with 50% carryover
Char Yield	Thermoset: 25% by mass
	Carbon, 50% diffusion metals
Soot Yield	0.05 g/g
	Aromatic rings, C6H6

Figure 22 Pilot Case Study 1 – Input Data Parameters

RADIONUCLIDE RELEASE - MODE: BEAM ON									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.707	7.29E+06	1.24E+07	0.09189	6.70E+05	1.11693	8.14E+06	0.00	0.00
H-3	0.284	1.45E+07	4.12E+06	0.00766	1.11E+05	0.27677	4.01E+06	0.00	0.00
Cu-66	0.00841	1.67E+10	1.40E+08	0.00	0.00	0.00	0.00	0.00421	7.02E+07
Cu-64	0.00841	8.20E+10	6.90E+08	0.00	0.00	0.00	0.00	0.00421	3.45E+08
Cu-67	0.00841	3.85E+07	3.24E+05	0.00	0.00	0.00	0.00	0.00421	1.62E+05
Cu-61	0.00841	4.26E+06	3.58E+04	0.00	0.00	0.00	0.00	0.00421	1.79E+04
Ni-66	0.00841	5.63E+05	4.74E+03	0.00	0.00	0.00	0.00	0.00421	2.37E+03

Figure 23 Pilot Case Study 1 – Radionuclide Release (Beam On)
(Isotope and activity levels are illustrative only and are not specific to CERN or LHC)

RADIONUCLIDE RELEASE - MODE: COOLDOWN (10 days after shutdown)									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.707	0.00	0.00	0.09189	0.00	1.11693	0.00	0.00	0.00
H-3	0.284	1.45E+07	4.12E+06	0.00766	1.11E+05	0.27677	4.01E+06	0.00	0.00
Cu-66	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-64	0.00841	1.68E+05	1.41E+03	0.00	0.00	0.00	0.00	0.00421	7.06E+02
Cu-67	0.00841	2.62E+06	2.20E+04	0.00	0.00	0.00	0.00	0.00421	1.10E+04
Cu-61	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Ni-66	0.00841	2.70E+04	2.27E+02	0.00	0.00	0.00	0.00	0.00421	1.14E+02

Figure 24 Pilot Case Study 1 – Radionuclide Release (Cooldown)
(Isotope and activity levels are illustrative only and are not specific to CERN or LHC)

RADIONUCLIDE RELEASE - MODE: SHUTDOWN (120 days after shutdown)									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.707	0.00	0.00	0.09189	0.00	1.11693	0.00	0.00	0.00
H-3	0.284	1.42E+07	4.05E+06	0.00766	1.09E+05	0.27677	3.94E+06	0.00	0.00
Cu-66	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-64	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-67	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-61	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Ni-66	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00

Figure 25 Pilot Case Study 1 – Radionuclide Release (Shutdown)
(Isotope and activity levels are illustrative only and are not specific to CERN or LHC)

7 Parameter Uncertainty and Sensitivity

The purpose of Objective 5 is to identify sources of uncertainty and gain insights into the relative sensitivity of the numerous input variables that influence the frequency of cable fire sequences and the radiation release fraction from cable fires. As with all quantitative risk analyses, the most valuable insights provided are not necessarily the absolute values of the estimated frequencies and consequence. Rather, the most useful information is the relative importance of the variables on the results – in other words, which variables exhibit the greatest influence on the results.

Understanding the sources of uncertainty and relative ranking of influence parameters is essential for risk management decision making and cost-benefit analysis. Such information fosters objective decision making and allows for optimisation of resources.

This thesis does not attempt an exhaustive uncertainty and sensitivity study of all variables. As an initial proof-of-concept research effort, the goal here is to identify the sources of uncertainty and provide a qualitative assessment of sensitivity. As the methods are further refined and enhanced in support of production work, a comprehensive assessment of uncertainty and sensitivity will be necessary.

7.1 Sources of Uncertainty

Sources of uncertainty for the cable fire sequence model and ignition source frequencies are identified in Table 13.

Table 13 Sources of Uncertainty – Cable Fire Model

Source	Uncertainty Level	Comments
Ignition source bins	Medium	Some CERN equipment is unique and does not fit neatly into conventional binning categories
Ignition source frequencies	High (applicability) Low (data spread)	Initial data is from nuclear plants and is based on full facility annual fire frequencies. The relative proportion of equipment (bin count) at CERN differs from nuclear plants, which introduces substantial uncertainty for calculation of individual ignition source frequency
Zone of Influence (ZOI)	Medium	Generic treatment of uncertainty for electrical cabinet and other ignition source ZOIs result in uncertainty for individual cases.
Overcurrent protection	Low (proper settings) Medium (performance) High (test/maintenance) Medium (arcing faults)	Self-ignited cable fires are highly sensitive to proper design, performance, and maintenance/testing.
Virtual fire compartments	Low	Cross-boundary conditions must be accounted for in the design fire scenario

Source	Uncertainty Level	Comments
Cable materials	Low	CERN maintains specifications for cables
Cable location	Medium	Correlation of all target cables to cable type not always straightforward.
Cable installed conditions	Medium	The propensity for a cable fire can be highly configuration dependent. It is not feasible to track cable tray loading and positioning for all cables. Thus, nominal values are used.
Electrical enclosure sealing	Medium	Electrical penetration sealing to cabinets and equipment directly influence ability for fire propagation out of an enclosure.
Electrical equipment operating status	Low	Operating mode dependent. Might not be practical to determine through field walkdowns.
Transient Frequency	Medium	Transient fire frequency for CERN is not known. The uncertainty for transient fire frequency will decrease with new fire tracking methods.
Cable mass estimates	High	Self-ignited cable fires require a mass weighting per compartment. Cable combustible mass is not currently tracked and must be estimated.

Sources of uncertainty for the fractional radiation release calculations are identified in Table 14.

Table 14 Sources of Uncertainty – Radionuclide Release Fraction Calculations

Source	Uncertainty Level	Comments
Cable activation levels	Low (computer computation) Medium (location) Low (cumulative irradiation) Medium (cable materials)	Numerous variables carry uncertainty with respect to calculation of the source term values.
Arcing faults	High (frequency) Medium (magnitude) High (duration) Medium (vaporization rate) High (overcurrent protection)	Arcing faults can produce vaporized metal radionuclide. The amount of conductor material vaporized is dependent on numerous variables.
Metal out-diffusion	High (temperature influence) High (duration influence) High (conductor size affect) High (fractional release)	The primary variables effecting out-diffusion are understood. The importance and uncertainty for the variables is not well established. CERN is supporting ongoing research into this topic.
Residual char	Medium (yield) Medium (constituents) Low (burning conditions) Medium (ventilation conditions) Medium (base materials) Medium (additives)	Char characteristics are dependent on many variables. Characterisation of CERN specific conditions is necessary to reduce uncertainties.
Soot	Medium (yield) High (constituents)	Soot characteristics are dependent on many variables. Characterisation of CERN specific

Source	Uncertainty Level	Comments
	Low (burning conditions) Medium (ventilation conditions) Medium (base materials) Medium (additives)	conditions is necessary to reduce uncertainties. CERN is supporting ongoing research into this topic.
Combustion gases	Medium (yield) Medium (constituents) Low (burning conditions) Low (ventilation conditions) Medium (base materials) Medium (additives)	Uncertainty for combustion gases is similar to that of soot. However, the radionuclide release fraction is less sensitive to the gas composition.
Cable specifications	Low (material type) Medium (mass fractions) Low (size)	
Operating status	Low	Operating status is readily defined.

7.2 Cable Fire Sequence Models & Frequencies

Based on the cable fire sub-model fault tree and use of the fault tree for several pilot cases, the following observations are made with respect key fault tree parameters:

Operating Mode: Most of the high-energy systems for LHC and the experiments are deenergised while in Shutdown mode. This significantly reduces the quantity of electrical ignition sources and essentially eliminates the likelihood of self-ignited cable fires and HEAF events (two of the major contributors to overall cable fire probability). It is also observed that dominant risk sequences shift from fixed ignition sources to transient ignition sources when in Shutdown mode.

Circuit Classification: The type of circuit (i.e., power, control, instrument) heavily influences the dominant cable fire sequences in the fault tree due to available energy. Therefore, it is important to use the circuit type parameter as a key distinguishing point when conducting walkdowns (e.g., do not treat a 400 V power cable the same as instrument cables).

Electrical Ignition Source Type: The binning process and frequency assignment is based on type of ignition hazard. Electrical equipment is binned based on type, and the frequencies can vary substantially (e.g., a motor has a different fire frequency than an electrical panel). This parameter has a direct impact on the overall frequency. The equipment type with the highest failure probability is electrical cabinets, thus accurate accounting of this ignition source category is important.

Baseline Fire Frequency: The baseline fire frequency for each ignition source bin is assigned to the facility. Individual item frequency is obtained by dividing the baseline frequency by the number of bin items at the facility (number of compartments for transient ignition hazards). Hence, the analysis is sensitive to the quantity of each ignition source type. Since the baseline frequencies from nuclear plants are those developed for the nuclear power industry, it is essential that over time the data is updated to reflect CERN-specific failure rates. This parameter currently has a high uncertainty since no CERN data is included in the analysis. Bayesian updates (or similar) could be one possible means to periodically replace the initial nuclear plant data with CERN-specific values.

Self-Ignited Cable Fires: Since self-ignited cable fires are driven by high-energy circuits and the LHC tunnel and experiment caverns have proportionally fewer of these circuits (most of those at LHC are above ground), the cable fire frequencies for the tunnel and experiment caverns are less sensitive to the parameters for self-ignited cable fires.

Overcurrent Protection Reliability: This research assumes proper electrical protection and coordination of circuits. Experience indicates that overcurrent device performance can significantly degrade with time if appropriate maintenance and testing are not completed. A reduction in protective device reliability can measurably affect the self-ignited cable fire frequency.

7.3 Radionuclide Release Fraction

Based on the methodology for assessment of radionuclide release and application of the methods for several pilot cases, the following observations are made with respect to the key influence parameters:

Operating Mode: Operating mode has a major impact on the source term for short-lived radionuclides and negligible impact on the source term for long-lived radionuclides.

Activation Levels: The initial source term activation levels are a main driver of the overall potential radioactive release. For this reason, accuracy in modelling (including location) is essential. It is not recommended to use worst case activation levels for the sake of expediency given the significance of this parameter.

Out-Diffusion: Even though out-diffusion of conductor metals into the insulation is a small fraction (usually about 0.1%), the analysis shows this parameter to be a key contributor to radionuclide release. Additionally, the fraction of diffused metals that are evolved during the fire is highly speculative (recall this analysis assumes 50%). Both parameters associated with out-diffusion have a high uncertainty and require further research.

Cable Quantity and Materials: Both quantity and material type have a direct impact on potential radionuclide release. The analysis process must include accurate collection of cable quantity and cable material specifications.

Char and Soot Yield: Surprisingly, char yield and soot yield have less of an impact than other parameters. It was originally believed that these two parameters would be dominant. As an example, increasing the char fraction from 25% to 50% is minor compared to activation level changing from E+3 to E+4 range.

8 Conclusions

This thesis researches risk informed methods for estimating radiation release from cable fires at high energy physics facilities. The research effort is focused on the CERN LHC, but the concepts and methods extend to any facility operating high-energy particle accelerators. CERN has embarked on a large-scale, multi-year project (the FIRIA Project) to enhance CERN's fire safety engineering capabilities and analysis tools [4]. A fundamental goal of the FIRIA Project is to develop quantitative risk assessment methods for fire-induced radiation release [4], [5], [7]. Cable fires are a major concern with respect to fire-induced radiation release.

The current state-of-knowledge for fire-induced radiological release is limited; analyses usually devolve to a crude assumption that all affected radioactive materials are liberated by the fire – new tools and more accurate modelling methods are needed. In alignment with the FIRIA Project goals, this thesis has focused on advancing technical capabilities for two specific aspects of cable fire analysis:

- Develop a more accurate framework for modelling cable fire sequences and quantitatively estimating cable fire frequencies
- Develop quantitative methods for estimating the portion of radioactive isotopes released into the smoke plume of fires involving electrical cables that have become radioactive through proton activation.

The key findings of this work and suggested future research are summarised below.

8.1 Cable Fire Sequence Models and Frequency

A viable cable fire sub-model was developed based on two underlying concepts:

1. Electrical engineering principles and operating experience can be used to categorise and refine cable fire sequences to more precisely model cable fire hazards using fault tree analysis.
2. Ignition source characterisation methods developed by the nuclear industry can be adapted to CERN such that fire risk analysis methods incorporate weighting factors to assign fire frequencies more accurately to specific locations, operating modes, and conditions.

The cable fire sub-model consists of a fault tree with primary branches representing three defined cable fire categories – external exposure fire, self-ignited fire, and terminal equipment fire. Each main branch contains sub-branches to capture the various mechanistic failures that can initiate a cable fire. The cable fire fault tree was successfully applied to three pilot cases. Key observations for this aspect of the thesis are:

- Use of the cable fire sub-model affords a more detailed breakdown of cable fire risk, thereby allowing better insights into relative fire risk. The detailed results support improved cost-benefit analysis because major risk contributors are not masked by generic treatment of hazards.

- The LHC tunnel and experiment main caverns do not contain fire compartmentation. Treatment of these locations as single fire compartments significantly reduces the benefits of risk weighting factors. The concept of “virtual fire compartments” was introduced as a surrogate means of retaining the benefits of refined modelling.
- Proper application of the sub-model requires collection and management of a significant amount of ignition source data and target cable information. However, this same data is necessary for development of design fire curves in accordance with accepted performance-based design criteria.
- The initial baseline ignition source frequencies used in this project are from nuclear plant data. This data is considered representative and adequate for proof-of-concept development. However, a concerted should be made to progressively replace this initial data set with CERN-specific data to reduce uncertainty.
- Distinguishing fire risk between operating modes is essential. The pilot studies show a dramatic shift in risk from fixed equipment hazards to transient ignition hazards between operating and shutdown modes.

8.2 Radionuclide Release Fraction

A quantitative methodology was developed for determining fractional release of radionuclides from burning cables. The methodology is based on two concepts:

1. The combustion chemistry is blind to the isotopes associated with the fuel materials.
2. The fractional release can be determined by employing conservation of mass to pre-fire and post-fire activated elements. The pre-fire activity per unit mass must equal the post-fire activity per unit mass.

The radionuclide release fraction method is essentially an inventory balance of the radioactive isotopes. The isotopes and their activation levels are determined through specialized software analysis and are taken as the key input to the analysis. Key observations for this aspect of the thesis are:

- The analysis method is a viable means of estimating activity levels for the combustion species input into FDS. The methodology requires further verification and validation of input and influence parameters to support full-scale implementation, but it is a substantial improvement over assuming all activity is liberated by a fire.
- The most significant parameter in the radionuclide release estimations is the input activity levels. Significant attention to this input parameter is warranted. The use of bounding worst-case values is not recommended.
- It is important to track char, soot, and gaseous yields in the proper elemental proportion to ensure the radionuclide inventory balance is maintained.
- Operating mode is important for short-lived isotopes but relatively insignificant for long-term isotopes.
- Pilot case studies validate the usability of the methodology; however, further research is needed to confirm critical assumptions for residual char, soot yield, and out-diffusion (see Section 8.3 for additional information).

- Application of the methodology requires rigorous accounting of the mass fraction of cable materials. Calculations on an individual cable-by-cable basis are not practical. The pilot case studies demonstrate how target cable groups can be created and activity levels converted from a unit mass to unit length measure.
- Out-diffusion of metal particles from the cable conductor to the insulation materials is a small percentage, but this parameter has a major influence on the overall radionuclide release.

8.3 Future Research

Analysis of fire-induced radiological release is an immature technology. Hence, it is not surprising that this research effort has identified numerous areas for additional R&D. High-priority areas for advancing analysis methods and practices are:

1. Experimentation and tests to accurately characterise the constituents of char residue from burning cables. Several facets of char residue require further investigation:
   - Char mass yield as a function of materials, installation configuration (cable loading density), and burning regimen (under-ventilated and over-ventilated): Based on existing tests and information [24]–[26], [40], char yields of 25% and 5% for thermoset and thermoplastic materials respectively are recommended by this thesis. Give the wide variation in values, further research is suggested to determine more precise values for the specific cable materials used at CERN.
   - Char constituents: Available information identifies char from burned polymers as primarily "carbonaceous" materials [40]. Further testing and analysis are required to characterise the char constituents of CERN cable materials more precisely. This thesis conservatively treats the char as 100% carbon, which overestimates release of some radioactive isotopes. In support of improved radionuclide inventory calculations, a better understanding of radionuclides bound up in the char residue is needed, including metals from out-diffusion.
   - Fractional release of out-diffused metals from burning cables: The high temperatures of burning cable polymers causes diffusion of metal ions from the cable conductor to the insulation. This phenomenon has not been extensively studied. Hence, further research is needed to investigate what fraction of the diffused metals will be liberated into the smoke plume and what fraction will remain in the char residue. CERN has an ongoing research effort to better quantify the out-diffusion process; it is suggested that fractional release be incorporated into this work. A release fraction of 50% was used for pilot case studies, but this value does not have a strong basis and thus significant uncertainty exists for this parameter.
2. Development of a CERN-specific fire events database to record and characterise all fire events at CERN facilities (large and small). The fire frequency estimates used in this thesis stem from nuclear facility data. The data is judged as reasonably representative of CERN given the similar operating conditions. However, with no CERN data included in the frequency estimates, the uncertainty for this critical parameter is high. Regular Bayesian updates with CERN specific data would greatly enhance the methodology.

3. Estimation of water vapor condensation in below ground facilities. The production of water vapour is inherent in the combustion process. Tritium (H-3) is a major isotope of concern. Future research efforts to quantify fractional condensation of water vapour within underground structures prior to the combustion products being vented to atmosphere would help provide more accurate estimates on the potential environmental release of this radionuclide.

9 References

[1] CERN, “The Large Hadron Collider,” *About CERN*, 2020. https://home.cern/science/accelerators/large-hadron-collider (accessed Feb 25, 2020).

[2] CERN, “LHC Facts & Figures, Season 2,” *About CERN*. https://home.cern/sites/home.web.cern.ch/files/2018-07/factsandfigures-en_0.pdf (accessed Feb 25, 2020).

[3] D. Forkel-Wirth, “FIRIA project: addressing fire safety at CERN,” *At CERN*, Mar 01, 2019. https://home.cern/news/news/cern/firia-project-addressing-fire-safety-cern (accessed Feb 25, 2020).

[4] Saverio La Mendola, “FIRIA Project,” *At CERN*, 2020. https://hse.cern/content/firia (accessed Feb 25, 2020).

[5] HSE FSE Team, “FIRIA Project Kickoff: A Fire Induced Radiological Integrated Assessment for facilities facing fire and radiological risks (EDMS 1982653v1),” Jun 2018.

[6] ISO/TC 92/SC4, “ISO 16732-1:2011, Fire safety engineering - Fire risk assessment (Part 1 - General),” ISO Standard, 2011.

[7] Giordana Gai, “The FIRIA project: an integrated approach to address fire and fire-induced radiological release risks at CERN (EDMS 2149906 v.1),” presented at the International Technical Safety Forum ITSF 2019, May 13, 2019.

[8] Kevin McGrattan, Simo Hostikka, Randall McDermott, Jason Floyd, and Marcos Vanella, “Fire Dynamics Simulator User’s Guide, Sixth Edition,” NIST, Feb 2019.

[9] NCNR Health Physics, *Neutron activation and scattering calculator*. NIST, 2020.

[10] Xabier Vidal and Ramon Manzano, “Magnetic dipoles - Taking a closer look at LHC,” *CERN Courier*, vol. Vol 51, p. pp 21-27, Oct 2011.

[11] Education, Communications and Outreach Group, “LHC FAQ - The guide.” CERN, Feb 2017, [Online]. Available: https://home.cern/sites/home.web.cern.ch/files/2018-07/CERN-Brochure-2017-002-Eng_0.pdf.

[12] “CERN LHC.jpeg (1503×1020).” https://spectrum.ieee.org/image/Mjk3ODI5OQ.jpeg (accessed Mar 04, 2020).

[13] Angela Harrison, “Risk Analysis of the LHC Underground Area,” CERN, Thesis CERN-THESIS-2007-044, Jul. 2007. [Online]. Available: https://cds.cern.ch/record/1044825/files/thesis-2007-044.pdf.

[14] G. Cumer, “CERN Technical Note: Description of the CERN Electrical network (ELG-HVNET-ON-0004).” CERN, Oct 19, 2015.

[15] S.P. Nowlen *et al.*, “NUREG/CR-6850 (EPRI 1011989), Vol 1, EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Volume 1: Summary and Overview,” NRC, Sep 2005.

[16] S.P. Nowlen *et al.*, “NUREG/CR-6850 (EPRI 1011989), Vol 2, EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Volume 2: Detailed Analysis,” NRC, Sep 2005.

[17] “NUREG/KN-0003, Fire Protection and Fire Research Knowledge Management Digest, 2013,” NRC, Jan 2014.

[18] Vytenis Babrauskas, “How do electrical wiring faults lead to structure ignitions?,” in *Fire and Materials 2001 Conference*, London, 2001, pp. 39–51.

[19] S.P. Nowlen, “NUREG/CR-5384, A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987,” NRC, Dec 1989.

[20] US NRC, “Regulatory Guide 1.191, Fire Protection Program for Nuclear Power Plants During Decommissioning and Permanent Shutdown,” May 2001.

[21] S. Tsuchino *et al.*, “NUREG/IA-0470, Vol 1, Nuclear Regulatory Authority Experimental Program to Characterize and Understand High Energy Arcing Fault (HEAF) Phenomena,” NRC, Aug 2016.

[22] Nuclear Energy Institute, “NEI 00-01, Rev 2, Guidance for Post Fire Safe Shutdown Analysis,” NEI, May 2009.

[23] NEA, “The OECD/NEA PRISME Project,” *NEA PRISME Project*, Jul 07, 2014. https://www.oecd-nea.org/jointproj/prisme.html (accessed Apr 28, 2020).

[24] Kevin McGattan *et al.*, “NUREG/CR-7010, Vol 1, Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE), Phase 1: Horizontal Trays,” NRC, Jul 2012.

[25] Kevin McGattan, Scott Bareham, and Dave Stroup, “NUREG/CR-7010, Vol 2, Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE), Phase 2: Vertical Trays,” NRC, Dec 2013.

[26] S.P. Nowlen, “NUREG/CR-4679, Quantitative Data on the Fire Behavior of Combustible Materials Found in Nuclear Power Plants: A Literature Review,” NRC, Feb 1987.

[27] Dan Madsen *et al.*, “Fire-Induced Radiological Integrated Assessment - Aerosol Characterization: Soot Testing Campaign: Deliverable AD-01,” Lund university, WP-AT: T-LU-AD_FD-01, May 2019.

[28] Dan Madsen *et al.*, “Fire-Induced Radiological Integrated Assessment - Fire properties of selected materials and products: Soot Testing Campaign: Deliverable FD-03,” Lund University, WP-AT: T-LU-AD_FD-01, Sep 2019.

[29] US NRC *et al.*, “NUREG-2178 (EPRI 3002005578), Vol 1, Refining And Characterizing Heat Release Rates From Electrical Enclosures During Fire (RACHELLE-FIRE) — Volume 1: Peak Heat Release Rates and Effect of Obstructed Plume,” NRC, Apr 2016.

[30] US NRC, EPRI, Jensen Hughes, EPM, Duke Energy, and S. Nowlen, “NUREG-2178 (EPRI 3002005578), Vol 2 (draft), Refining And Characterizing Heat Release Rates From Electrical Enclosures During Fire (RACHELLE-FIRE) — Volume 2: Fire modeling guidance for electrical cabinets, electric motors, indoor dry transformers, and the main control board,” NRC, Jun 2019.

[31] US NRC, EPRI, and Jensen Hughes, “NUREG-2230 (EPRI 3002016051), Methodology for Modeling Fire Growth and Suppression Response of Electrical Cabinet Fires in Nuclear Power Plants (draft),” NRC, Apr 2019.

[32] Kevin McGattan, Scott Bareham, and Dave Stroup, “NUREG/CR-7197, Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE),” NRC, Apr 2016.

[33] K. Canavan and J.S. Hyslop, “NUREG/CR-6850 (EPRI 1019259), Supplement 1, Fire Probabilistic Risk Assessment Methods Enhancements,” NRC, Sep 2010.

[34] US NRC, EPRI, and ERIN (now Jensen Hughes), “NUREG-2169 (EPRI 3002002936), Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability Estimation Using the Updated Fire Events Database: United States Fire Event Experience Through 2009,” NRC, Jan 2015.

[35] IEEE Industry Applications Society, *IEEE 242-2001, IEEE recommended practice for protection and coordination of industrial and commercial power systems*. New York, NY: Institute of Electrical and Electronics Engineers, 2001.

[36] NFPA Technical Committee on Electrical Safety in the Workplace, *NFPA 70E-2018, Standard for electrical safety in the workplace*. NFPA, 2018.

[37] Insulated Cable Engineers Association, "ICEA P-32-382-2007 (R2018), Short Circuit Characteristics of insulated Cable," ICEA, Aug 2018.

[38] R.H. Kaufmann and J.C. Page, "Arcing Fault Protection for Low-Voltage Power Distribution Systems - Nature of Problem," *AIEE Transactions Part III, Power Apparatus and Systems*, vol. 79, pp. 160–167, Jun 1960.

[39] R.H. Kaufmann, "Ignition and Spread of Arcing Faults," in *Industrial and Commercial Power Systems and Electric Space Heating and Air Conditioning Joint Technical Conference*, May 1969, pp. 70–72.

[40] M. J. Hurley, Ed., *SFPE handbook of fire protection engineering*, Fifth edition. New York: Springer, 2016.

[41] M. J. Hurley and E. R. Rosenbaum, *Performance-Based Fire Safety Design*. Hoboken: CRC Press, 2015.

[42] Greg A. Casto, "FPRA FAQ 16-0011, Cable Tray Ignition." NRC, Mar 20, 2018.

[43] J.S. Hyslop, "H. B. Robinson, Fire Event, March 28, 2010.," Mar 28, 2010. https://www.nrc.gov/docs/ML1021/ML102160224.pdf.

[44] C. R. Robertson, *Fundamental electrical and electronic principles*, 3rd ed. Amsterdam: Newnes, 2008.

[45] Milton Gussow, *Schaum's Outline of Basic Electricity, Second Edition*. McGraw-Hill.

[46] IEEE Industry Applications Society/Petroleum & Chemical Industry (IAS/PCI), *IEEE Std 1584-2018, IEEE Guide for Performing Arc-Flash Hazard Calculations.* IEEE, 2018.

[47] Reyes Alemany, Mike Lamont, and Stephen Page, "Functional Specification - LHC Modes (LHC-OP-ES-0005, rev 1.0)." CERN, Nov 26, 2007, [Online]. Available: https://lhc-commissioning.web.cern.ch/systems/data-exchange/doc/LHC-OP-ES-0005-10-00.pdf.

[48] IEC GEL/8, "IEC 60038:2009, IEC Standard Voltages," IEC, Jun 2009.

[49] R.H. Kaufmann, "Some Fundamentals of Equipment Grounding Circuit Design," *AIEE Transactions on Applications and Industry, Part II*, vol. 73, pp. 227–231, 1954.

[50] J.R. Dunki-Jacobs, "The Effects of Arcing Ground Faults on Low-Voltage System Design," *IEEE Transactions on Industrial Applications*, vol. IA-8, no. 3, pp. 223–230, May 1972.

[51] "Copper," *Wikipedia*. Apr. 15, 2020, Accessed: Apr 28, 2020. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Copper&oldid=951162366.

[52] "Aluminium," *Wikipedia*. Apr. 26, 2020, Accessed: Apr 28, 2020. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Aluminium&oldid=953251189.

[53] IEC Technical Committee 64, "IEC 60364-4-43, Low-voltage electrical installations. Installations électriques à basse tension. Part 4-43, Partie 4-43, Part 4-43, Partie 4-43," IEC, Geneva, 2008.

[54] NETA, "MTS-2019, Standard for Maintenance Testing Specifications for Electrical Power Equipment and Systems," NETA, 2019.

[55] NEMA, "NEMA AB 4-2017, Guidelines for Inspection and Preventive Maintenance of Molded-Case Circuit Breakers Used in Commercial and Industrial Applications," NEMA, Aug 2017.

[56] D. Drysdale, *An introduction to fire dynamics*, 3rd ed. Chichester, West Sussex: Wiley, 2011.

[57] Helmut Vincke and Chris Theis, “ActiWiz - Optimizing your nuclide inventory at proton accelerators with a computer code,” Jun 05, 2013.

[58] C. Adorisio, S. Roesler, C. Urscheler, and H. Vincke, “Chapter 11: Radiation Protection Considerations,” Feb 2016. [Online]. Available: https://cds.cern.ch/record/2131740/files/Radiation%20Protection%20Considerations.pdf.

[59] J.R. Dunki-Jacobs, “The Escalating Arcing Ground-Fault Phenomenon,” *IEEE Transactions on Industrial Applications*, vol. IA-22, no. 6, pp. 1156–1161, Nov 1986.

[60] B. Karlsson and J. G. Quintiere, *Enclosure fire dynamics*. Boca Raton, FL: CRC Press, 2000.

[61] Ipsos, “Global Citizen Reaction to the Fukushima Nuclear Plant Disaster,” Jun 2011, Accessed: Feb. 26, 2020. [Online]. Available: https://www.lefigaro.fr/assets/pdf/sondage-nucleaire-IPSOS.pdf.

[62] N. McCarthy, “Majority Of Americans Oppose Nuclear Energy For The First Time [Infographic],” *Forbes*, Mar 21, 2016.

[63] CERN, “LHC magnet types.” http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/components/magnets/types_of_magnets.htm (accessed Feb 24, 2020).

[64] CERN, “Taking a closer look at LHC - High vacuum.” https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.high_vacuum (accessed Mar 05, 2020).

[65] CERN, “About the ATLAS Experiment,” *ATLAS Experiment at CERN*, Mar 26, 2015. https://atlas.cern/discover/about (accessed Mar. 05, 2020).

[66] Giordana Gai, *FIRIA Methodology Flowchart (EDMS 2213206, v.1)*.

[67] M. Hofert *et al.*, “Radiation protection considerations in the design of the LHC, CERN’s Large Hadron Collider,” in *EUROPEAN LABORATORY FOR PARTICLE PHYSICS*, San Jose, California, Oct 1996, [Online]. Available: https://www.researchgate.net/publication/41585989_Radiation_protection_considerations_in_the_design_of_the_LHC_CERN's_Large_Hadron_Collider.

[68] Oriol Rios, “Activités de recherche sur les suies (tests de caractérisation + simulation),” presented at the FIRIA Collaborators Visit, Jan 29, 2020.

[69] R. W. Assmann *et al.*, “Requirements for the LHC collimation system,” *CERN Document Server*, Jul 24, 2002. https://cds.cern.ch/record/572775 (accessed Mar 04, 2020).

[70] Xabier Vidal and Ramon Manzano, “Ionizing radiation - Taking a closer look at LHC.” https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.ionizing_radiation (accessed Feb 24, 2020).

[71] O. US EPA, “Radioactive Decay,” *US EPA*, May 22, 2015. https://www.epa.gov/radiation/radioactive-decay (accessed Feb 28, 2020).

[72] Assignment Point, “Ionizing Radiation,” *Assignment Point*, Oct 10, 2015. https://www.assignmentpoint.com/science/physics/ionizing-radiation.html (accessed Apr 28, 2020).

[73] “Radioactive Decay - Equation - Formula,” *Nuclear Power*. https://www.nuclear-power.net/nuclear-power/reactor-physics/atomic-nuclear-physics/radioactive-decay/radioactive-decay-law/radioactive-decay-equation-formula/ (accessed Feb 28, 2020).

[74] “CERN’s accelerator complex2015bis.png (1590×1125).” https://espace.cern.ch/acc-tec-sector/Pictures/CERN's%20accelerator%20complex2015bis.png (accessed Apr 29, 2020).

[75] "LHC-Underground-Layout.png (2339×1653)." http://te-epc-lpc.web.cern.ch/te-epc-lpc/machines/lhc/pagesources/LHC-Underground-Layout.png (accessed Mar 04, 2020).

[76] maalpu, "LHC General Layout." http://maalpu.org/lhc/LHC.main.htm (accessed Mar 04, 2020).

[77] Sarah Charley, "3D-dipole.jpg (1600×900)," *Symmetry*. https://www.symmetrymagazine.org/sites/default/files/styles/2015_hero/public/images/standard/3D-dipole.jpg?itok=Y4tZugJi (accessed Mar 05, 2020).

[78] CERN, "Cryogenics: Low temperatures, high performance | CERN." https://home.cern/science/engineering/cryogenics-low-temperatures-high-performance (accessed Apr 29, 2020).

[79] CERN, "A vacuum as empty as interstellar space | CERN." https://home.cern/science/engineering/vacuum-empty-interstellar-space (accessed Mar 05, 2020).

[80] J. Jimenez, "LHC: The world's largest vacuum systems being operated at CERN," *Elsevier*, vol. 84, 2009, Accessed: Mar 05, 2020. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S0042207X09002887?token=ABE0A4594DAFB96640A68E42EE59B426AF5C502A9344BBB5222D036A2A0537D9492D4AAB67A94CD18F68E05F9407DBB6.

[81] "LHC Power Converters: A Precision Game," *CERN Document Server*, Aug 20, 2001. https://cds.cern.ch/record/45206 (accessed Mar. 05, 2020).

[82] F. Bordry, R. Denz, K.-H. Mess, B. Puccio, F. Rodriguez-Mateos, and R. Schmidt, "MACHINE PROTECTION FOR THE LHC: ARCHITECTURE OF THE BEAM AND POWERING INTERLOCK SYSTEMS," p. 33.

[83] R. Schmidt, "Machine Protection and Interlock Systems for Circular Machines - Example for LHC," *arXiv:1608.03087 [physics]*, Aug 2016.

[84] C. Wiesner, W. Bartmann, C. Bracco, E. Carlier, and L. Ducimeti, "LHC Beam Dump Performance in View of the High Luminosity Upgrade," p. 4, 2017.

[85] "The ATLAS detector walks another mile," *CERN Courier*, Aug 20, 2007. https://cerncourier.com/a/the-atlas-detector-walks-another-mile/ (accessed Apr 29, 2020).

[86] "CMS images gallery | CERN." https://home.cern/resources/image/experiments/cms-images-gallery (accessed Apr 29, 2020).

[87] S.A Eide, T.E. Wierman, C.D. Gentillon, D.M. Rasmuson, C.L. Atwood, and A-Marie Grady, "NUREG/CR-6928, Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants," NRC, Feb 2007.

Appendix A
CERN FIRIA Project

This appendix provides an overview of the FIRIA Project and explains in more detail how the key objectives of this thesis tie into the project. To set context for the FIRIA Project, the discussion starts with a summary of the unique fire safety challenges that exist at CERN. The process of modelling fire-induced radiation release is not well researched and is made especially challenging based on the non-standard nature of CERN facilities. The project title is intended to reflect the importance of an integrated analysis concept that embeds the unique concern of fire-induced radioactive release. Any sort of undesired radiation release is highly sensitive and can have severe repercussions to CERN [7] [5], [7].

A.1 A Unique Facility with Unique Fire Safety Challenges

CERN particle accelerator structures and facilities, most notably the LHC machine, pose unique fire safety challenges. The most visible of these concerns is a fire involving combustible radioactive materials. However, other features of the LHC machine also present fire safety challenges and fire risk analysis difficulties:

- The LHC beam apparatus is contained in an underground 27 km circular tunnel located partially in Switzerland and partially in France. Length of the tunnel alone makes fire localization and response difficult [2] [11].
- The tunnel is approximately 100 m below ground level with a limited number of access points for emergency evacuation, smoke control, and firefighting operations [5].
- The 27 km LHC tunnel is a continuous area with no fire rated compartmentation. This design attribute is a significant weakness from a perspective of traditional defence-in-depth fire safety concepts [41].
- The width and height of the tunnel are relatively small (a few metres), which results in a small cross-sectional area to function as a smoke reservoir. Consequently, smoke from a fire of any appreciable size is expected to migrate rapidly down the tunnel, creating a long distance of untenable conditions and low visibility.
- The long, non-compartmented narrow tunnel geometry does not lend itself to accurate analysis by computerized fire modelling, including zone models and computational fluid dynamics (CFD) models [8].
- The particle beam apparatus includes one-of-a-kind components. The unusual nature of this equipment and the extreme operating conditions cannot be overstated:

[7] The Chernobyl and Fukushima nuclear reactor accidents have left general society with a zero-tolerance attitude towards unintended release of radioactive materials [61]. A direct comparison of CERN to these past events is certainly not of the same order of magnitude. However, the public's sensitivity to unintended radiological release remains highly relevant to the FIRIA Project [62].

- Powerful magnets are used to accelerate and steer the proton beam. The electrical current required to power these magnets exceeds 10,000 A. To accommodate this high current without overheating, the magnets are constructed of a special niobium-titanium (Nb-Ti) material that is superconducting at extremely low temperatures. The magnets are operated at -271.3°C (about 1.7°C above absolute zero) using supercooled helium [10], [63].
- The two beam particle tubes are maintained at a near perfect vacuum to avoid undesired collisions of the proton particles and random atoms within the beam tubes [64].

Maintaining these extreme conditions over the entire 27 km length of the LHC is a monumental task.

- The experiment facilities associated with the LHC (ATLAS, CMS, ALICE, and LHCb) are also one-of-a-kind devices. They are massive in size and located in large underground caverns along the beam line [11], [65].
- Similar to the LHC tunnel, each experiment is located in a large underground space with no compartmentation (NB: the main support equipment for the experiment device is located in a separate fire compartment) [1], [11].
- The experiment devices are densely constructed units consisting of many different exotic materials and non-uniform dimensions. Representation of the device geometries and materials at a detailed level is not feasible.
- Reliability and failure data for the LHC and the experiment facilities are difficult to obtain. It is a unique, state-of-the-art machine of unprecedented size, complexity, and operating environment; there exists no comparable machine like it in the world. Further, it is typical that the machine is modified/enhanced during each successive long-term shutdown period. Thus, performance of equipment during previous operating cycles is not necessarily representative of future performance.

Self-evident are the challenges associated with fire risk analysis, design of fire protection features, and firefighting activities for the LHC and its associated experiment facilities. Regardless, CERN shoulders a responsibility to ensure fire risks are managed to acceptable levels for all stakeholders.

A.2 FIRIA Mission Statement

The CERN HSE Unit makes the following statement regarding the FIRIA Project:

"In order to define the fire safety requirements applicable to the Organization's research facilities, CERN's HSE Unit needs to assess the risks relating to fire in general and to the release of radioactive substances as a consequence of fire in particular. In the absence of detailed knowledge of those risks, the worst-case approach has been used until now. Such an approach may lead to the implementation of overly expensive, conservative mitigation measures and to misconceptions of the actual fire-related hazards.

In this context, the HSE Unit decided to launch a three-year project called FIRIA, which stands for Fire-Induced Radiological Integrated Assessment. The objective of the FIRIA project is to develop a general methodology for assessing the fire-related risks present in CERN's facilities, which may contain radioactive materials during their service life.

The methodology, based on ISO 16732-1, will be suitable for assessing fire-induced conventional and radiological risks to life, the environment and property, taking into account the complexity and specific characteristics of each facility, typically an experimental area. The project is highly multidisciplinary and aims to refine the methodological and physical assumptions in use, supported by testing campaigns as necessary. A framework for conducting more precise risk assessments will be established, which will facilitate the prioritisation of consolidation activities and the assignment of material and human resources. Dedicated IT tools will be developed to automatise the relevant analyses. State-of-the-art knowledge in areas including materials science, fire propagation, computational fluid dynamics, dispersion of pollutants, environmental modelling, radiation protection, quantitative risk analysis and parallel computing will be applied [4]."

A.3 FIRIA Project Objectives

The level of effort and resources necessary to accomplish the FIRIA Project objectives go well beyond a one-person master's thesis project. However, background information about the FIRIA Project establishes the framework and context for this thesis, which involves research into a specific area of the project – radioactive release from cable fires (addressed fully in Section 1.2).

As evidenced by the FIRIA mission statement, CERN is investing heavily into fire safety research efforts to advance the state-of-knowledge for fire risk analysis of high-energy physics facilities. The unique considerations for these facilities were covered in the previous section. The project aims to assess the safety outcomes (including radiological impact) for postulated credible fire scenarios at CERN facilities that are operating under a given fire safety regimen. Specific objectives of the FIRIA Project include [4], [5], [7]:

1. Develop a FIRIA methodology
2. Develop FIRIA models and computational tools
3. Implement prudent and technically defensible risk-informed, performance-based analysis methods to produce FIRIA assessments for critical facilities
4. Migrate the FIRIA methodology to a "production mode" that allows consistent, high-calibre service to clients

Cable fires are of specific interest with respect to fire-induced radiological release:

- The LHC and experiment facilities contain large quantities of cable
- Cable insulation and jacket materials are a known combustible hazard
- Cable insulation, jacket, and conductor materials are susceptible to proton activation (i.e., they can become radioactive as result of normal LHC operation, depending on proximity to the beam tubes)
- The inherent function of cables places them next to ignition sources (electrical short circuits)

A.4 FIRIA Project Research Efforts

The FIRIA Project team is organized into functional work areas as shown in Figure 26. The figure also indicates the main research efforts for each functional area. This structure is intended to focus research and development (R&D) activities within the specific technical areas and establish clear interfaces between project elements. The FIRIA Project team is supported by several other groups within CERN. Additionally, numerous external resources have been contracted to provide special expertise or services as necessary to support R&D efforts. Supporting Organisations include universities, fire research laboratories and test facilities, fire science SMEs, and NIST (FDS code owners and fire modelling experts) [5].

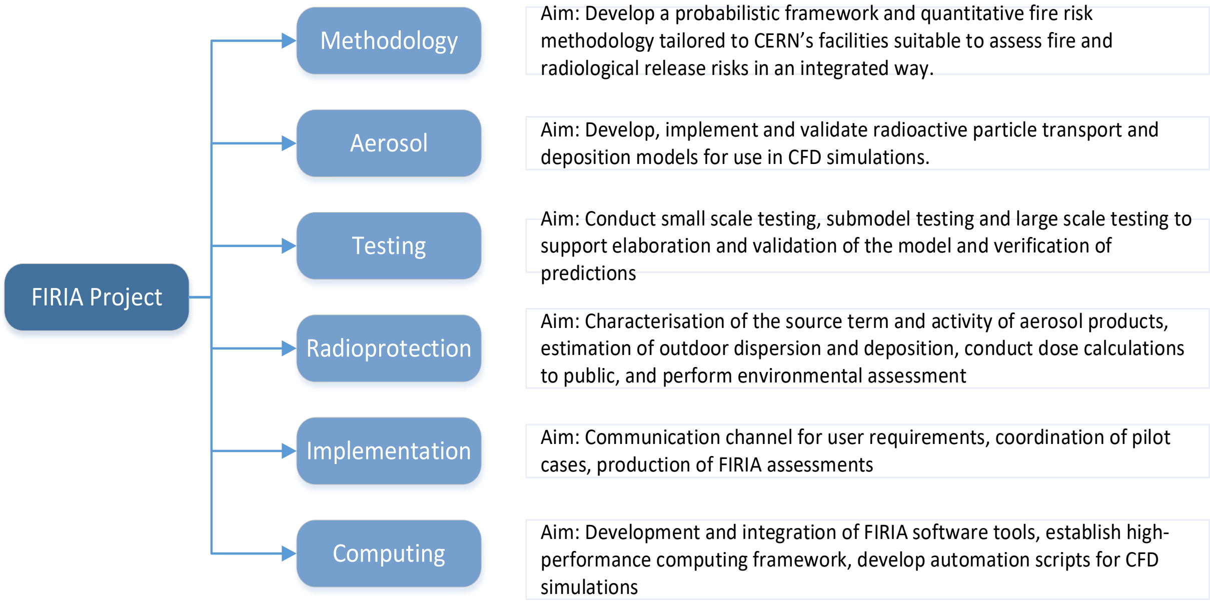

Figure 26 FIRIA Project Functional Organisation

By any measure, the R&D effort undertaken by the FIRIA Project team is ambitious and challenging. Upon its successful completion, the FIRIA Project will serve to significantly improve several areas of fire risk analysis and modelling – not only for CERN but for the entire fire safety engineering community.

A.5 FIRIA Methodology and Framework

The overall framework envisioned for the FIRIA methodology is shown in Figure 27. CERN has complex facilities with complex problems. It is not, therefore, surprising that the FIRIA methodology and framework are also quite complex. That said, the overall FIRIA Project methodology is based on ISO 16732-1 [6] and thus has its roots in accepted risk analysis methods. Figure 28 shows the ISO 16732-1 recommended flowchart for conducting a fire risk assessment.

As applied to CERN, the ISO 16732-1 flowchart is fine as a high-level roadmap to facilitate a systematic approach. Accompanying directions in the ISO standard provide good general insights and recommendations; however, consistent with the discussion in Section 3.2.1, the standard does not provide guidance for scenario identification and initiating event frequency at a level sufficient to serve as a best practice for special facilities such as LHC. Lower-tier standards and guidance documents are geared toward more conventional buildings and facilities and consequently are of limited help for the unique conditions at LHC.

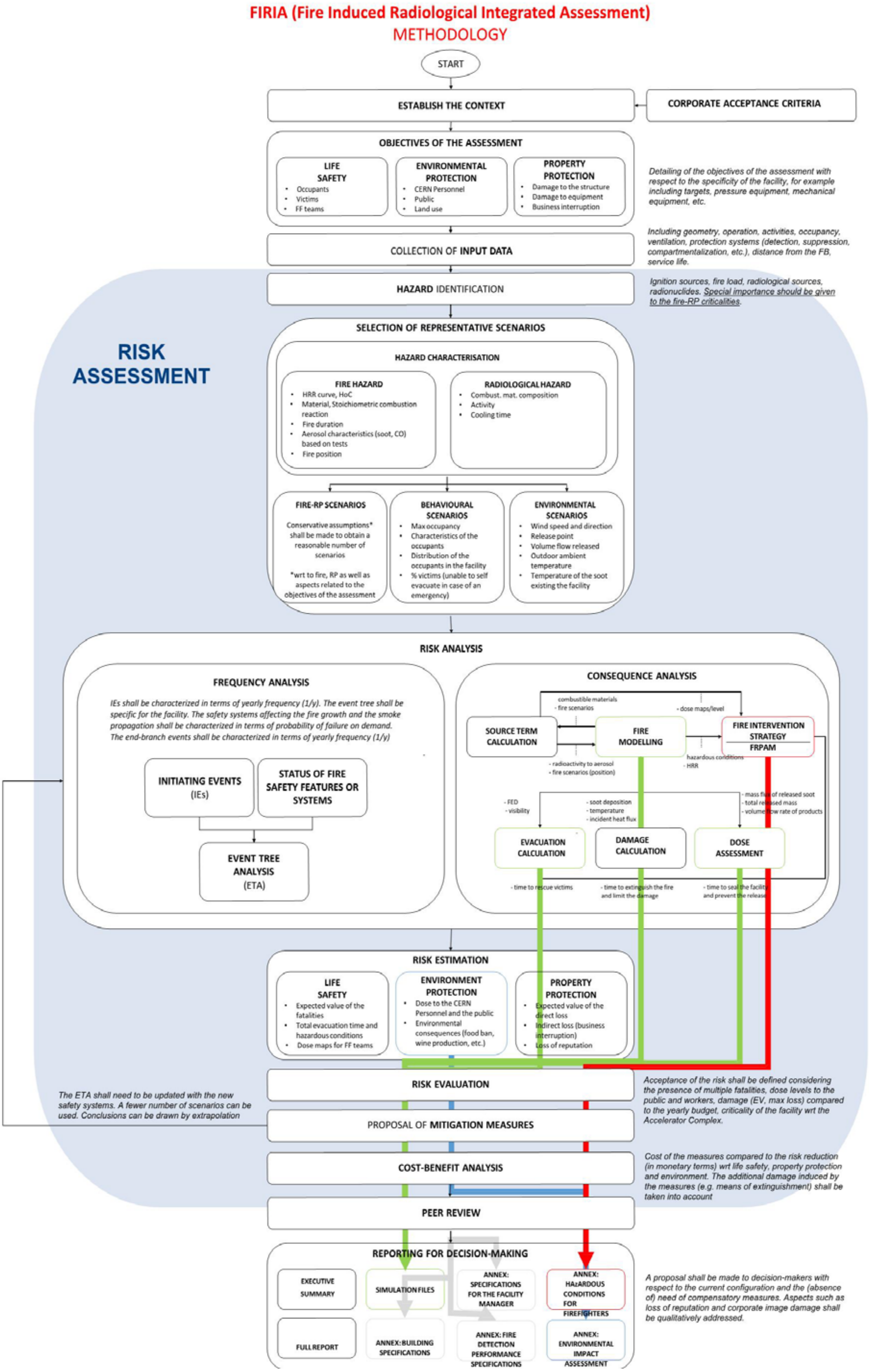

Figure 27 FIRIA Methodology Workflow Chart *(modified for appearance only)* [66]

FIRIA Risk Analysis Framework

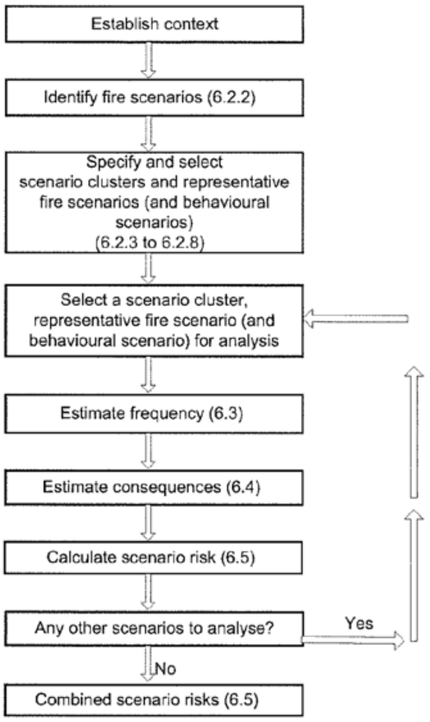

Figure 28 Fire Risk Estimation Flow Chart [6]
(Figure 2 from ISO 16732-1)

A.5.1 Objective 2 Relationship to FIRIA Project

Figure 29 shows a portion of the FIRIA methodology flowchart related to hazard identification, scenario definition/grouping, and initiating event frequency. In pursuing new modelling techniques for cable fires (Objective 2), it is important to pinpoint where, within the overall framework, the new cable fire sub-model fit. As shown in the figure, modelling improvements associated with Objective 2 will target three specific areas:

1. Categorise cable fire hazards – Cables are unique in that they are both a potential ignition source and a fuel source. In categorising cable fire hazards, both aspects must be considered.
2. Create fault tree templates to represent cable fire sequences – Logical grouping of cables by application, cable type, and electrical system operating parameters lends itself to systematic representation of specific fire event sequences. These fire event sequences can be represented in fault tree diagrams that function within the overall methodology to assign probability values to the different branches of the cable fire scenario event trees.
3. Using available data and electrical failure modes, derive frequency/probability estimates for the basic events captured in the fault trees.

Section 3.2.2 contains the reasoning behind and technical basis for these three elements of Objective 2.

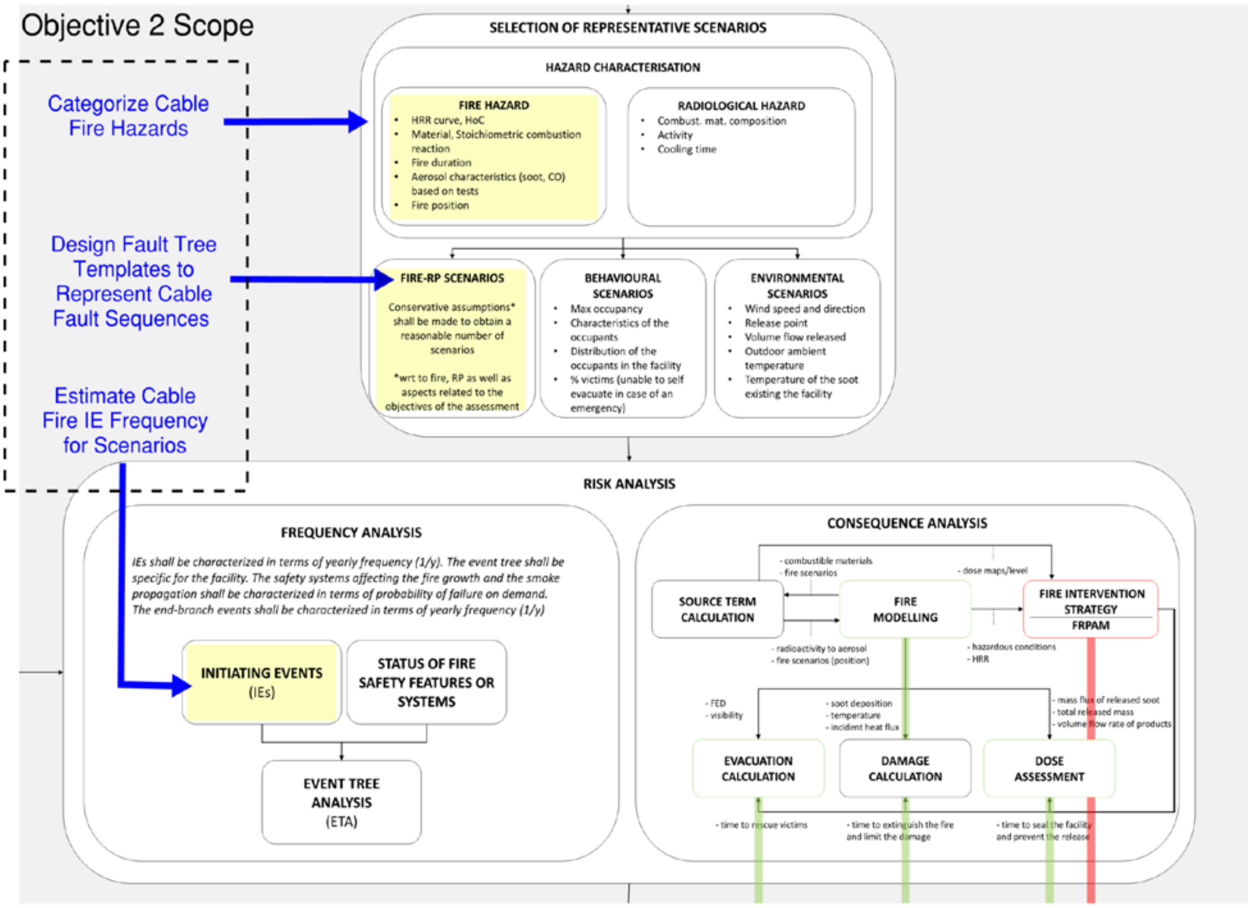

Figure 29 FIRIA Methodology – Cable Failure Sub-Model Functional Area [66]
(extract from Figure 27 with annotations)

A.5.2 Objective 3 Relationship to FIRIA Project

Figure 30 explicitly depicts the scope of Objective 3 as regards to the overall FIRIA Project framework. With reference to the figure, the amount of radioactive materials released during a cable fire is a function of many variables.

First, the radioactive isotopes within the cables must be identified and the activity level of each isotope determined. Appendix Section B.1 explains why activity level is a function of the number of operational cycles, time running or time since shutdown, and half-life of each radionuclide of concern. Next, the cable failure mode must be understood to determine if metal radionuclides are released due to arcing faults (metal vaporisation).

The fraction of each radionuclide released as a result of the burning process (pyrolysis and combustion products) must then be estimated (i.e., what fraction of the original radionuclides are evolved as smoke and pyrolysis gases due to burning). The design fire scenario will provide input as to how much material is burned and under what conditions.

Finally, aerosol transport and particle deposition must be accounted for in determining the final percentage of the original amount of radionuclide activity that is transported over the full distance from the fire to the vent point. Some of the radionuclides will be gaseous, some will be water vapor, and others will be soot particles. The transport and deposition efficiency will be different for each species of radionuclide and will likely vary as a function of the fire ventilation conditions (especially for under-ventilated conditions). For fires during operation, some short-lived radionuclides are also of concern. Short-lived isotopes are generally not a concern during shutdown conditions (as demonstrated in Section 6).

As shown on Figure 30, the scope of Objective 3 addresses only one aspect of radiological release from cable fires, that being the fractional amount of radionuclides evolved from the burning cables. CERN's Radiological Protection Department has conducted computer analyses and surveys to determine cable activation levels at various locations [57], [67]. This information represents the source term for the cables and the starting point for Objective 3 research. Once the fractional evolution of radionuclides is determined for the scenario, this information becomes the radiological source term for the design fire scenario. Information about the radioactive species and activation levels become the starting point for CFD fire modelling in FDS [8].

A key part of improving estimates for fire-induced radiological release to the environment is accurate aerosol modelling (smoke transport and deposition). Simulation of smoke transport using CFD modelling has improved significantly; however, modelling of soot deposition has largely been ignored. Deposition of soot (specifically radioactive soot) is an important part of determining radionuclide losses during smoke transport. Accordingly, the FIRIA Project is investing significant effort into refining methods for aerosol modelling, including verification and validation of FDS modelling software [5], [68]. CERN is working with NIST, the FDS software owner, on these improvements. The scope of this thesis project does not include research into any aspect of smoke transport and soot deposition. It is mentioned only for completeness, in that the data format for representing fractional radionuclide evolution must be compatible with the source term input format for the modelling software.

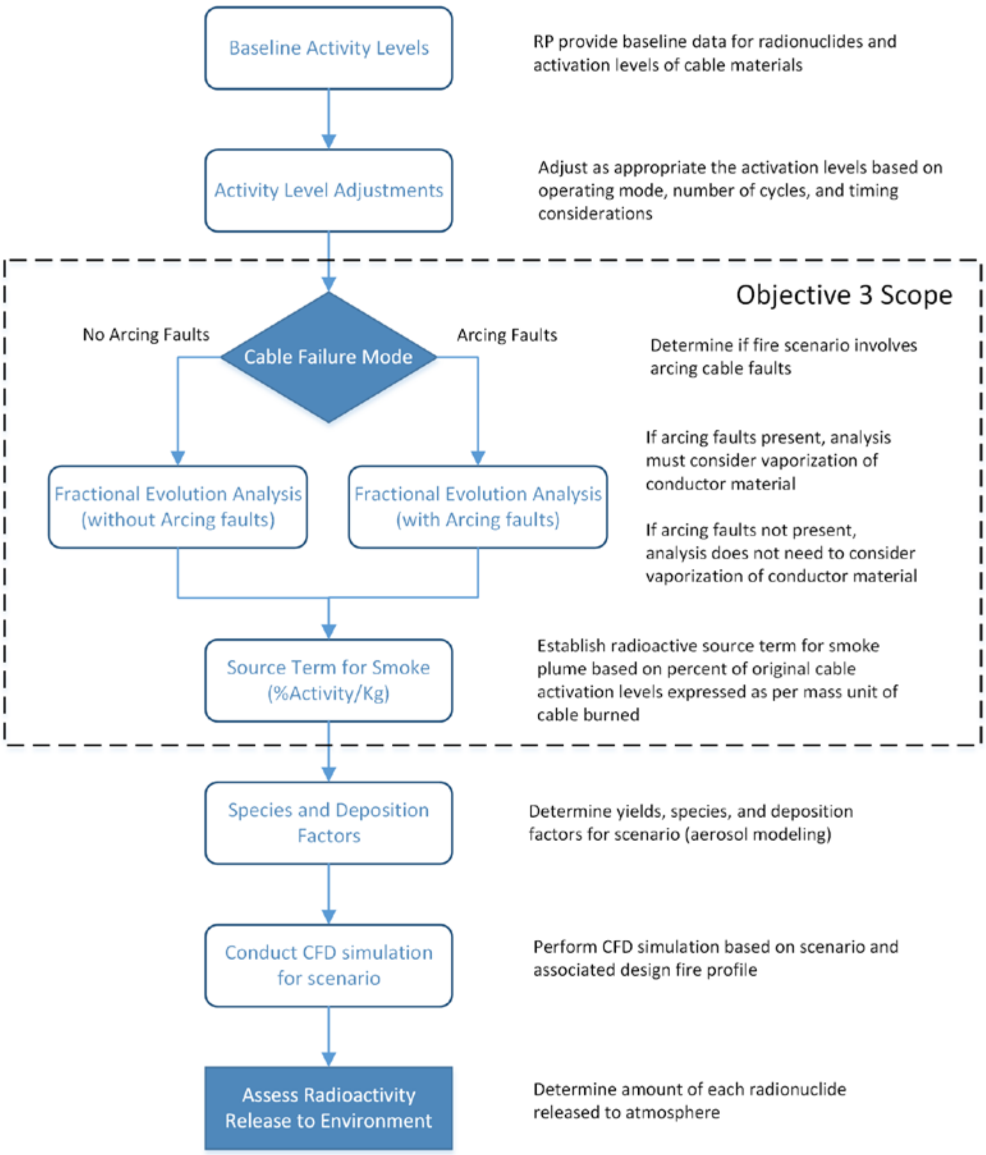

Figure 30 FIRIA Methodology – Fire-Induced Radiological Release Flow Chart

Appendix B
Fire-Induced Radiation Concerns at CERN LHC

It is important to understand why a radiological hazard exists at some CERN facilities, and the mechanism by which a fire can cause an uncontrolled release of radioactive material.

B.1 Proton Activation and Ionizing Radiation[8]

An inevitable aspect of operating high-energy particle accelerators is dealing with radiological hazards. During operation, some of the high energy particles escape the main beam line (a process called beam loss [69]) and travel into surrounding materials at high velocity [11], [58], [70]. These high energy particles can dislodge electrons from the atoms of materials through which they travel, causing damage to the underlying material. A stream of particles having sufficient energy to cause this type of damage is called *ionizing radiation* [58], [71], [72]. Ionizing radiation can damage biological materials (e.g., people, animals) and non-biological materials (e.g., metals, polymers). Figure 31 illustrates in a simplistic manner how radiation dislodges electrons from atoms, causing these atoms to become ionized.

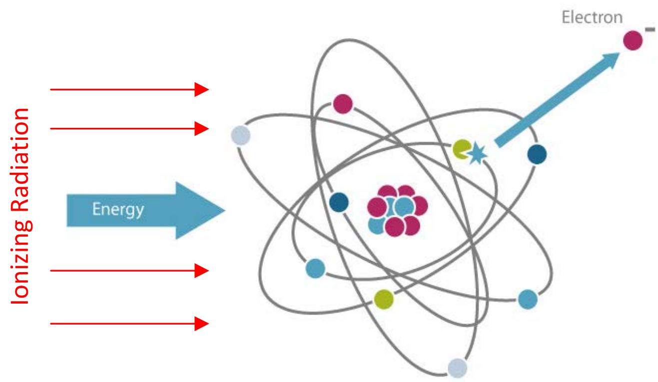

Figure 31 Ionizing Radiation and Electron Displacement (*as modified*) [72]

Additionally, heavy particles such as neutrons and protons can interact with the nucleus of atoms, thereby making unstable isotopes of the atoms. These unstable isotopes then undergo radioactive decay and emit additional ionizing radiation in the form of particles and electromagnetic waves (photons). This process is referred to as *activation* since the high energy protons or neutrons "activate" material to become radioactive [70]. The CERN LHC uses a proton

[8] The science of radioactivity, nuclear decay, and material activation is a complex area of study in and of itself. With deference to colleagues having expertise in radiation science, your tolerance is appreciated regarding the basic manner in which radiation concerns are covered in this thesis. However, the intent is to maintain focus on the fire science aspects of this research effort.

beam for operation, so proton activation of materials is the mechanism by which LHC materials are transformed into radioactive isotopes.

To summarize, LHC operation starts an inevitable sequence of events that leads to material activation and an ionizing radiation hazard [70]:

LHC operation → High energy protons produced → Beam loss →
Proton activation of LHC materials → Creation of unstable isotopes →
Radioactive decay of unstable isotopes → Production of ionizing radiation

High energy protons are present only when the LHC is operating. Therefore, proton activation and direct proton emission hazards do not exist when the LHC beam is off. Accordingly, no additional radioactive isotopes are being produced by proton activation when the LHC is shut down. However, during shutdown periods, radioactive decay of the already activated materials continues, and thus a radiation concern remains even when the LHC is not running. The highest radiation levels are present immediately after the beam line is shut down. As natural decay of activated materials progresses during a shutdown period, the radiation levels decrease exponentially with time. The cumulative amount of activated materials increases with each subsequent operating cycle. This in turn results in a continuous increase in the baseline radiological hazard over the life of the LHC.

Radioactive isotopes do not decay in the same manner. Different isotopes produce different disintegration products and the process occurs at different rates. Radioactive disintegration products consist of particles and electromagnetic waves (photons). These products have different energy levels depending on the original isotope; isotopes with higher energy decay products are a greater radiological concern because the decay process yields a more hazardous radiation field (i.e., higher energy decay products produce greater amounts of ionization damage when striking surrounding materials).

The rate at which radioactive isotopes decay is measured in half-life, which is defined as the average time for half of the original material to undergo a decay event. The half-life of a material is an important consideration in determining the radiological risk of a material. For example, a radionuclide with a half-life of a few seconds is a much lower concern than a radionuclide with a half-life of several hundred years. The half-life concept yields the well know radioactive decay equation:

$$\mathrm{N}(t) = N_0 \left(\frac{1}{2}\right)^{t/t_{\frac{1}{2}}} = N_0 e^{-\lambda t} \qquad [73]$$

Where: $\mathrm{N(t)}$ is the quantity of original radioactive isotope remaining after time t

$\mathrm{N_0}$ is the initial quantity of the radioactive isotope

$t_{1/2}$ is the half-life of the original radioactive nuclide

λ is the decay constant for the radioactive isotope

$$\lambda = {ln(2)}/{t_{\frac{1}{2}}}$$

Basic concepts of radiological activation, radioactive decay, and ionizing radiation hazards have been presented. These phenomena were shown to be a function of LHC operating mode, number of operating cycles, continuous time with beam present, continuous time with beam not present, activated materials and isotopes, and level of ionizing radiation hazard for the activated materials – all of which must be taken into consideration to estimate accurately the potential consequences of a fire-induced radiological release over the machine life.

B.2 Smoke Transport of Radioactive Material

As described in the previous section, normal operation of the LHC causes some surrounding materials to become radioactive by means of proton activation. Affected materials include metals, gases, oils, and polymers (natural and synthetic). Many types of polymers are used in the construction products for the LHC (e.g., plastics, resins, rubbers). As noted, these materials can become radioactive through normal operation of the LHC and they are also combustible. Consequently, a fire involving radioactive materials is problematic since the radioactive materials can participate in the pyrolysis and combustion reactions. That is, the smoke plume will contain radioactive pyrolysis and combustion products, both as gases and carbonaceous particulates (soot). Smoke migration due to buoyant plume forces and natural/forced ventilation will transport the now radioactive smoke to other locations within the LHC tunnel or affected facilities, and eventually some fraction of the smoke will likely be vented to atmosphere. Figure 32 illustrates the concerns of a fire-induced release of radioactive materials via smoke transport and the potential radiological hazard to CERN employees, first responders, the general public, and the surrounding environment.

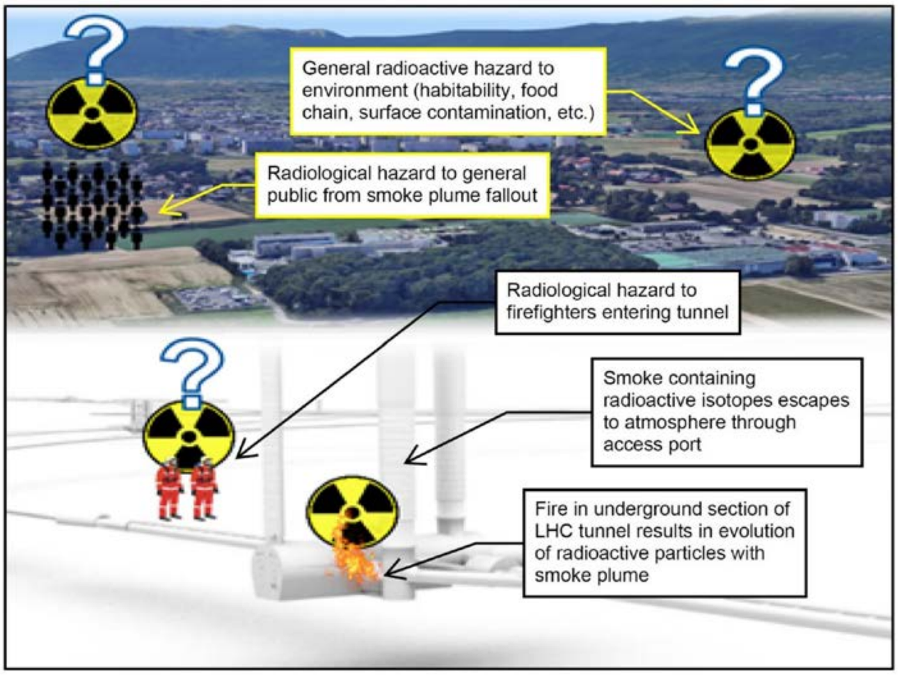

Figure 32 Fire-Induced Radiological Release Hazards [5]
(as modified with annotations)

The consequences of an event will of course depend on fire size, location, and duration. At a minimum, loose radioactive contamination as a result of smoke deposition to surfaces must be cleaned up. A worst case scenario might involve significant release of radioactive materials to atmosphere, which could impact nearby population centres and the general environment [5].

Appendix C
CERN LHC Description

This appendix provides an overview of the CERN main facilities and general description of the LHC machine. As explained in Section 2, it is intended to provide an exhaustive discussion about all CERN facilities and equipment, but rather to explain in most basic terms the major parts of the system and how it works. A basic understanding of the machine and its operation is necessary to put in context the unique fire risk considerations at CERN (as being addressed by the FIRIA Project). By extension, this information sets the foundation and framework for this thesis.

C.1 General Overview

CERN is comprised of a series of accelerators that work as an overall system to achieve the desired energy level for particles. Each accelerator represents a succession in higher energy capability, which reflects technological advances over time [11]. Figure 33 shows the interrelationship between the particle accelerators at the CERN complex.

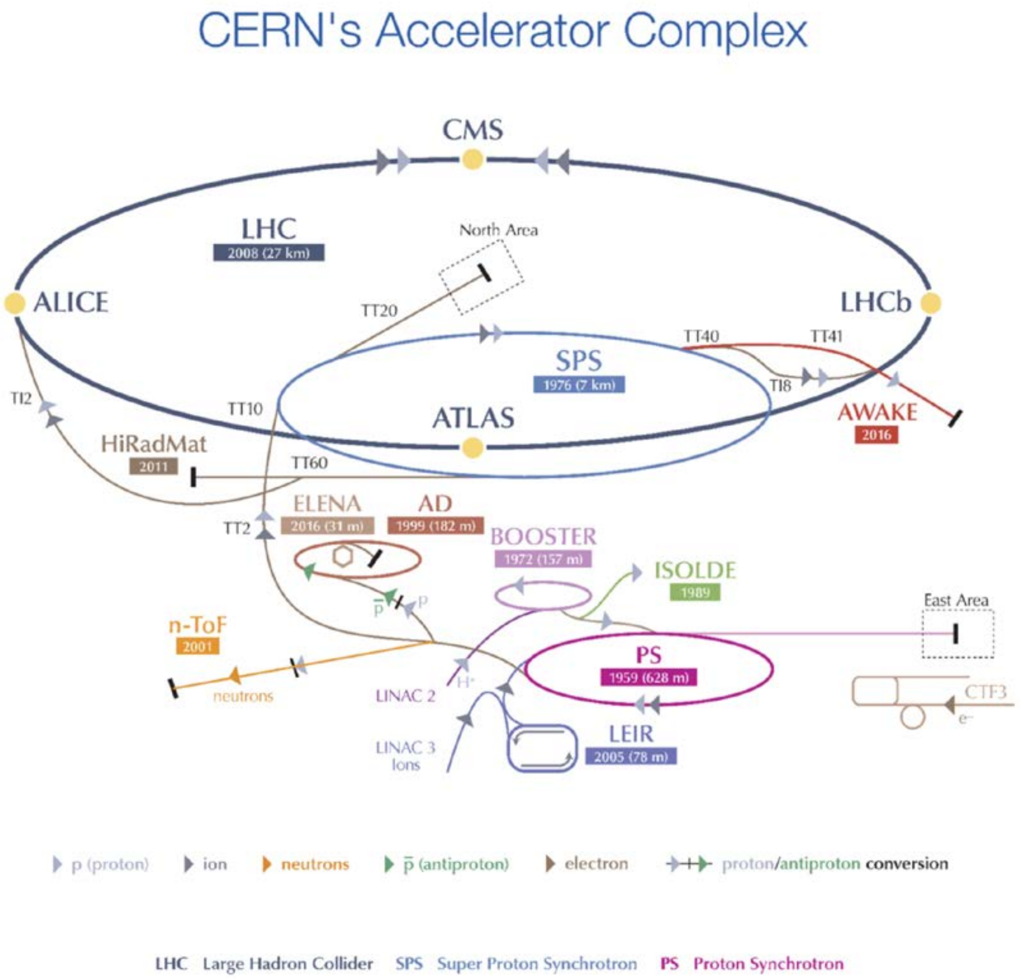

Figure 33 CERN Complex – Overview of Major Facilities and Structures [74]

Each accelerator receives the particle beam from its lower-energy sibling. It then accelerates the particle beam from the injection energy (energy at which it received the particles) to the maximum energy within its design capability. It then injects the particle beam into the next accelerator unit, where the process repeats itself. With reference to Figure 33, the overall sequence is depicted by the follow steps [11]:

Step 1 Pure Hydrogen atoms from a bottle and subjected to an electrical field that strips away the electrons, leaving only the Hydrogen nucleus (i.e., individual protons).

Step 2 The protons enter Linear Accelerator 2 (Linac2), where they are accelerated to 50 MeV and then injected into the Proton Synchrotron Booster (PSB).

Step 3 The PSB, a circular accelerator, increases the energy level to 1.4 GeV and then injects the particles into the Proton Synchrotron (PS).

Step 4 The PS, also a circular accelerator, increases the energy level to 25 GeV and then injects the particles into the Super Proton Synchrotron (SPS).

Step 5 The SPS, a large, high-energy accelerator, increases the energy level to 450 GeV, at which point the proton beam is transferred to the LHC. The beam is split during this transfer process so that approximately half the particles enter one of the LHC beam tubes traveling in the clockwise direction and the other half are directed to the second LHC beam tube in the counterclockwise direction.

Step 6 Once in the LHC, proton energy in each of the two beam tubes is increased to 6.5 TeV. At each experiment (ATLAS, CMS, ALICE, LHCb) the counter circulating particle beams are made to cross, thereby steering the beams directly at each other to create near head-on collisions. When solid collisions occur the nuclei of the protons are shattered, and various sub-atomic particles are created. The sub-atomic particles travel outward from the collision area and into the experiment detectors.

Step 7 The experiments are designed to look for different sub-atomic particles and thus have radically different designs to accommodate different types of detectors. Raw measurement data from the detectors is captured and stored by a massive computer network.

Figure 34 summarizes the capability of the different accelerators. Note also that the lower-energy accelerators also support their own regimen of experiments since not all research requires the ultrahigh energy of the LHC.

Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC
Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2		

Figure 34 CERN Particle Accelerator Capabilities Summary [11]

C.2 Large Hadron Collider (LHC)

In particle physics language, the objective of the LHC is to create collisions with an energy level of about 14 TeV or 22.4 x 10^{-7} J. At these energy levels each colliding proton is traveling at 99.9999991 percent the speed of light [11]. Physicists theorize that this energy range for particle collisions approximates the universe at 10^{-12} seconds after the Big Bang [11]. When expressed in Joules this seems like an exceedingly small energy level. However, consider that 1 gram of protons accelerated to this energy level has an energy content of about 4.5 x 10^{13} J, which is nearly the amount of energy release by the atomic bomb dropped on Hiroshima. During a typical run, the LHC circulates only nanograms of protons, resulting in a beam energy of about 350 MJ [11]. This energy level is substantial and the LHC is configured with a sophisticated safety system and interlocks to protect against an uncontrolled loss of beam.

The LHC machine is comprised of the high-energy beam accelerator structure, support equipment, and experiment facilities [1]. The main beam accelerator is contained in an underground circular tunnel approximately 27 km in length and 100 m deep. The “experiments” are stand-alone facilities located at discrete locations along the beam loop. At these locations, particle collisions are made to occur in the presence of sophisticated high-energy particle physics detection and measuring equipment. To some degree, the term “experiment” is misleading in that the physical size, complexity, and uniqueness of these individual facilities cannot be overstated. Similarly, the infrastructure and support systems for the LHC are complex and extensive.

C.2.1 LHC Tunnel Configuration

Figure 35 shows an illustration of the LHC underground infrastructure and a pictorial layout of the system. The LHC is not a perfect circle but instead is laid out in an octagon shape that logically divides the LHC into eight natural sectors, as shown on the figure [11]. The main experiments and other primary operational facilities are located at the centre of each sector. These locations represent “interaction points” for the beam and are labelled IP1 – IP8 (e.g., ATLAS is IP1 and CMS is IP4). Each octant section is straight at the IPs and curves at each end as it transitions to the adjacent octant. The octants and labelling scheme will be used throughout this report. From Figure 35 it is evident that the LHC tunnel contains other smaller caverns along its length. These smaller caverns are called alcoves and house various support equipment for the vacuum system, cryogenic system, and other functions.

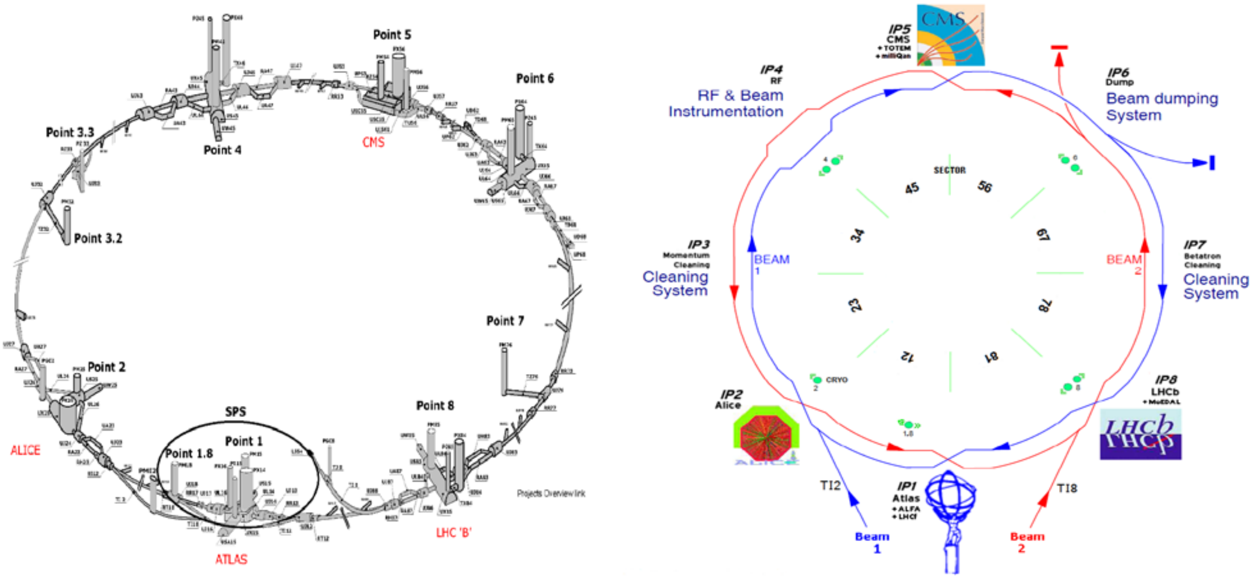

Figure 35 LHC Underground Infrastructure [75] [76]

As shown by the figure, the main LHC tunnel can be accessed at each interaction point, including the four experiments, beam dump, collimation (cleaning) system, and RF (accelerator) system. Note from the figure the two counter-rotating beam lines and crossing points at the experiments, as discussed previously. The two figures help illustrate the fire safety challenges for such a large and complex underground structure, including detection and alarm, automatic and manual suppression, evacuation, smoke control, fire service operations, and recovery.

C.2.2 Beam Line Apparatus

Figure 36 shows a dipole section of the beam line apparatus. The figure is labelled with the key parts within the LHC. Recall that the beam lines within each of the beam pipes run in opposite directions. The superconducting dipole magnets surround each beam pipe; they are smaller than one would imagine given the high magnetic field they create. The vacuum system maintains pressure within the beam pipes at an extremely high vacuum. The cryogenic system maintains temperature of the superconducting magnets at a mere 1.9 K.

From a fire risk perspective, it is evident that the LHC beam system itself is constructed primarily of non-combustible materials. Flammable materials consist of the dipole coil wire insulation, instruments, and instrument wires.

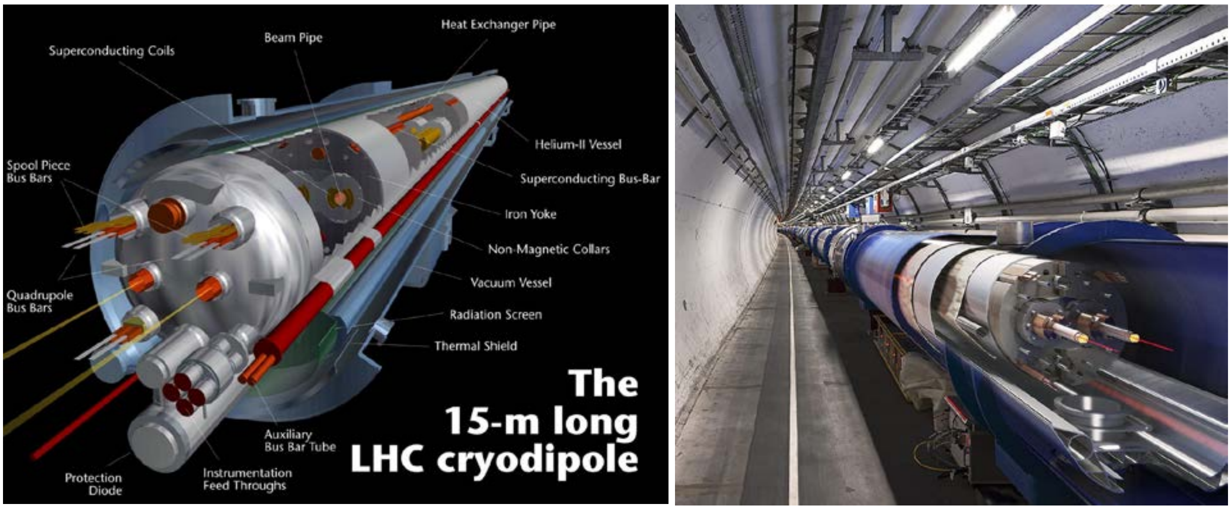

Figure 36 Beam Line Apparatus – Dipole Magnet Section [2] [77]

C.2.3 Superconducting Dipole Magnets

Critical to operation of the LHC are high intensity magnets installed at the curved parts of the LHC loop. The proton beams have a large momentum that must be "steered" through the arc sections of the octants. The ability to manage the proton beams through the curves is a limiting factor in the design of particle accelerators. Conventional magnets are not feasible to generate the high-intensity magnetic field required for the LHC due to high conductor/coil heating losses and saturation effects in the iron core. Consequently, development of the superconducting dipole magnets represents a technological breakthrough that made construction of the LHC possible.

The dipole magnets are constructed with special Niobium-Titanium (Nb-Ti) wire. This material becomes superconducting at exceptionally low temperatures. When operating at superconducting conditions, the magnet coils have virtually no resistance to electrical current flow and thus resistive heating is not as problem. The dipole magnets are cooled to 1.9 K (–271.3°C) by the LHC cryogenic system to maintain superconducting conditions [10], [63]. Helium is used as coolant in the system.

The dipole magnets carry over 11,800 A in a very small cross-section of the special Nb-Ti wire. The magnets for each curved section of an octant are connected in series and receive power from the 18 kV distribution system. The cables that supply power each section of dipole magnets are conventional copper conductor power cables. The connection of these conventional cables to the high-performance superconducting cables is considered a critical location with respect to potential electrical failure. Similarly, the internal connections between the dipole sections are also considered a critical failure point. Special attention will be given to these connections as part of the risk analysis methodology development.

It is noteworthy that the dipole magnet electrical interconnections were upgraded in 2013 to include shunts to function as an alternative, parallel current path in case of connection failure. Additionally, the superconducting magnets have been configured with improved quench protection to provide greater control of energy dissipation should abnormal voltage develop across a magnet (i.e., electrical failure) [2].

C.2.4 Cryogenic System

A critical support system for the LHC is the cryogenic system. The system maintains the critical superconducting temperature of 1.9 K (–271.3°C) needed for the dipole magnets with an elaborate refrigeration process using supercooled helium, liquid helium, and nitrogen. Considering that the system serves the entire LHC loop, it is massive in size. Five separate cryogenic facilities are located along the tunnel. 120 tons of helium and 10,000 tons of nitrogen are needed for the system, making it the largest cryogenic system in the world [78]. From a practical point of view, the cryogenic system is an entire industrial complex by itself.

C.2.5 Vacuum System

Analogous to the cryogenic system, the LHC vacuum system is the world's largest vacuum. The vacuum system is unique in that it actually is three separate systems, which function to maintain different levels of vacuum in different parts of the machine [79].

The most critical system is that used for the beam pipes, where any stray gas molecules represent large obstacles for the high-speed protons. Collisions between the high-speed protons and stray gas particles is highly undesirable. The vacuum in the beam pipes is around 10^{-7} Pa; however, near the experiments it is reduced even further to 10^{-9} Pa to optimize proton-proton collisions, a near perfect vacuum [64], [79].

The other two vacuum systems serve an insulating function for the superconducting magnets and the cryogenic system's helium distribution lines. These vacuum systems decrease the heat losses between components operating at cryogenic temperatures and external room temperature [80]. The vacuum requirements for these systems are not as stringent as that for the beam line pipes; however, the physical size and volume of the area to be pumped down and maintained under vacuum (9000 m^3) represents a major challenge.

C.2.6 CERN Electrical Power System and LHC Power Converters

The CERN complex uses a large amount of electrical power and the LHC is a significant portion of the electrical demand. The CERN complex is supplied by a 400 kV line and 130 kV line. The main source of power is the 400 kV line to the on-site BE substation, where the incoming 400 kV power is stepped down to 66 kV. The 66 kV power is then routed via underground feeders to the main facilities along the LHC (IP1 – IP8) loop [14]. At each facility, the 66 kV incoming power is stepped down further to 18 kV, which is the main service voltage for the facilities. An intertie scheme is used to connect the 18 kV power systems of all facilities in a loop configuration. This design provides cross-feed capability in case of a failure of the primary feeder at each facility.

The dipole magnets demand a significant amount of current to achieve the required magnetic field level. Custom high precision DC power converters are used to generate the high-current, low voltage power to supply the superconducting magnets. Nearly 1800 power converters are installed along the tunnel to serve this function. The conventional copper cables between the power converters and LHC superconducting magnets must be kept short to minimize resistive heat loss [81]. This requirement drives the need to install the power converters in the tunnel itself instead of above ground in a normal service equipment area. This design is of course less desirable from a fire safety point of view since it increases the likelihood and consequence of an electrical failure within the underground area.

C.2.7 Safety System and Interlocks

The circulating proton beams of the LHC contain a significant amount of energy – on the order of 340 MJ in each beam at maximum energy. Similarly, the energy stored in the magnetic fields of the LHC dipole superconducting magnets is a staggering 10 GJ (1.2 GJ per octant) [82]. Any perturbations or failures that impact management of the beam or superconducting conditions for the magnets can have catastrophic results. Failure modes that lead to a loss of superconducting conditions or uncontrolled beam loss are diverse and many. Accordingly, sensitive, highly reliable safety features are implemented.

A complete treatment of the safety systems and interlocks is well beyond the scope of this thesis. Understanding the overall safety concept is, however, important to properly characterise fire risk. The LHC protection system includes four main subsystems:

- Beam interlocks
- Powering interlock
- Beam dump
- Quench protection

Figure 37 shows the relationship between the interlock systems and the major LHC subsystems.

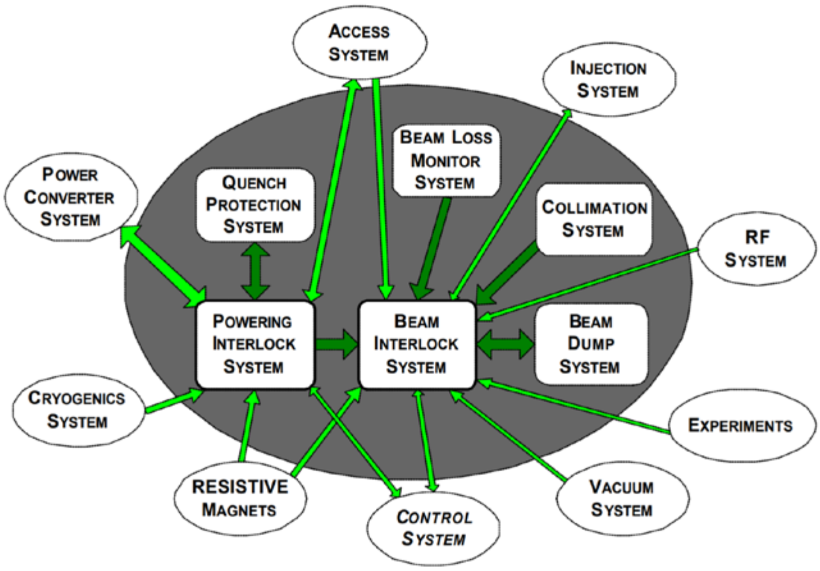

Figure 37 LHC Protection System [82]

<u>Beam Interlock System</u>

The beam interlock system serves two functions:

- Prevent beam injection if anything is amiss in the LHC machine (i.e., no protons can be injected from the SPS unless all conditions for safe beam operation are satisfied)
- Initiate an immediate beam dump if unsafe conditions are detected when beams are in the LHC. (i.e., shutdown the system and safely direct the circulating beams to the beam dump facility for safe dissipation of the beam energy)

Figure 38 shows a block diagram of the beam interlock safety system. The takeaway from this diagram is that many operating parameters are monitored, and the interlock controller blocks insertion or initiates a beam dump upon detection of any operating parameter outside a safe operating envelope. The beam interlock system is a failsafe design with a target reliability greater than 10^{-7} per operating design characteristics of the beam interlock system will be factored into the fire risk analysis hour [82], [83]. The as a fire that disables this system creates a secondary failure that can have catastrophic consequences.

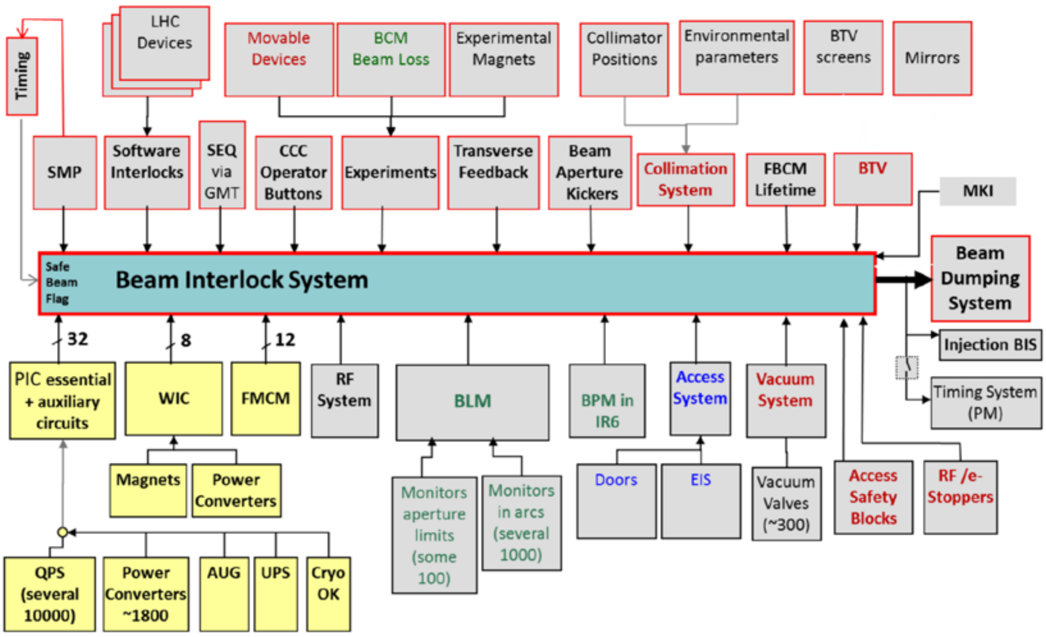

Figure 38 LHC Beam Interlock System [83]

Power Interlock System and Quench Protection System

The power interlock system and quench system function to ensure safe operation of superconducting magnets. The power interlock controller monitors key subsystems and operating parameters and allows the superconducting magnets to be powered on only when safe conditions are maintained. The quench protection system operates in coordination with power interlocks to immediately disengage the power converters if a quench event occurs.

Quenching is the term used to describe a condition in which the superconducting conditions are lost. As conductors transition out of superconducting, resistance increases which results in a rapid localized temperature excursion due to resistive losses from the high current level. This failure is rapid and catastrophic. The conductors can reach melting temperatures in a fraction of a second. The quench protection system also includes features to dissipate the high energy stored in the magnets. As discussed in previous section on superconducting dipole magnets, the quench system was upgraded in 2013 to provide greater protection.

Any event that triggers quench protection or the power interlock system also initiates the main beam interlock to fully shutdown the entire system.

Beam Dump System

The beam dump system is designed to extract the proton beams from the LHC under any conditions of operation. It is a critical link in the LHC protection system. The system consists of a group of magnets that redirect the proton beams into separate tunnels, where the beam energy is dissipated in a controlled manner using graphite blocks. With a combined energy over 650 MJ for the two beams this is not an insignificant task. The beam dump is located at IP6 [84].

The beam dumps are used under normal conditions at the end of a run to extract the beams from the LHC. More critically, they are used during an emergency shutdown when beam extraction is initiated by the beam interlock system. Failure of the beam dump system in a critical event could result in the beams leaving the beam tubes in an uncontrolled manner within the LHC tunnel. This dangerous condition could result in major damage to equipment and increased radiological risks.

C.2.8 Radio Frequency (RF) System

The RF system is located at IP4. It is used to increase the energy of the protons. The system uses special electromagnets called RF cavities to accelerate the proton beams. Like all LHC equipment, the RF cavities are complex, precision devices. They operate under superconducting conditions and provide an electrical impulse through use of 400 MHz electromagnet waves to increase proton energy levels [11].

C.3 Experiments

The experiments are custom designs since each has different research objectives. These machines push the boundaries of technology for science, design, and construction. They are giant machines built in underground cavities, yet are highly precise in their design, construction, and operation. From a fire safety perspective, the experiments are non-standard in many respects:

- They are very large but have no appreciable compartmentation for the main machine
- They are on average 100 m below ground
- Construction materials are exotic and, in many cases, cannot be categorised with respect to ignition hazard and flammability
- Conventional fire detection and suppression concepts are ineffective
- Many materials in the unit are activated through operation of LHC and thus pose a radiological concern
- The geometries, scale, and range of unknows make fire modelling extremely challenging
- Fire service response time is not optimal based on the installed conditions

A brief description of the major experiments is provided. For this thesis only the ATLAS experiment is considered further.

C.3.1 ATLAS Experiment

ATLAS is the largest detector ever constructed for a particle accelerator. It is specifically designed to take advantage of the higher energy proton beams generated in the LHC. It was built to find new subatomic particles and move the science of particle physics to the next level. Atlas is 46 m long, 25 m in diameter, weighs 7,000 tons, and was assembled in a cavern 100 m below ground. It is located at IP1 [11], [65].

The detector consists of six different detecting subsystems that surround the beam line in layers at the point of collisions. The detectors are designed to record the trajectory, momentum, and energy of particles. Using this information, researchers can individually identify and measure the particles, which are essentially byproducts of the high energy collisions between protons.

A large magnet system is integral to the detector design. It bends the path of charged particles so that the particle's momentum can be measured precisely. The magnet system is large and requires significant power. Compared to the smaller instrument systems, it is of greater fire safety concern because of the energy levels involved.

The main ATLAS machine is shown in Figure 39 and Figure 40. The overall size of the machine is evident from the workers in the lift truck (Figure 40).

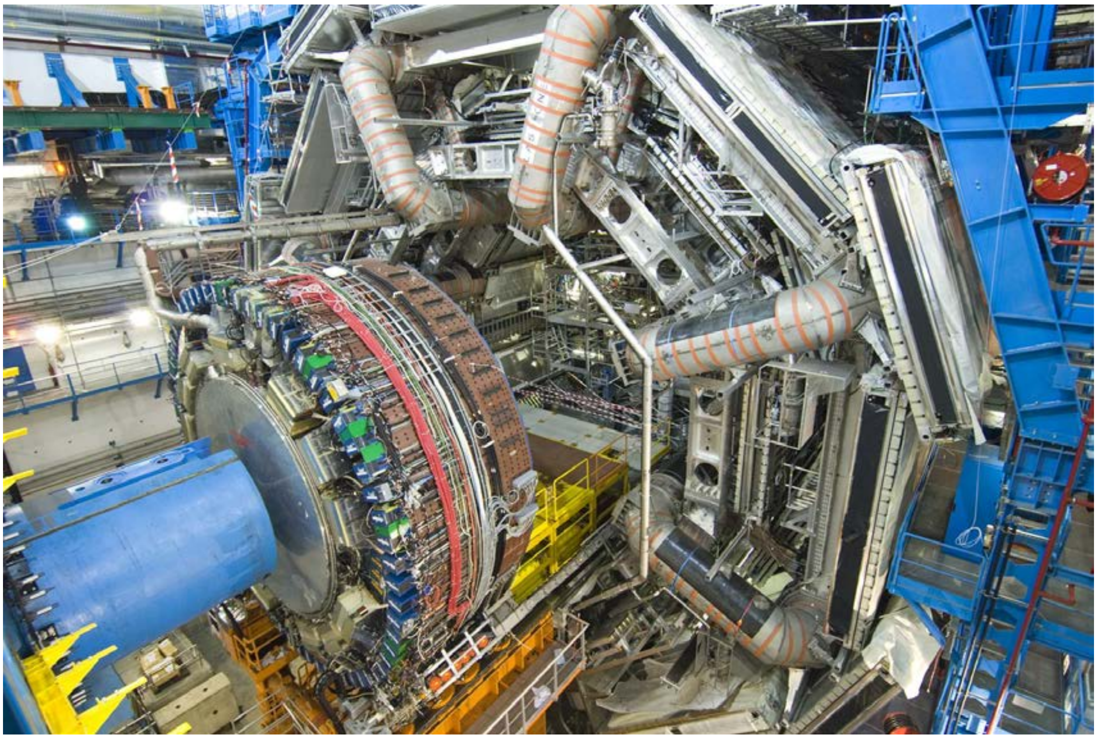

Figure 39 ATLAS Experiment – General View [85]

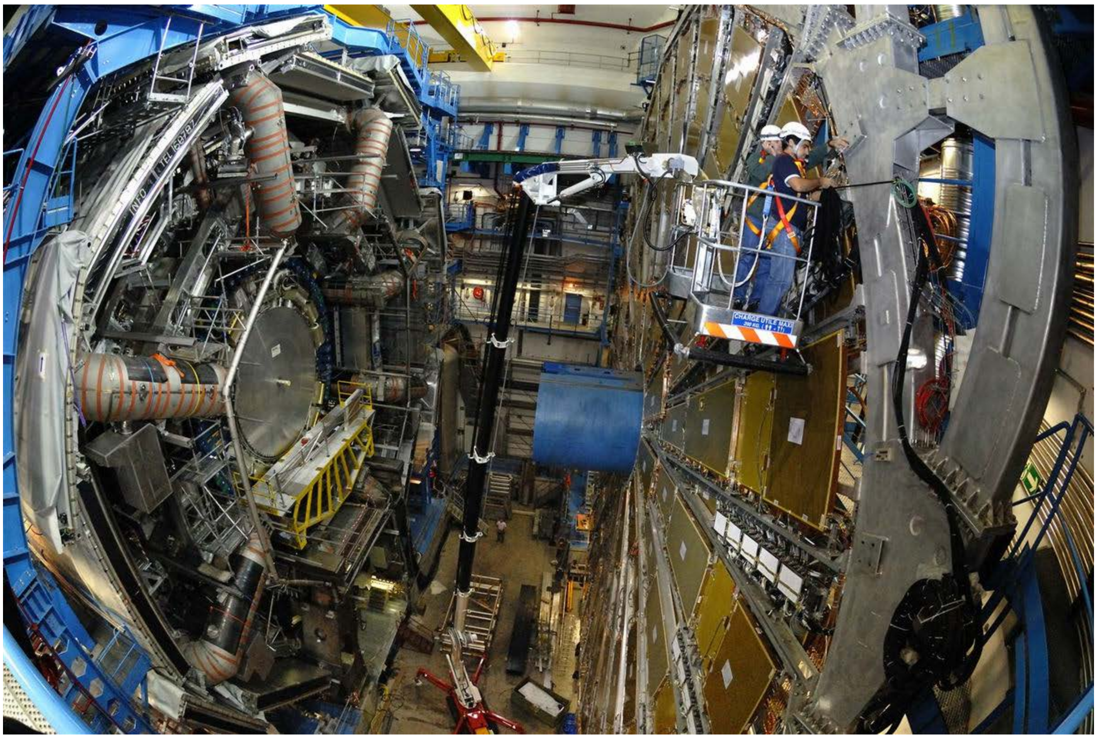

Figure 40 ATLAS Experiment – Maintenance Operations [85]

C.3.2 CMS Experiment

The CMS experiment is similar in research objective to the ATLAS machine. It is a state-of-art machine designed to explore fundamental particle physics. The CMS machine is smaller than ATLAS, with a length of 21 m and height of 15 m. However, at 14,000 tons it is twice as heavy as ATLAS. CMS is located at IP5 [11].

At the core of CMS is a large solenoid magnet, which is the largest in the world. It circulates 18,500 A under superconducting condition. Although more compact than ATLAS, the overall fire safety considerations are similar. CMS is shown in Figure 41.

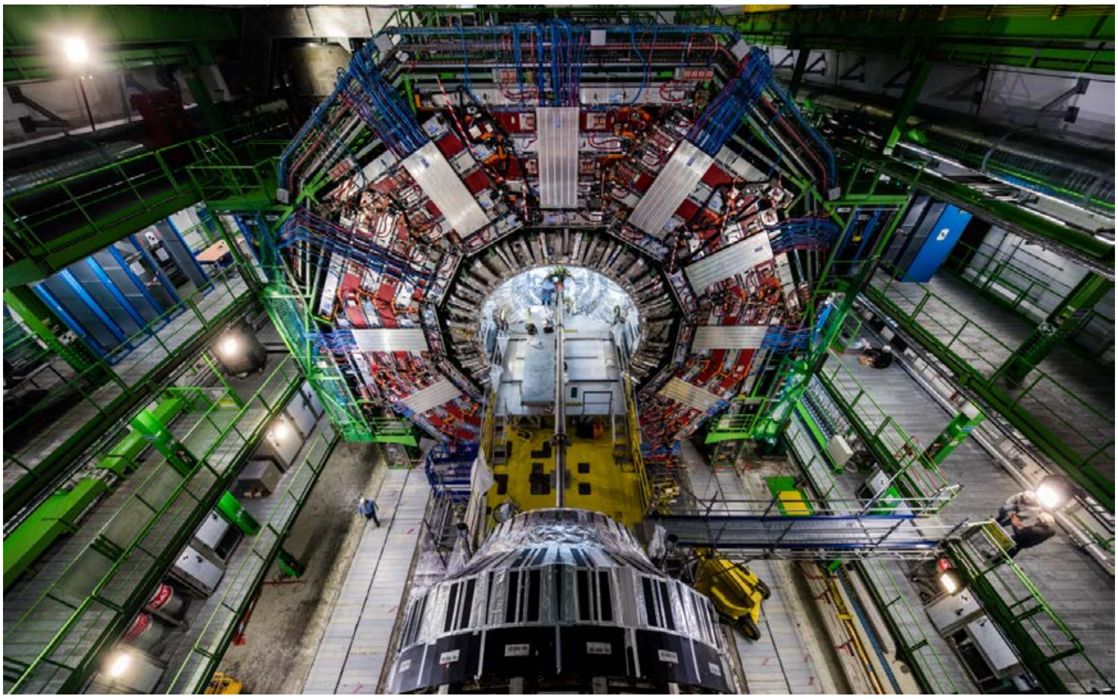

Figure 41 CMS Experiment – General View [86]

C.3.3 ALICE Experiment

ALICE is designed to study heavy ion collisions, with a specific focus on the physics of strongly interacting matter at heavy densities. These conditions give rise to a study of quark-gluon plasma. ALICE is about the same size as CMS and is located at IP2.

C.3.4 LHCb Experiment

The purpose of the LHCb experiment is to investigate the asymmetry between matter

and antimatter. This line of research is based on studying “beauty quark” (also called the b quark). LHCb is about the same size as ALICE and CMS and is located at IP8.

C.4 Operating Modes

The LHC machine has many modes of operation. From a fire safety and radiological perspective, the operating modes can be simplified to operating states:

Beam On	This operating state covers any mode and sub-mode in which the beam is ON or the system is in the process of starting up. The Beam On

	operating state represents the highest radiological concern because proton activation is taking place.
Short-term Cooldown	This operating state covers a time frame of approximately one month from time of shutdown (Beam Off). During this period, short-lived isotopes are given a chance to decay to harmless levels prior to accessing the LHC tunnel or experiment caverns.
Long-term Shutdown	This operating state begins at the end of the cooldown period and continues until the next restart of the machine. During shutdown periods, the LHC tunnel and experiment caverns are accessed for service and maintenance activities.

Appendix D
Ignition Source Frequency

As explained in Section 5.5.2, CERN-specific ignition source frequency data is not available and thus the values from NUREG-2169 [34] are used as representative. Table 3-1 of NUREG-2169 lists the defined bins for fixed ignition sources and Table 4-4 lists the probability values for these bins. Many of these bins are not applicable CERN and thus the entire table is not reproduced in this appendix.

D.1 Ignition Source Frequency Bins

The relevant bins and frequency values are shown in Table 15. The nuclear industry tracks all fire events in a centralized database maintained by EPRI. The data is periodically updated from previous information using a two-stage hierarchical Bayesian update with noninformative and minimally informed diffuse empirical priors [34].

Ky application considerations:

Plant Wide Frequency Values: The values represent plant wide probabilities and thus it is necessary to divide each bin probability by the number of bin items at the facility to obtain individual ignition source probability values to be applied in the analysis of each compartment. The same process is applied to CERN using assumed numbers for the bins.

Treatment of Transient Hazards: Transient fire hazards are not as easily parsed since they cannot be counted like fixed ignition sources. The nuclear industry implements a qualitative weighting factor for each compartment based on typical maintenance activities, normal occupancy, access limitations, and approved storage locations for transient combustibles. The implementation of this process is judged as overly complicated given the weighting factors are largely subjective. For the purposes of this thesis, the facility-wide transient values are assumed to be equality divided over the defined number of compartments. The number of compartments is assumed for the pilot case examples. Additionally, the nuclear plant binning for transients includes maintenance activities. It is suggested that a better approach for CERN is to maintain separate bins for maintenance activities and transients. Table 15 includes this split.

Self-Ignited Cable Fires: The nuclear plant ignition source binning tables include a generic category for self-ignited cable fires. Weighting factors are applied based on estimated cable mass within each compartment. The process has no accounting for the circuit type (i.e., power, control, instrument), voltage level, energy level, or protective device factors. This generic approach is a weakness in the nuclear plant methodology. Utilising the concepts discussed in Sections 5.2.2 and 5.3, a more technically refined approach is applied (See Section A.2).

Table 15 Ignition Source Frequencies [34]
(partial list from NUREG-2169)

Bin Description	Mean	5th Percent	95th Percent
Fixed Equipment			
Batteries (See note 1)	1.96E-5	1.97E-7	7.70E-4
Air compressors	4.69E-3	1.5-E-5	1.45E-2
Battery chargers	1.12E-3	2.83E-6	3.52E-3
Self-ignited cable fires	7.02E-4	1.29E-5	2.21E-3
Electric motors	5.43E-3	1.15E-4	1.57E-2
Electrical cabinets	3.00E-2	3.72E-3	8.00E-2
Power Cabinet HEAF (low voltage)	1.52E-4	1.28E-7	5.89E-4
Power Cabinet HEAF (medium voltage)	2.13E-3	5.36E-5	5.93E-3
Pumps	2.72E-2	8.85E-3	5.13E-2
Backup diesel generators	7.81E-3	4.87E-4	2.01E-2
Transformers	9.56E-3	1.55E-4	3.05E-2
Junction Box	3.61E-3	8.77E-6	1.13E-2
Ventilation Unit	1.64E-2	1.06E-3	4.68E-2
Transient / Hot Work			
Welding/Cutting	2.77E-4	4.13E-7	9.45E-4
Transient (see note 2)	4.28E-3	4.68E-4	1.04E-2
Maintenance Activity (see note 2)	4.28E-3	4.68E-4	1.04E-2

Notes:

1. The battery ignition source values are likely not representative of batteries at CERN. Nuclear plants use flooded lead acid batteries and CERN generally uses sealed type batteries, which have a higher failure rate due to lower thermal management capability.
2. The original NUREG-2169 [34] frequency for transients has been split equally into the separate bins for transients and maintenance activities.

D.2 Self-Ignited Cable Fire Frequencies

Consistent with the concepts discussed in Sections 5.2.2 and 5.3, self-ignited cable fires depend on numerous parameters and therefore are not equally likely for all circuits. For this reason, the generic approach implemented in NUREG-2169 is considered inconsistent with the overall objective of assigning weighted values to the fire risk category.

The plant-wide self-ignited cable fire frequency from NUREG-2169 (Refer to Table 16) is considered a good start point to decompose the parameters of interest, as defined in the cable fire fault tree. NUREG/CR-6928, Table 5-1 [87] provides failure rate data applicable to 400 V and 18 kV style power breakers (individual component). From this data, the frequency of overcurrent challenges can be back calculated. One can ask: why deconstruct the self-ignition frequency if it is to be reconstructed in the fault tree? The reason is that weighting factors for the different circuit categories can be applied on a compartment-by-compartment basis. Thus, a compartment having no 18 kV circuits (most underground areas) is not burdened with a fictitious fraction of the 18 kV overall self-ignition frequency.

Table 16 Self-Ignited Cable Fire Frequency [34], [87]

Bin Description	Mean	5th Percent	95th Percent
Self-ignited cable fires (plant wide)	7.02E-4	1.29E-5	2.21E-3
Power circuit breaker failure (individual)	2.55E-3	4.40E-5	8.68E-3

The mean frequency of 7.02E-4 is decomposed based on the following considerations:

- Insulation overheating conditions predominately occur on power circuits. The inherently low energy capability of instrument circuits and low voltage control circuits generally preclude self-ignition as a failure mode.
- Low voltage control power circuits can be supplied from energy sources having significant energy potential. DC control power circuits with battery backup are a notable case. However, the energy levels are much lower than 400 V and 18 kV high-energy distribution circuits; thus, the low voltage contribution to self-ignited cable fires is estimated at 10%.
- Based on a split fraction of the number of circuits and damage potential, the contribution from 400 V circuits is judged to be 40% and contribution from 18 kV is 50%.
- As shown by the time-current plots in Section 5.2.2, a properly designed circuit will protect a cable from self-ignition by either the primary or backup overcurrent device. Thus, both devices must fail to cause a self-ignited cable fire.
- Due to the high energies involved, only rapid primary protection is credited with preventing against HEAF events on cables.
- Moulded-case circuit breaker failure rates are higher than that of power circuit breakers and are estimated as twice as likely, giving an individual failure rate of t about 1E-2 on an individual component basis.
- The importance of proper maintenance and testing was discussed in Section 5.3.7. The status of CERN electrical device periodic maintenance programs is not known. Additional influence factors should be considered if recommended maintenance and testing are not conducted.

Based on the above considerations the basic event elements for self-ignited cable fire frequencies have been calculated and are shown in Table 17. It is assumed that CERN facilities have an average of 80 power circuit breakers (60 at 400 V and 20 at 18 kV) and 80 control power panel moulded case circuit breakers.

Table 17 Breakdown of Self-Ignited Cable Fire Basic Event Frequencies

Bin Description	Mean
Self-ignited cable fires (plant wide)	7.02E-4
Self-ignited cable fires – Control power	7.02E-5
Self-ignited cable fires – 400 V power	2.81E-4
Self-ignited cable fires – 18 kV power	3.51E-4
400 V Power circuit breaker failure (60)	1.53E-1
18 kV Power circuit breaker failure (20)	5.10E-2
Molded case circuit breaker (80)	4.08E-1
18 kV overcurrent challenge	1.35E-1
400 V overcurrent challenge	1.20E-2
Control power overcurrent challenge	4.22E-4

D.3 Terminal Equipment Fire Propagation

Ignition sources for termination fires are the same as that used for external cable fires. The difference is the mechanism by which a cable fire is initiated. For termination fires the mechanism is by propagating of an electrical equipment fire along the cable(s) connected to the equipment. The likelihood of propagation is difficult to quantify and has not been extensively studied. However, some basics concepts can be applied:

- A propagation factor of 0.7 is suggested for HEAF equipment (400 V and 18 kV power equipment)
- Cables connected to equipment via proper penetration seals can assume no propagation.
- Cables routed to equipment via metal conduit can assume no propagation.
- Cables connected to equipment via flexible non-metallic conduit should assume propagation
- Cables connected to equipment via non-sealed wireways or cable tray should assume propagation
- Based on a lack of quantitative data, it is suggested that likelihood of propagation be treated as a binary event (Yes or No), corresponding to a factor of one or zero (except for HEAF equipment where a 0.7 factor is recommended.

Appendix E
Cable Fire Test Data

This appendix contains select data from cable fire test. The data serves as the primary information upon which the methodology and process are based for estimating fractional release of radioactivity from cable fires. Included in this appendix are:

Table 1 of NUREG/CR-4679	Cable characterisation tests, including char fractional amount after burning	Figure 42
Table 6 of NUREG/CR-4679	Cable characterisation tests, including combustion product yield rates	Figure 43
Table 10 of NUREG/CR-4679	Carbon distribution in combustion products for polymers	Figure 44
Table 12 of NUREG/CR-4679	High temperature degradation products for PVC	Figure 45
Table 15 of NUREG/CR-4679	High temperature degradation products for PE	Figure 46
Table 3-2 and Figure 3-1 of NUREG/CR-7010, Vol 1	Specifications and cross-sectional pictures for cables included in characterisation fire tests	Figure 47
Figures 5-3 and 5-5 of NUREG/CR-7010, Vol 1	Cable fire test combustion product yields and residual char fraction after burning	Figure 48
Table 7-1 of NUREG/CR-7010, Vol 1	Cable fire test combustion product yields and residual char fraction after burning	Figure 49
Table 3-2 of NUREG/CR-7010, Vol 2	Specifications for cables included in characterisation fire tests	Figure 50
Table 4-1 of NUREG/CR-7010, Vol 2	Cable fire test combustion product yields and residual char fraction after burning	Figure 51
Table 4-2 of NUREG/CR-7010, Vol 2	Summary of average residual char fraction and HRR for thermoset and thermoplastic cable	Figure 52

Table 1: Physical properties of cables used in FMRC small-scale characterization tests [Reference 31]

Number	Insulation/Jacket Materials[a]	Conductor No.	Conductor Size (AWG)	Outer Cable Diameter in. (m)	Insulation/Jacket Materials (% of total cable weight)	Insulation Jacket Materials remaining as char (% of initial wt. of insulation/jacket materials)	IEEE-383 Rating
					Polyethylene (PE)/No Jacket		
1	Low density PE (ℓdPE), no jacket	1	14	0.128(0.003)	23.9	0.10	-
					Polyethylene/Polyvinyl chloride (PE/PVC)		
3	PE/PVC	1	-	0.945(0.024)	15.6	21.9	
4	PE/PVC	1	12	0.164(0.004)	26.5	0.6	Fail
5	PE/PVC	3	-	0.438(0.011)	49.9	20.8	Fail
6	PE/PVC	5	-	0.748(0.019)	51.0	25.6	
7	PE/PVC	12	-	1.000(0.025)	57.8	24.4	
					Polyethylene, Polypropylene/Chlorosulfonated Polyethylene (PE, PP/Cℓ·S·PE)		
8	PE,PP/Cℓ·S·PE (silicone coating)	1	-	0.445(0.011)	23.2	41.6	Pass
9	PE,PP/FRCℓ·S·PE[b]	1	6	0.368(0.009)	40.2	46.4	Pass
10	PE,PP/Cℓ·S·PE	1	12	0.192(0.005)	42.9	45.6	Pass
11	PE,PP/Cℓ·S·PE	5	14	0.668(0.017)	77.1	48.3	Pass
12	PE,PP/Cℓ·S·PE	2	16	0.426(0.011)	77.4	40.5	Pass
					Cross-Linked Polyethylene/Cross-Linked Poyethylene (XPE/XPE)		
13	XPE/FRXPE[b]	3	12	0.458(0.012)	61.4	44.9	Pass
14	XPE/XPE	2	14	0.377(0.010)	73.5	-	Pass
					Cross-Linked Polyethylene/Chlorosulfonated Polyethylene (XPE/Cℓ·S·PE)		
15	FRXPE/Cℓ·S·PE[b]	4	16	0.368(0.009)	56.2	29.5	Pass
16	XPE/Cℓ·S·PE	4	16	0.442(0.011)	62.1	31.0	Pass
					Cross Linked Polyethylene/Neoprene (XPE/Neo)		
17	XPE/Neo	3	16	0.369(0.009)	73.2	43.9	Pass
2	XPE/Neo	7	12	0.630(0.016)	53.6	-	
					Polyethylene, Nylon/Polyvinyl chloride, Nylon (PE, Ny/PVC, Ny)		
18	PE, Ny/PVC, Ny	7	12	0.526(0.013)	39.9	-	
19	PE, Ny/PVC, Ny	7	12	0.520(0.013)	43.5	-	
					Teflon		
20	Teflon	34	-	0.516(0.013)	48.9	3.9	Pass
					Silicone		
21	Silicone, glass braid	1	-	0.363(0.009)	34.0	-	
22	Silicone, glass braid/asbestos	9	14	0.875(0.022)	70.5	59.4	Pass

[a] Generic class as given by the suppliers. Cable samples belonging to similar generic class may not be similar because of different types and amounts of unknown additives in the cable samples.

[b] FR - with fire retardant chemical

Figure 42 Table 1 of NUREG/CR-4679 [26]

Table 6: Generation rates of primary fire products during FMRC small-scale cable fire tests [Reference 31]

YIELD OF CO_2, CO, AND GASEOUS HYDROCARBONS FROM THE COMBUSTION OF CABLE SAMPLES IN NORMAL AIR AT 60 kW/m^2 [a]

Cable Sample	Yield (g/g)[b] Y_{CO_2}	Y_{CO}	Y_{HC} [c]
ℓdPE (granular)[d]	2.28	0.06	0.02
ℓdPE (#1)	2.25	0.05	0.01
PE/PVC (#3)	2.08	0.10	0.02
PE, PP/Cℓ·S·PE (#8)	1.95	0.07	0.01
XPE/FRXPE (#13)	1.78	0.11	0.03
PE/PVC (#4)	1.75	0.05	0.01
PE, PP/Cℓ·S·PE (#11)	1.74	0.15	0.02
Nylon (granular)[d]	1.67	0.04	0.01
Silicone, glass braid (#21)	1.65	0.01	0.001
Silicone, glass braid/asbestos (#22)	1.47	0.03	0.0003
PE/PVC (#6)	1.39	0.17	0.04
PE/25%Cℓ (granular)[d]	1.31	0.06	0.03
PE/PVC (#7)	1.29	0.15	0.04
PE, PP/Cℓ·S·PE (#10)	1.21	0.07	0.01
PE, PP/Cℓ·S·PE (#12)	0.99	0.18	0.09
FRXPE/Cℓ·S·PE (#15)	0.95	0.12	0.02
XPE/Cℓ·S·PE (#16)	0.89	0.12	0.02
XPE/XPE (#14)	0.83	0.10	0.02
XPE/Neo (#2)	0.68	0.12	0.03
PE/36%Cℓ (granular)[d]	0.65	0.05	0.02
XPE/Neo (#17)	0.63	0.08	0.01
PE-Ny/PVC-Ny (#18)	0.63	0.08	0.02
PE, Ny/PVC, Ny (#19)	0.49	0.08	0.03
PVC (granular)[c]	0.46	0.06	0.03
PE/48%Cℓ (granular)[d]	0.45	0.05	0.02
Teflon (#20)	0.18	0.09	0.01

[a] Average peak values
[b] Yield = mass generation rate of the product/mass loss rate
[c] HC = gaseous hydrocarbons (as CH_4)
[d] Research samples, data from Ref (9)

Figure 43 Table 6 of NUREG/CR-4679 [26]

Table 10: Mean distribution of carbon in the combustion products of liquids and polymers [Reference 34]

Mean Distribution of Carbon in the Combustion Products of Liquids and Polymers[a]

Liquid-Polymer	Chemical formula from elemental composition	Gases, $f_i \times 100$			Pyrolyzate, $f_i \times 100$		
		CO_2	CO	HC	Pyr[b]	Pyr-*f*[c]	$(Pyr)^d_{liquid-1}$
Methanol	CH_4O	99.3	0.1	0	0.6	0	0.6
Polymethylmethacrylate	$CH_{1.6}O_{0.4}$	78.6	0.8	0.1	20.5	4.0	16.5
Polyoxymethylene	CH_2O	76.5	0.2	0.1	23.2	–	–
Acetone	$CH_2O_{0.33}$	76.2	0.1	0	23.7	–	–
Cellulose	$CH_{0.83}O_{0.33}$	71.6	0.5	0.1	27.8	–	–
Nylon 6/6	$CH_{1.83}O_{0.17}N_{0.17}$	71.5	2.6	2.1	23.8	21.8	2.0
Polyethylenes	CH_2	68.5	2.0	1.2	28.3	13.0	15.3
Heptane	$CH_{2.29}$	66.8	3.8	5.7	23.7	–	–
Polyurethane foam-$CaCO_3$ (I-A)	$CH_{1.91}O_{0.26}N_{0.06}$	65.6	0.6	0.1	33.7	30.0	3.7
Polypropylene	CH_2	64.4	1.8	2.3	31.5	–	–
Polyurethane foam (GM-21)	$CH_{1.80}O_{0.29}N_{0.05}$	60.8	0.7	0.4	38.1	31.6	6.5
Polyurethane foam (GM-25)	$CH_{1.75}O_{0.32}N_{0.07}$	59.4	2.3	0.7	37.6	31.0	6.6
Polyurethane foam (GM-23-FR)	$CH_{1.76}O_{0.35}N_{0.06}$	59.0	2.1	0.6	38.3	32.9	5.4
Polyethylene-25%Cl	$CH_{1.87}Cl_{0.13}$	57.1	3.8	2.4	36.7	39.3	0
Styrene	CH	54.0	3.0	2.2	40.8	39.7	1.1
Polystyrene	CH	51.9	2.9	2.8	42.4	19.0	23.4
Polyurethane foam (GM-27/FR)	$CH_{1.71}O_{0.30}N_{0.08}$	51.7	4.0	1.6	42.7	36.6	6.1
Polystyrene foam (GM-47)	$CH_{1.01}$	48.2	2.7	1.0	48.1	26.8	21.3
Benzene	CH	47.1	5.4	3.3	44.2	–	–
Styrene-Butadiene	$CH_{1.01}$	47.1	2.3	1.1	49.5	31.4	18.1
Aniline	$CH_{1.17}N_{0.17}$	46.3	2.7	1.2	49.8	–	–
Epoxy-FR-fiberglass	$CH_{1.32}N_{0.12}$	45.4	2.3	0.6	51.7	13.6	38.1
Polyurethane foam (GM-31-FR)	$CH_{1.17}O_{0.22}N_{0.10}$	40.7	5.1	1.9	52.3	51.2	1.1
Polyurethane foam (GM-29)	$CH_{1.15}O_{0.23}N_{0.10}$	40.1	5.4	1.5	53.0	32.6	20.4
Polyvinyl chloride	$CH_{1.5}Cl_{0.5}$	32.7	6.3	5.5	55.5	55.5	0
Polyethylene-36%Cl	$CH_{1.78}Cl_{0.22}$	31.6	3.9	2.7	61.8	63.6	0
Polyethylene-48%Cl	$CH_{1.65}Cl_{0.36}$	26.8	4.6	2.9	65.7	–	–

[a] Fires not fully ventilated.
[b] Total pyrolyzate calculated from Eq. (25).
[c] Pyr-*f* pyrolyzate fraction collected on the filter paper consisting of low-vapor pressure liquids and solid compounds.
[d] $(Pyr)_{liquid-1}$: high-vapor-pressure liquids in the pyrolyzate which cannot be collected on the filter paper calculated from Eqs. (25) and (26).

Figure 44 Table 10 of NUREG/CR-4679 [26]

Table 12: High temperature degradation products for PVC formulations [Reference 43]

Pyrolysis products of PVC materials generated at high temperature, separated on the Carbowax-20M and SE-54 columns.

Insulation	T_R (min)	Carbowax-20M	T_R (min)	SE-54
Virgin PVC	3.7	1-methyl-2-ethylbenzene	3.2	6,6-dimethylfulvene
	4.8	m-methylstyrene	3.7	phenylacetaldehyde
	6.5	styrene	4.0	methyltoluene
	7.4	3-methylindene	4.5	2,2,4-trimethylheptane
	8.8	naphthalene	4.8	α-methylstyrene
	10.0	1-methylnaphthalene	5.4	2,5-dimethylheptane
	11.1	biphenyl	5.5	2-methylindane
	11.5	1,3-dimethylnaphthalene	6.4	methylallylbenzene
	11.9	2-ethylnaphthalene	6.6	1,2-dihydronaphthalene
	14.0	allylnaphthalene	7.1	azulene
	14.5	fluorene	8.2	3-methyl-1,2-dihydronaphthalene
	17.6	phenanthrene	8.6	2-methylnaphthalene
	19.1	4-methyl phenanthrene	8.8	1-methylnaphthalene
	22.8	1,2,3,4-tetrahydrofluoranthene	9.9	acenaphthene
	24.1	dioctylphthalate	14.8	phenanthrene
	24.7	fluoranthene	16.2	2-methyl anthracene
	26.4	5,6-benzo-7-phenylbicyclo (2,2,1) hept-2-ene		
PVC-3	3.6	xylene	4.1	ethyltoluene
	4.4	p-ethyltoluene	4.9	propenylbenzene
	5.1	isopropyl benzyl heptane	6.4	allyltoluene
	9.6	naphthalene	7.1	naphthalene
	10.8	1-methylnaphthalene	8.9	methylnaphthalene
	11.9	1-ethylnaphthalene	9.6	phthalic acid
	12.1	phenol	16.5	butyl phthalate
	12.2	biphenyl		
	15.3	phthalic anhydride		
	15.5	2-hydroxy-4-methoxy-6-methylbenzaldehyde		
	15.9	ethylene glycol dibenzoate		
	18.7	dibutyl phthalate		
	20.4	4-methylphenanthrene		
PVC-78	7.9	1-phenyl-1,2-propandione	4.5	isooctyl alcohol
	8.8	naphthalene	7.1	azulene
	10.4	1-methylnaphthalene	8.7	benzoic acid
	11.4	biphenyl	9.8	1-methylnaphthalene
	11.9	1,2-dimethylnaphthalene	10.0	phthalic anhydride
	14.4	phthalic acid	17.4	di-(2-ethylhexyl) phthalate
PVC-104	3.5	o-xylene	3.1	6,6-dimethyl fulvene
	3.9	isopropylbenzene	3.7	phenylacetaldehyde
	4.1	styrene	3.9	benzyl ester
	9.5	naphthalene	4.1	isopropylbenzene
	10.9	1-methylnaphthalene	4.9	methylstyrene
	12.1	phenol	5.6	o-allyltoluene
	18.6	anthracene or phenanthrene	11.4	2,6-di-tert-butyl-4-methyl phenol
			16.7	stearic acid

Figure 45 Table 12 of NUREG/CR-4679 [26]

Table 15: High temperature degradation products for Polyethylene formulations [Reference 43]

Pyrolysis products of polyethylene generated at high temperature and separated on the Carbowax-20M column.

Insulation	T_R (min)	Carbowax-20M
Virgin polyethylene	5.3	1,3-dimethyl-4-cyclopentane
	7.2	1-hexadecene
	?	naphthalene
	?	1-methyl-2-cyclohexylcyclohexane
	10.4	x-methylnaphthalene
	10.6	o-nenthane
	11.4	phenylbenzene
	11.6	methyldicyclohexylmethane
	12.4	acenaphthene
	13.2	biphenylene
	13.6	1,1-dicyclohexylpentane
	22.9	dihexyldiacetylene
	25.0	dioctylphthalate
Polyethylene-77	3.7	styrene
	6.1	1-methylphenylacetylene
	8.9	naphthalene
	10.2	hexahydrofarneool and methylnaphthalene
	10.5	3-methylpentine
Polyethylene-95	3.1	undecanol-1
	4.1	oct-1-ene
	5.3	acetic acid
	6.4	4,6,8-trimethylnonene-1
	7.7	2,2-dimethyl-1-acetylcyclopentane
	7.8	1-hexadecene

Figure 46 Table 15 of NUREG/CR-4679 [26]

Table 3-2. Properties of the cables used in CHRISTIFIRE

Cable No.	Insulation Material	Jacket Material	Classification	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per unit Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Material Mass Fraction
2	XLPE	Neoprene	TS	4	19	2	1.5	0.568	0.46	0.33	0.17	0.04
3	XLPE	Neoprene	TS	19	24	2.5	1	1.104	0.53	0.26	0.21	0.00
7	XLPE	Neoprene	TS	12	21	2.5	1	0.752	0.48	0.32	0.19	0.00
11	XLPE	CSPE	TS	37	32	3.1	1.1	1.985	0.55	0.23	0.22	0.00
16	XLPE	Neoprene	TS	4	19	2.2	1.8	0.671	0.52	0.27	0.18	0.03
17			TS	5	14	1.8	1	0.345	0.44	0.35	0.18	0.03
22			TS	9	18.5	2.1	1	0.606	0.45	0.34	0.19	0.02
23	XLPE	CSPE	TS	6	14	2.7	0.9	0.253	0.31	0.48	0.16	0.05
25	XLPE	Neoprene	TS	3	10	1.6	1	0.146	0.32	0.47	0.19	0.02
34			TS	12	19	2.2	0.7	0.499	0.38	0.40	0.17	0.05
43	XLPE	Neoprene	TS	12	15	2.3	0.8	0.357	0.38	0.38	0.21	0.03
45			TS	7	17	2	0.9	0.456	0.47	0.36	0.15	0.01
46	XLPE	Neoprene	TS	7	15	1.9	1.2	0.437	0.48	0.32	0.20	0.00
47			TS	2	9	1.6	0.9	0.114	0.30	0.54	0.12	0.03
212	EPR	CSPE	TS	3	13	2	1.5	0.247	0.23	0.45	0.22	0.10
219	EPR	CSPE	TS	3	14	2.4	1.5	0.296	0.39	0.39	0.22	0.00
220	EPR	CSPE	TS	7	18	2.6	1.2	0.560	0.38	0.32	0.30	0.00
261	XLPE	XLPE	TS	10	18	2.5	0.9	0.397	0.27	0.42	0.29	0.02
269	XLPE	CSPE	TS	1	12	1.0	0.6/3.6	0.240	0.47	0.30	0.23	0.00
270	XLPE	CSPE	TS	1	12	0.6	0.8/3.5	0.235	0.49	0.27	0.24	0.00
271	XLPE	XLPE	TS	2	10	1.6	0.9	0.123	0.30	0.48	0.15	0.07
272			TS	8	14	1.5	0.7	0.252	0.40	0.31	0.26	0.04
273	XLPE	XLPE	TS	18	20	1.9	0.7	0.532	0.57	0.29	0.12	0.02
312	EPR	Neoprene	TS	3	12	1.6	1	0.239	0.38	0.45	0.16	0.00
327			TS	5	17.5	2.5	1.5	0.454	0.33	0.46	0.19	0.02
337			TS	1	24	6	N/A	1.381	0.72	0.28	0.00	0.00
367	EPR		TS	1	16	2.3	3.5	0.441	0.27	0.45	0.28	0.00
503			TS	7	15.5	2.2	1	0.457	0.48	0.33	0.19	0.00
505			TS	2	10	1.2	1	0.120	0.31	0.44	0.14	0.11
612			TS	3	12	1.7	1	0.237	0.39	0.41	0.16	0.04
700	XLPE		TS	7	12	1.0	0.7	0.322	0.67	0.17	0.16	0.00
701	PE	PVC	TP	7	14	1.5	0.8	0.366	0.58	0.24	0.18	0.00

11 13 15 16 20 21 23 43 46 219 220 269 270 271 367 700 701

Figure 47 Table 3-2 and Figure 3-1 of NUREG/CR-7010, Vol 1 [24]

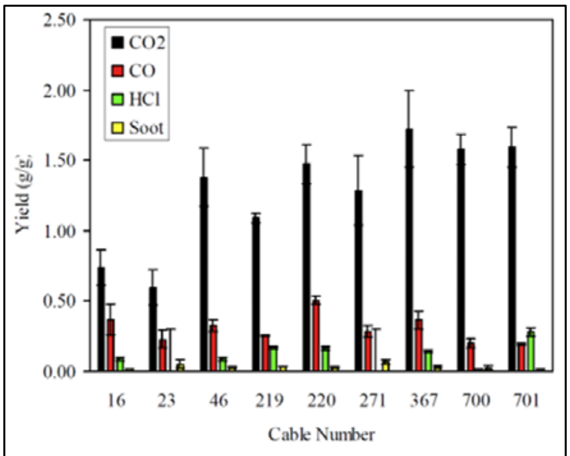

Figure 5-3. Yields of various product gases.

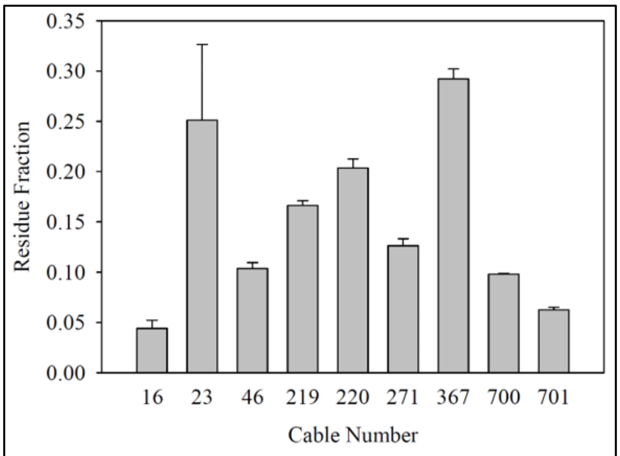

Figure 5-5. Residue/char yield of various cables

Figure 48 Figures 5-3 and 5-5 of NUREG/CR-7010, Vol 1 [24]

NB: The report notes that the residual char fraction from the Tube Furnace tests (Figure 5-5) are lower than expected and less than the values from the micro-calorimeter tests. The difference is attributed to the Tube Furnace tests being well-ventilated with a continuous supply of fresh air.

Table 7-1. Summary of the Radiant Panel Experiments

Test No.	Cable No.	Nominal Heat Flux (kW/m^2)	No. of Cables	Percent of NEC Fill Limit	Packing	Max HRR (kW)	Avg HRRPUA (kW/m^2)	Heat of Comb. (MJ/kg)	Mass Consumed (kg)	Residue (% of total plastic)
RP-0	700	27	40	33	Loose	79	138	19.4	2.4	44
RP-1	700	24	80	67	Loose	60	55	18.9	4.5	48
RP-2	700	32	40	33	Loose	104	153	--	4.0	5
RP-3	701	32	44	50	Loose	163	264	16.1	8.1	0
RP-4	701	16	22	25	Loose	172	252	16.6	4.5	0
RP-5	701	17	22	25	Loose	160	184	15.6	3.3	18
RP-6	16	32	24	50	Loose	55	82	14.4	3.9	49
RP-7	16	16	24	50	Loose	55	64	19.8	4.2	46
RP-8	16	5	24	50	Loose	45	30	9.4	2.2	72
RP-9	16	22	24	50	Loose	51	88	15.6	4.3	44
RP-10	16	32	24	50	Loose	76	119	14.8	5.8	25
RP-11	367	32	25	37	Dense	181	234	18.1	6.9	15
RP-12	367	17	25	37	Dense	124	199	17.6	6.2	23
RP-13	367	15	25	37	Dense	143	205	17.6	6.1	25
RP-14	43	32	30	39	Dense	93	116	--	4.3	35
RP-15	43	17	30	39	Dense	63	100	--	4.7	30
RP-16	46	26	28	37	Dense	55	85	--	4.2	34
RP-17	46	15	28	37	Dense	47	60	15.9	2.9	54
RP-18	271	26	44	26	Dense	224	210	16.5	3.5	8
RP-19	271	13	44	26	Dense	149	160	16.1	3.5	7
RP-20	271	14	44	26	Dense	143	167	14.6	3.7	2
RP-21	11	32	14	84	Dense	135	142	16.3	9.0	28
RP-22	11	32	7	42	Loose	140	184	17.1	5.9	6
RP-23	219	32	32	36	Dense	118	135	15.7	4.6	20
RP-24	219	13	32	36	Dense	192	214	19.3	4.1	30
RP-25	220	27	24	45	Dense	221	180	17.1	5.0	40
RP-26	220	17	24	45	Dense	213	236	17.6	4.6	45
RP-27	23	28	34	39	Dense	78	104	12.3	3.9	35
RP-28	23	14	34	39	Dense	95	107	16.0	3.3	45
RP-29	23	15	66	75	Dense	111	66	12.2	10.6	8
RP-30	701	14	44	50	Dense	244	266	18.3	7.1	12
RP-31	701	28	44	50	Dense	258	231	15.2	7.4	9
RP-32	270	24	80	67	Loose	167	270	13.9	11.4	1

Figure 49 Table 7-1 of NUREG/CR-7010, Vol 1 [24]

Table 3-2. Cable properties.

Cable No.	Insulation Material	Jacket Material	Class.	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Mass Fraction
800	PVC	PVC	TP	7	12.4	1.26	0.69	0.31	0.66	0.19	0.11	0.01
801	PVC/Nylon	PVC	TP	7	12.5	1.28	0.62	0.31	0.66	0.19	0.11	0.01
802	XLPE	CSPE	TS	7	15.0	2.32	1.16	0.42	0.50	0.30	0.20	0.01
803	XLPE	CSPE	TS	7	15.0	2.37	1.02	0.44	0.48	0.32	0.19	0.01
804	XLPE	PVC	Mix	7	15.1	1.63	0.96	0.41	0.52	0.23	0.22	0.01
805	Tefzel®		TP	7	10.2	0.76	0.45	0.29	0.74	0.08	0.15	0.02
806	XLPE	XLPO	TS	7	12.2	1.17	0.84	0.32	0.66	0.18	0.17	0.00
807	PE	PVC	TP	7	14.0	1.54	0.27	0.37	0.59	0.24	0.15	0.01
808	VITA-LINK®		TS	7	19.6	2.40	1.74	0.48	0.26	0.33	0.43	0.01
809	SR	Aramid Braid	TS	7	14.5	1.21	1.10	0.35	0.62	0.08	0.31	0.01
810	PVC/Nylon	PVC	TP	3	15.2	1.73	1.06	0.43	0.63	0.23	0.12	0.01
811	XLPE	CSPE	TS	3	16.3	1.86	1.72	0.43	0.55	0.29	0.16	0.03
812	XLPE	CSPE	TS	3	16.3	2.52	1.70	0.54	0.53	0.29	0.14	0.03
813	XLPE	CSPE	TS	12	12.7	1.46	1.18	0.25	0.37	0.33	0.29	0.01
814	PVC	PVC	TP	12	11.3	1.15	0.54	0.19	0.56	0.03	0.40	0.00
815	PVC/Nylon	PVC	TP	12	11.3	1.20	0.49	0.19	0.59	0.02	0.29	0.06
816	XLPE	CSPE	TS	4	16.7	2.93	1.10	0.42	0.26	0.45	0.22	0.07
817	XLPE	CSPE	TS	2	7.8	1.64	0.92	0.11	0.24	0.58	0.15	0.00
818	PE	PVC	TP	1	6.3	1.35	1.41	0.06	0.38	0.40	0.07	0.15
819	SR	Glass Braid	TS	3	16.3	1.42	20.1	0.52	0.47	0.08	0.24	0.19
822	SR	Glass Braid	TS	1	3.7	0.26	1.04	0.03	0.48	0.18	0.31	0.01
823	XLPE		TS	1	3.8	1.15	0	0.04	0.70	0.30	0.00	0.00
824	EPR	CSPE	TS	1	5.1	1.42	1.13	0.08	0.34	0.46	0.20	0.00

Figure 50 Table 3-2 of NUREG/CR-7010, Vol 2 [25]

Table 4-1. Summary of cone calorimeter measurements.

Cable No.	Insulation Material	Jacket Material	Diam. (mm)	Class	Time to Ignition (s) Imposed Heat Flux 50	Time to Ignition (s) Imposed Heat Flux 75	Average Heat Release Rate (kW/m^2) Imposed Heat Flux 50	Average Heat Release Rate (kW/m^2) Imposed Heat Flux 75	Heat of Combustion (MJ/kg)	Residue Fraction
800	PVC		12.4	TP	33	19	154	200	12.3	0.24
801	PVC/Nylon	PVC	12.5	TP	32	15	138	179	13.8	0.26
802	XLPE	CSPE	15.0	TS	42	22	129	155	17.8	0.42
803	XLPE	CSPE	15.0	TS	60	29	105	138	17.8	0.42
804	XLPE	PVC	15.1	Mix	36	20	150	203	14.4	0.33
805	Tefzel®		10.2	TP	241	81	105	147	7.1	0.17
806	XLPE	XLPO	12.2	TS	121	40	143	202	20.4	0.32
807	PE	PVC	15.0	TP	35	20	200	275	17.5	0.18
808	VITA-LINK		19.6	TS	87	46	54	67	24.9	0.61*
809	SR	Aramid Braid	14.5	TS	22	11	114	144	22.0	0.65*
810	PVC/Nylon	PVC	15.2	TP	35	15	130	148	13.4	0.25
811	XLPE	CSPE	16.3	TS	58	21	201	266	22.5	0.22
812	XLPE	CSPE	16.3	TS	51	25	110	139	20.0	0.43
813	XLPE	CSPE	12.7	TS	40	18	152	182	17.5	0.39
814	PVC		11.3	TP	34	15	188	230	12.5	0.05
815	PVC/Nylon	PVC	11.3	TP	32	12	164	201	13.9	0.05
816	XLPE	CSPE	16.7	TS	61	26	93	134	17.7	0.52
817	XLPE	CSPE	7.8	TS	77	31	111	144	17.1	0.49
818	PE	PVC	16.3	TP	64	22	352	525	21.2	0.18
819	SR	Glass Braid	15.0	TS	38	16	75	95	24.1	0.77*
822	SR	Glass Braid	3.7	TS	75	41	69	77	24.0	0.69*
823	XLPE		3.8	TS	94	42	196	259	15.9	0.13
824	EPR	CSPE	5.1	TS	39	17	92	135	17.9	0.43

* Cables 808, 809, 819, and 822 formed a hard crust that partially sealed the opening of the sample holder.

Figure 51 Table 4-1 of NUREG/CR-7010, Vol 2 [25]

Table 4-2. Average heat release rates and residue fractions for TS and TP cables.

Class	Average Residue Fraction	Average Heat Release Rate (kW/m^2) 50	Average Heat Release Rate (kW/m^2) 75
TP	0.17	179	238
TS	0.38	117	153

Figure 52 Table 4-2 of NUREG/CR-7010, Vol 2 [25]

Appendix F
Pilot Cases – Cable Fire Sequence Frequencies

This appendix provides three working examples for applying the cable fire sub-model fault tree to calculate the probability of a cable fire for given compartment, including the proportional contribution from each of the main cable fire hazard categories.

The pilot cases are:

Case 1: LHC tunnel dipole magnet section (Curved section of beam) with Beam On operating mode.

Case 2: Same as Case 1 but with Long-term Shutdown operating mode.

Case 3: ATLAS experiment inner detector zone (instrument cables only). The pilot case is done for Long-term Shutdown operating mode.

F.1 Case 1 – LHC Tunnel Dipole Magnet Section (Beam On)

Case 1 is covered in full in Section 5.5.3 as part of explaining application of the methodology, and thus will not be repeated here.

F.2 Case 2 – LHC Tunnel Dipole Magnet Section (Long-Term Shutdown)

Case 2 is the same compartment as Case 1 except the mode is long-term shutdown. During shutdown conditions, the equipment status is considerably different. Most power equipment is deenergised and only a portion of the control and instrument circuits are in service. The Excel calculation spreadsheets for this case are shown below. Some comparative observations:

- Although the fixed ignition source contributions are lower, the overall fire risk is now primarily driven by the increase in transient ignition sources.
- The HEAF concern is zero since no 400 V equipment is energised during shutdown
- The self-ignited cable fire contribution is also significantly reduced since only low-energy control power circuits are energised.

CABLE FIRE IGNITION SOURCE & TARGET INVENTORY	
Scenario Description	
Facility	LHC tunnel
Compartment	LHC tunnel, Sector 4 dipole magnet
Operating Mode	Long-tern Shutdown
Walkdown Source Reference	EDMS 2305884, 22-6-2018
Frequency Basis Reference	EDMS 23272233, 05-10-2019

Ignition Source Inventory		
Item	Bin ID	Energized
B-042	Battery	Y
B-066	Battery	Y
EC-0292	Electrical Cabinet	Y
EC-0658	Electrical Cabinet	Y
EC-0623	Electrical Cabinet	N
EC-0244	Electrical Cabinet	N
JB-0376	Junction Box	N
JB-0378	Junction Box	N
CP-056	Electrical Cabinet	Y
PP-065	Power Panel (LV)	N
ME-22	Electric Motor	N
ME24	Electric Motor	N
	Welding/Cutting	Y
	Transients	Y
	Maintance Activity	Y

Ignition Source Frequency			
Bin ID	Bin Count	$Freq_{base}$	$Freq_{ind}$
Battery	25	1.96E-05	7.84E-07
Elec Cab	280	3.00E-02	1.07E-04
Junct Box	190	3.61E-03	1.90E-05
Power Pnl (LV)	90	1.52E-04	1.69E-06
Elec Mtr	95	5.43E-03	5.72E-05
Weld/Cut	48	2.77E-04	5.77E-06
Transients	48	4.28E-03	8.91E-05
Maintenance	48	4.28E-03	8.91E-05

Targets			
Raceway	Type	Function	Energized
P134	Tray	Power	N
P276	Tray	Power	N
C038	Tray	Control	Y
S005	Tray	Signal	N
P228	Conduit	Power	N
S066	Conduit	Signal	Y

ZONE OF INFLUENCE MATRIX

IS/Target	P134	P276	C038	S005	P228	S066	Consolidated
B-042	0	0	0	0	0	0	0
B-066	0	0	0	0	0	0	0
EC-0292	1	1	1	1	0	0	1
EC-0658	1	1	1	1	0	0	1
EC-0623	1	1	0	0	0	0	1
EC-0244	1	1	0	0	0	0	1
JB-0376	0	0	0	1	0	0	1
JB-0378	0	0	0	1	0	0	1
CP-056	0	1	1	0	0	0	1
PP-065	1	1	0	0	0	0	1
ME-22	0	0	0	0	0	0	0
ME24	0	0	0	0	0	0	0
Weld/Cut	1	1	1	1	0	0	1
Transiet	1	1	1	1	0	0	1
Maintenance	1	1	1	1	0	0	1

EXTERNAL CABLE FIRE					
Bin ID	Count	$Freq_{ind}$	$Freq_{comp}$	ZOI	Binn Totals
Battery	2	7.84E-07	1.57E-06	0	0.00E+00
Electrical Cabinet	3	1.07E-04	3.21E-04	1	3.21E-04
Junction Box	0	1.90E-05	0.00E+00	1	0.00E+00
Power Panel (LV)	0	1.69E-06	0.00E+00	1	0.00E+00
Electric Motor	0	5.72E-05	0.00E+00	0	0.00E+00
Welding/Cutting	1	5.77E-06	5.77E-06	1	5.77E-06
Transients	1	8.91E-05	8.91E-05	1	8.91E-05
Maintenance Activity	1	8.91E-05	8.91E-05	1	8.91E-05
				TOTAL	**5.05E-04**

SELF-IGNITED CABLE FIRES							
Circuit Class	Fraction	Energized	$Freq_{site}$	$Freq_{comp}$	$\lambda_{breaker}$	$\lambda_{protection}$	SI Totals
Control Power	7%	Y	4.22E-04	2.95E-05	4.08E-01	1.66E-01	4.91E-06
400 V Power	5%	N	1.20E-02	6.00E-04	1.53E-01	2.34E-02	0.00E+00
18 kV Power	0%	N/A	1.35E-01	0.00E+00	5.10E-02	2.60E-03	0.00E+00
						TOTAL	**4.91E-06**

TERMINATION FIRE - HEAF					
HEAF EQ ID	Energized	Volt Class	$Freq_{ind}$	Prop Factor	$Freq_{comp}$
PP-065	N	400 V	1.69E-06	7.00E-01	0.00E+00
				TOTAL	**0.00E+00**

TERMINATION FIRE - PROPAGATION			
IS/Target	$Freq_{ind}$	Prop Factor	$Freq_{comp}$
B-042	7.84E-07	0	0.00E+00
B-066	7.84E-07	0	0.00E+00
EC-0292	1.07E-04	0	0.00E+00
EC-0658	1.07E-04	0	0.00E+00
EC-0623	1.07E-04	0	0.00E+00
EC-0244	1.07E-04	1	0.00E+00
JB-0376	1.90E-05	0	0.00E+00
JB-0378	1.90E-05	0	0.00E+00
CP-056	1.07E-04	1	1.07E-04
ME-22	5.72E-05	0	0.00E+00
ME24	5.72E-05	1	0.00E+00
		TOTAL	**1.07E-04**

F.3 Case 3 – Inner Detection Zone (Long-Term Shutdown)

Case 3 is markedly different than the previous examples. The ATLAS Experiment detector area does not contain power equipment or power cables; it only has cable bundles of instrument signal cables. Also, in a long-term shutdown condition all equipment in the detector area is deenergised. Thus, the only contribution to fire risk is from transient sources (i.e., work in the detector area). The Excel calculation spreadsheets for this case are shown below.

CABLE FIRE IGNITION SOURCE & TARGET INVENTORY							
Scenario Description							
Facility	ATLAS Experiment						
Compartment	ATLAS Experiment Inner Detection Zone 3						
Operating Mode	Long-Term Shutdown						
Walkdown Source Reference	EDMS 2306231, 14-3-2019						
Frequency Basis Reference	EDMS 23272233, 05-10-2019						
Ignition Source Inventory			Ignition Source Frequency				
Item	Bin ID	Energized	Bin ID	Bin Count	$Freq_{base}$	$Freq_{ind}$	
EC-4275	Electrical Cabinet	N	Elec Cab	742	3.00E-02	4.04E-05	
EC-4276	Electrical Cabinet	N	Junct Box	535	3.61E-03	6.75E-06	
EC-4277	Electrical Cabinet	N	Weld/Cut	35	2.77E-04	7.91E-06	
EC-4278	Electrical Cabinet	N	Transients	35	4.28E-03	1.22E-04	
JB-7742	Junction Box	N	Maintenance	35	4.28E-03	1.22E-04	
JB-7743	Junction Box	N	Targets				
JB-7744	Junction Box	N	Raceway	Type	Function	Energized	
JB-7745	Junction Box	N	Open	D1 Bundle	Signal	N	
	Welding/Cutting	Y	Open	D2 Bundle	Signal	N	
	Transients	Y	Open	D3 Bundle	Signal	N	
	Maintance Activity	Y	Open	D4 Bundle	Signal	N	

ZONE OF INFLUENCE MATRIX					
IS/Target	D1 Bundle	D2 Bundle	D3 Bundle	D4 Bundle	Consolidated
EC-4275	1	1	1	1	1
EC-4276	1	1	1	1	1
EC-4277	1	1	1	1	1
EC-4278	1	1	1	1	1
JB-7742	1	1	1	1	1
JB-7743	1	1	1	1	1
JB-7744	1	1	1	1	1
JB-7745	1	1	1	1	1
Weld/Cut	1	1	1	1	1
Transiet	1	1	1	1	1
Maintenance	1	1	1	1	1

EXTERNAL CABLE FIRE					
Bin ID	Count	$Freq_{ind}$	$Freq_{comp}$	ZOI	Binn Totals
Electrical Cabinet	0	4.04E-05	0.00E+00	1	0.00E+00
Junction Box	0	6.75E-06	0.00E+00	1	0.00E+00
Welding/Cutting	1	7.91E-06	7.91E-06	1	7.91E-06
Transients	1	1.22E-04	1.22E-04	1	1.22E-04
Maintenance Activity	1	1.22E-04	1.22E-04	1	1.22E-04
				TOTAL	**2.52E-04**

SELF-IGNITED CABLE FIRES							
Circuit Class	Fraction	Energized	$Freq_{site}$	$Freq_{comp}$	$\lambda_{breaker}$	$\lambda_{protection}$	SI Totals
Control Power	0%	N/A	4.22E-04	0.00E+00	4.08E-01	1.66E-01	0.00E+00
400 V Power	0%	N/A	1.20E-02	0.00E+00	1.53E-01	2.34E-02	0.00E+00
18 kV Power	0%	N/A	1.35E-01	0.00E+00	5.10E-02	2.60E-03	0.00E+00
						TOTAL	**0.00E+00**

TERMINATION FIRE - PROPAGATION			
IS/Target	$Freq_{ind}$	Prop Factor	$Freq_{comp}$
EC-4275	4.04E-05	1	0.00E+00
EC-4276	4.04E-05	1	0.00E+00
EC-4277	4.04E-05	1	0.00E+00
EC-4278	4.04E-05	1	0.00E+00
JB-7742	6.75E-06	0	0.00E+00
JB-7743	6.75E-06	0	0.00E+00
JB-7744	6.75E-06	0	0.00E+00
JB-7745	6.75E-06	0	0.00E+00
		TOTAL	**0.00E+00**

Appendix G
Pilot Cases – Radionuclide Release Examples

This appendix provides three working examples of the radiological release methodology outlined in Section 6. These examples are intended to serve as proof-of-concept test cases, thereby satisfying Objective 4 of the thesis.

> **NB: The radionuclide data for these examples was generated from the NIST activation calculator [9], with arbitrarily assigned activation levels. Therefore, the numeric results should not be construed as representative of actual LHC radiation levels. However, the objective here is to confirm viability of the methodology, so the actual numeric results are not of great significance.**

The test cases are:

Case 1: Two target cable trays with multiple cables located in the LHC tunnel dipole section. One tray contains smaller control and instrument cables and the other tray contains larger power cables. The cables are thermoset insulation with a thermoset jacket. No arcing faults are present. The fire scenario is an exposure fire that involves both cable trays.

Case 2: One cable tray containing three power cables located in the LHC tunnel dipole section. The cable materials are PE insulation and PVC jacket. The fire scenario is a self-ignited cable fire from a modest size HEAF event (4.2 MW at 400 V) that causes ignition of all three cables in the tray. The radioactivity levels include the vaporised conductor contribution from the arcing fault (calculated as 616.56 g of copper conductor).

Case 3: One instrument cable wireway containing eight multi-conductor instrument signal cables located in the ATLAS Experiment inner detector area. The cables are thermoset insulation with a thermoset jacket. Instrument cables are not subject to arcing faults. The fire scenario is a termination fire that results in propagation from a burning enclosure into the cable tray.

The pilot cases are conducted using Excel spreadsheets. Screen shots of the spreadsheet computations are shown for the three cases. It is assumed that the scenarios and target cable trays are identified during fire hazard walkdowns.

G.1 Case 1 – Cable Fire Radionuclide Release

Step 1: Identify the specific scenario under investigation and define the design inputs:

- Scenario identification
- Location
- Fire category
- Target cable trays and cables in the trays

- Cable description
- Irradiation baseline and operating modes of interest
- Influence factors
    - Arcing faults (No)
    - Metal diffusion basis
    - Soot, char, and gaseous yields

RADIONUCLIDE RELEASE FRACTION - CASE 1	
Scenario Description	
Location	LHC tunnel, Dipole curve
Fire Category	Exposure fire
Targets	Tray P220
	Tray C330
Cable Description	
Tray C330	Cable 1: 7 cond, 2.5 mm^2, XLPE/XLPE
Tray C330	Cable 2: 7 cond, 2.5 mm^2, XLPE/XLPE
Tray C330	Cable 3: 19 cond, 0.5 mm^2, XLPE/XLPE
Tray P220	Cable 4: 3 cond triplex, 50 mm^2, XLPE/XLPE
Tray P220	Cable 5: 3 cond triplex, 50 mm^2, XLPE/XLPE
Operation Mode	
Irradiation Basis	12 years (6 mo ON / 6 mo OFF)
Modes	Beam On
	Short-term Cooldown (0 - 1 mo): 10 days
	Long-term Shutdown (> 1 mo): 120 days
Influence Factors	
Arcing Faults	No
Conductor Diffusion	Chart @ T=800 C, t=30 min with 50% carryover
Char Yield	Thermoset: 25% by mass
	Carbon, 50% diffusion metals
Soot Yield	0.05 g/g
	Aromatic rings, C6H6

Step 2: Determine the cable specifications. Material types and mass fractions of the conductor, insulation, and jacket are essential to the process. Note that mass fractions are shown as percentage of overall cable mass per unit length.

CABLE DESCRIPTION AND SPECIFICATIONS												
Cable	Cable	Conductor			Insulation		Jacket		Mass/Length	Mass Fractions (%)		
Number	Function	Material	Size (mm^2)	Count	Material	Formula	Material	Formula	(kg/m)	Conductor	Insulation	Jacket
Cable 1	Control	Copper	2.5	7	XLPE	C_2H_4	XLPE	C_2H_4	0.38	65%	16%	19%
Cable 2	Control	Copper	2.5	7	XLPE	C_2H_4	XLPE	C_2H_4	0.38	65%	16%	19%
Cable 3	Instrument	Copper	0.5	19	XLPE	C_2H_4	XLPE	C_2H_4	1.05	52%	23%	25%
Cable 4	Power	Copper	50	3	XLPE	C_2H_4	XLPE	C_2H_4	1.65	63%	18%	19%
Cable 5	Power	Copper	50	3	XLPE	C_2H_4	XLPE	C_2H_4	1.65	63%	18%	19%

Step 3: Convert the cable conductor, insulation, and jacket percentage mass fractions to mass per unit length, expressed in Kg/m. Next determine the elemental mass fractions of the material constituents based on atomic weights. Note that both insulation and jacket mass fractions contribute to the carbon and hydrogen elemental mass values. The elemental mass for copper,

carbon, and hydrogen represent the pre-fire elemental inventory values. The conductor metal diffusion factors are also determined during this step. The diffusion factors differ based on conductor size. Thus, it is important to obtain the correct values from the applicable diffusion graphs.

CABLE BASELINE ELEMENTAL MASS FRACTIONS									
Tray Number	Cable Number	Mass/Length (kg/m)	Conductor (kg/m)	Insulation (kg/m)	Jacket (kg/m)	Copper 63/63	Carbon 24/28	Hydrogen 4/28	Metal Diff Factor
C330	Cable 1	0.38	0.247	0.061	0.072	0.247	0.114	0.019	0.50%
C330	Cable 2	0.38	0.247	0.061	0.072	0.247	0.114	0.019	0.50%
C330	Cable 3	1.05	0.546	0.242	0.263	0.546	0.432	0.072	1.05%
P220	Cable 4	1.65	1.040	0.297	0.314	1.040	0.523	0.087	0.01%
P220	Cable 5	1.65	1.040	0.297	0.314	1.040	0.523	0.087	0.01%
All	**All**	**5.11**	**3.119**	**0.957**	**1.034**	**3.119**	**1.707**	**0.284**	

Step 4: Calculate the elemental fractions for combustion particles. These calculations are based on the mass balance inventory concepts presented in Section 6.1. The post-fire carbon values for soot, char, and gas are based on the design input yields specified for soot and char. The gas fractions for carbon and hydrogen are taken as the difference between the pre-fire values and the amounts lost to soot and char. The metal diffusion total mass fraction is determined as a weighted value of copper materials and diffusion factor. All values are specified in mass per unit length (kg/m). The design fire scenarios determine the length of cable burned for a given scenario.

COMBUSTION PRODUCT YIELDS						
Soot (.05 g/g)		Char (25%)		Gas (CO, CO2, H2O)		Metal
C (72/78)	H (6/78)	C (12/12)	H (0/0)	C	H	Cu
0.0061	0.0005	0.0333	0.0000	0.0746	0.0185	1.24E-03
0.0061	0.0005	0.0333	0.0000	0.0746	0.0185	1.24E-03
0.0233	0.0019	0.1260	0.0000	0.2827	0.0701	5.73E-03
0.0282	0.0023	0.1526	0.0000	0.3425	0.0849	1.04E-04
0.0282	0.0023	0.1526	0.0000	0.3425	0.0849	1.04E-04
0.0919	0.0077	0.4978	0.0000	1.1169	0.2768	8.41E-03

Step 5: Obtain the activation levels for the material isotopes of interest (NB: recall that the isotopes used for pilot case studies are generated from the NIST neutron activation calculator and thus do not represent actual isotopes nor activation levels for LHC). Using the half-life for each isotope, calculate the activity for the three operating modes: Beam On. Cooldown, and Shutdown. The calculations use a “baseline” value to determine activity for each of the operating modes. In this example the Beam On mode is the same as the baseline, but this could be defined differently. Recall that Cooldown is specified at 10 days from removal of the beam and Shutdown is specified as 120 days from shutdown. These times are taken to be realistic yet conservative for each mode represented. In lieu of calculating activity levels, it is possible that direct values can be obtained from activation computations.

RADIONUCLIDE ACTIVATION LEVELS FOR OPERATING MODES									
Cable	Chemical	Radionuclide Characterization				Activity (Bq/g)			
Material	Formula	Isotope	Atomic No	Atomic Wt	Half Life	Baseline	Beam On	Cooldown	Shutdown
XLPE & PE	C_2H_4	C-11	6	11.011	20.36 min	7.29E+03	7.29E+03	0.00	0.00
		H-3	1	3.016	12.35 yr	1.45E+04	1.45E+04	1.45E+04	1.42E+04
Copper	CU	Cu-66	29	65.93	5.12 min	1.67E+07	1.67E+07	0.00	0.00
		Cu-64	29	63.93	12.70 hr	8.20E+07	8.20E+07	1.68E+02	0.00
		Cu-67	29	66.93	61.9 hr	3.85E+04	3.85E+04	2.62E+03	0.00
		Cu-61	29	61.93	1.65 hr	4.26E+03	4.26E+03	0.00	0.00
		Ni-66	28	65.93	54.8 hr	5.63E+02	5.63E+02	2.70.E+01	0.00

Step 6: The final step is to calculate based on per unit length the estimated activity levels of each radionuclide. These values are calculated using the elemental mass fractions of the materials and the activity levels for each of the operating modes. Notice that the mass fractions are based on the total of all cables in the scenario, thereby providing an efficient means doing the analysis. One set of activity levels is conducted for each operating mode. As a quantitative risk analysis, each operating mode should be treated as a separate scenario since the conditions, hazard, and consequence will be different for each mode.

RADIONUCLIDE RELEASE - MODE: BEAM ON									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.707	7.29E+06	1.24E+07	0.09189	6.70E+05	1.11693	8.14E+06	0.00	0.00
H-3	0.284	1.45E+07	4.12E+06	0.00766	1.11E+05	0.27677	4.01E+06	0.00	0.00
Cu-66	0.00841	1.67E+10	1.40E+08	0.00	0.00	0.00	0.00	0.00421	7.02E+07
Cu-64	0.00841	8.20E+10	6.90E+08	0.00	0.00	0.00	0.00	0.00421	3.45E+08
Cu-67	0.00841	3.85E+07	3.24E+05	0.00	0.00	0.00	0.00	0.00421	1.62E+05
Cu-61	0.00841	4.26E+06	3.58E+04	0.00	0.00	0.00	0.00	0.00421	1.79E+04
Ni-66	0.00841	5.63E+05	4.74E+03	0.00	0.00	0.00	0.00	0.00421	2.37E+03

RADIONUCLIDE RELEASE - MODE: COOLDOWN (10 days after shutdown)									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.707	0.00	0.00	0.09189	0.00	1.11693	0.00	0.00	0.00
H-3	0.284	1.45E+07	4.12E+06	0.00766	1.11E+05	0.27677	4.01E+06	0.00	0.00
Cu-66	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-64	0.00841	1.68E+05	1.41E+03	0.00	0.00	0.00	0.00	0.00421	7.06E+02
Cu-67	0.00841	2.62E+06	2.20E+04	0.00	0.00	0.00	0.00	0.00421	1.10E+04
Cu-61	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Ni-66	0.00841	2.70E+04	2.27E+02	0.00	0.00	0.00	0.00	0.00421	1.14E+02

RADIONUCLIDE RELEASE - MODE: SHUTDOWN (120 days after shutdown)									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.707	0.00	0.00	0.09189	0.00	1.11693	0.00	0.00	0.00
H-3	0.284	1.42E+07	4.05E+06	0.00766	1.09E+05	0.27677	3.94E+06	0.00	0.00
Cu-66	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-64	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-67	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Cu-61	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00
Ni-66	0.00841	0.00	0.00	0.00	0.00	0.00	0.00	0.00421	0.00

G.2 Case 2 – Cable Fire Radionuclide Release

The discussion and explanation for each step will not be repeated from Case 1. Unique difference will be pointed out.

Step 1: Identify the specific scenario under investigation and define the design inputs. Notice that the cable and insulation are different materials and that the arcing fault parameters are identified.

RADIONUCLIDE RELEASE FRACTION - CASE 2	
Scenario Description	
Location	LHC tunnel, Sector 4 dipole curve
Fire Category	Self-ignited cable fire
Targets	Tray P940
Cable Description	
Tray P940	Cable 1: 3 cond triplex, 50 mm^2, PE/PVC
Tray P940	Cable 2: 3 cond triplex, 50 mm^2, PE/PVC
Tray P940	Cable 3: 3 cond triplex, 50 mm^2, PE/PVC
Operation Mode	
Irradiation Basis	12 years (6 mo ON / 6 mo OFF)
Modes	Beam ON
	Short-term cooldown (0 - 1 mo): 10 days
	Long-term shutdown (> 1 mo): 120 days
Influence Factors	
Arcing Faults	Yes, 400V, 4,200 kW, 1 s → m_v = 616.56 g
Conductor Diffusion	Chart @ T=800 C, t=30 min with 50% carryover
Char Yield	Thermoplastic: 5% by mass
	Carbon, 50% diffusion metals
Soot Yield	0.05 g/g
	Aromatic rings, C6H6
Gas Yield	100% chloride from PVC

Step 2: Determine the cable specifications.

CABLE DESCRIPTION AND SPECIFICATIONS												
Cable	Cable	Conductor			Insulation		Jacket		Mass/Length	Mass Fractions (%)		
Number	Function	Material	Size (mm^2)	Count	Material	Formula	Material	Formula	(kg/m)	Conductor	Insulation	Jacket
Cable 1	Power	Copper	50	3	PE	C_2H_4	PVC	C_2H_3Cl	1.9	58%	20%	22%
Cable 2	Power	Copper	50	3	PE	C_2H_4	PVC	C_2H_3Cl	1.9	58%	20%	22%
Cable 3	Power	Copper	50	3	PE	C_2H_4	PVC	C_2H_3Cl	1.9	58%	20%	22%

Step 3: Convert the cable conductor, insulation, and jacket percentage mass fractions to mass per unit length, expressed in Kg/m and compute the elemental mass fractions. Notice that the carbon and hydrogen values for the insulation and jacket materials are based on different molecular weights.

CABLE BASELINE ELEMENTAL MASS FRACTIONS										
Tray	Cable	Mass/Length	Conductor	Insulation	Jacket	Copper	Carbon	Hydrogen	Chlorine	Metal
Number	Number	(kg/m)	(kg/m)	(kg/m)	(kg/m)	63/63	24/28 & 24/62	4/28 & 3/62	35/62	Diff Factor
P940	Cable 1	1.90	1.102	0.380	0.418	1.102	0.488	0.075	0.236	0.01%
P940	Cable 2	1.90	1.102	0.380	0.418	1.102	0.488	0.075	0.236	0.01%
P940	Cable 3	1.90	1.102	0.380	0.418	1.102	0.488	0.075	0.236	0.01%
All	**All**	**5.70**	**3.306**	**1.140**	**1.254**	**3.306**	**1.463**	**0.224**	**0.708**	

Step 4: Calculate the elemental fractions for combustion particles.

COMBUSTION PRODUCT YIELDS							
Soot (.05 g/g)		Char (25%)		Gas (CO, CO2, H2O, HCl)			Metal
C (72/78)	H (6/78)	C (12/12)	H (0/0)	C	H	Cl	Cu
0.0259	0.0022	0.1405	0.0000	0.3211	0.0723	0.2360	1.10E-04
0.0259	0.0022	0.1405	0.0000	0.3211	0.0723	0.2360	1.10E-04
0.0259	0.0022	0.1405	0.0000	0.3211	0.0723	0.2360	1.10E-04
0.0778	**0.0065**	**0.4215**	**0.0000**	**0.9632**	**0.2170**	**0.7079**	**3.31E-04**

Step 5: Obtain the activation levels for the material isotopes of interest.

RADIONUCLIDE ACTIVATION LEVELS FOR OPERATING MODES									
Cable	Chemical	Radionuclide Characterization				Activity (Bq/g)			
Material	Formula	Isotope	Atomic No	Atomic Wt	Half Life	Baseline	Beam On	Cooldown	Shutdown
PVC	C_2H_3Cl	C-11	6	11.011	20.36 min	7.29E+03	7.29E+03	0.00	0.00
		H-3	1	3.016	12.35 yr	1.45E+04	1.45E+04	1.45E+04	1.42E+04
		S-35	16	34.97	87.37 day	2.20E+06	2.20E+05	2.03E+06	8.49E+05
		Cl-38	17	37.97	37.24 min	6.00E+05	6.00E+04	0.00	0.00
		P-32	15	31.98	14.27 day	3.00E+03	3.00E+04	1.85E+03	8.82E+00
Copper	CU	Cu-66	29	65.93	5.12 min	1.67E+07	1.67E+07	0.00	0.00
		Cu-64	29	63.93	12.70 hr	8.20E+07	8.20E+07	1.68E+02	0.00
		Cu-67	29	66.93	61.9 hr	3.85E+04	3.85E+04	2.62E+03	0.00
		Cu-61	29	61.93	1.65 hr	4.26E+03	4.26E+03	0.00	0.00
		Ni-66	28	65.93	54.8 hr	5.63E+02	5.63E+02	2.70.E+01	0.00

Step 6: Calculate based on per unit length the estimated activity levels of each radionuclide.

RADIONUCLIDE RELEASE - MODE: BEAM ON									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.463	7.29E+06	1.07E+07	0.07782	5.67E+05	0.96322	7.02E+06	0.00	0.00
H-3	0.224	1.45E+07	3.24E+06	0.00648	9.40E+04	0.21705	3.15E+06	0.00	0.00
S-35	0.708	2.20E+08	1.56E+08	0.00	0.00	0.7079	1.56E+08	0.00	0.00
Cl-38	0.708	6.00E+07	4.25E+07	0.00	0.00	0.7079	4.25E+07	0.00	0.00
P-32	0.708	3.00E+07	2.12E+07	0.00	0.00	0.7079	2.12E+07	0.00	0.00
Cu-66	0.00033	1.67E+10	5.52E+06	0.00	0.00	0.00	0.00	0.00017	2.76E+06
Cu-64	0.00033	8.20E+10	2.71E+07	0.00	0.00	0.00	0.00	0.00017	1.36E+07
Cu-67	0.00033	3.85E+07	1.27E+04	0.00	0.00	0.00	0.00	0.00017	6.36E+03
Cu-61	0.00033	4.26E+06	1.41E+03	0.00	0.00	0.00	0.00	0.00017	7.04E+02
Ni-66	0.00033	5.63E+05	1.86E+02	0.00	0.00	0.00	0.00	0.00017	9.31E+01

RADIONUCLIDE RELEASE - MODE: COOLDOWN (10 days after shutdown)									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	1.463	0.00	0.00	0.07782	0.00	0.96322	0.00	0.00	0.00
H-3	0.224	1.45E+07	3.24E+06	0.00648	9.39E+04	0.21705	3.14E+06	0.00	0.00
S-35	0.708	2.03E+09	1.44E+09	0.00	0.00	0.7079	1.44E+09	0.00	0.00
Cl-38	0.708	0.00	0.00	0.00	0.00	0.7079	0.00	0.00	0.00
P-32	0.708	1.85E+06	1.31E+06	0.00	0.00	0.7079	1.31E+06	0.00	0.00
Cu-66	0.00033	0.00	0.00	0.00	0.00	0.00	0.00	0.00017	0.00
Cu-64	0.00033	1.68E+05	5.55E+01	0.00	0.00	0.00	0.00	0.00017	2.78E+01
Cu-67	0.00033	2.62E+06	8.66E+02	0.00	0.00	0.00	0.00	0.00017	4.33E+02
Cu-61	0.00033	0.00	0.00	0.00	0.00	0.00	0.00	0.00017	0.00
Ni-66	0.00033	2.70E+04	8.94E+00	0.00	0.00	0.00	0.00	0.00017	4.47E+00

RADIONUCLIDE RELEASE - MODE: SHUTDOWN (120 days after shutdown)										
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)		
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	
C-11	1.463	0.00	0.00	0.07782	0.00	0.96322	0.00	0.00	0.00	
H-3	0.224	1.42E+07	3.18E+06	0.00648	9.23E+04	0.21705	3.09E+06	0.00	0.00	
S-35	0.708	8.49E+08	6.01E+08	0.00	0.00	0.7079	6.01E+08	0.00	0.00	
Cl-38	0.708	0.00	0.00	0.00	0.00	0.7079	0.00	0.00	0.00	
P-32	0.708	8.82E+03	6.25E+03	0.00	0.00	0.7079	6.25E+03	0.00	0.00	
Cu-66	0.00033	0.00	0.00	0.00	0.00	0.00	0.00	0.00017	0.00	
Cu-64	0.00033	0.00	0.00	0.00	0.00	0.00	0.00	0.00017	0.00	
Cu-67	0.00033	0.00	0.00	0.00	0.00	0.00	0.00	0.00017	0.00	
Cu-61	0.00033	0.00	0.00	0.00	0.00	0.00	0.00	0.00017	0.00	
Ni-66	0.00033	0.00	0.00	0.00	0.00	0.00	0.00	0.00017	0.00	

Step 7: Calculate the estimated activity levels of each metal radionuclide based on the vaporised conductor resulting from the arcing fault. The values are calculated for all three operating modes.

Arcing Fault	
Mass (kg)	Activity (Bq)
0.61656	1.03E+10
0.61656	5.06E+10
0.61656	2.37E+07
0.61656	2.63E+06
0.61656	3.47E+05

Beam On

Arcing Fault	
Mass (kg)	Activity (Bq)
0.61656	0.00
0.61656	1.04E+05
0.61656	1.62E+06
0.61656	0.00
0.61656	1.67E+04

Cooldown

Arcing Fault	
Mass (kg)	Activity (Bq)
0.61656	0.00
0.61656	0.00
0.61656	0.00
0.61656	0.00
0.61656	0.00

Shutdown

G.3 Case 3 – Cable Fire Radionuclide Release

The discussion and explanation for each step will not be repeated from Case 1. Unique difference will be pointed out.

Step 1: Identify the specific scenario under investigation and define the design inputs.

RADIONUCLIDE RELEASE FRACTION - CASE 3	
Scenario Description	
Location	ATLAS Experiment Inner Detector
Fire Category	Termination Fire with Propagation
Targets	Tray S013
Cable Description	
Tray S013	Cable 1 - 4: 19 cond, 0.75 mm^2, XLPE/XLPE
Tray S013	Cable 5 - 8: 37 cond, 0.5 mm^2, XLPE/XLPE
Operation Mode	
Irradiation Basis	12 years (6 mo ON / 6 mo OFF)
Modes	Beam ON
	Short-term cooldown (0 - 1 mo): 10 day
	Long-term shutdown (> 1 mo): 3 mo
Influence Factors	
Arcing Faults	No
Conductor Diffusion	Chart @ T=800 C, t=30 min with 50% carryover
Char Yield	Thermoset: 25% by mass
	Carbon, 50% diffusion metals
Soot Yield	0.05 g/g
	Aromatic rings, C6H6

Step 2: Determine the cable specifications.

CABLE DESCRIPTION AND SPECIFICATIONS													
Cable	Cable	Conductor			Insulation		Jacket		Mass/Length	Mass Fractions (%)		
Number	Function	Material	Size (mm^2)	Count	Material	Formula	Material	Formula	(kg/m)	Conductor	Insulation	Jacket
Cable 1	Instrument	Copper	0.75	19	XLPE	C_2H_4	XLPE	C_2H_4	1.25	52%	23%	25%
Cable 2	Instrument	Copper	0.75	19	XLPE	C_2H_4	XLPE	C_2H_4	1.25	52%	23%	25%
Cable 3	Instrument	Copper	0.75	19	XLPE	C_2H_4	XLPE	C_2H_4	1.25	52%	23%	25%
Cable 4	Instrument	Copper	0.75	19	XLPE	C_2H_4	XLPE	C_2H_4	1.25	52%	23%	25%
Cable 5	Instrument	Copper	0.5	37	XLPE	C_2H_4	XLPE	C_2H_4	1.98	55%	23%	22%
Cable 6	Instrument	Copper	0.5	37	XLPE	C_2H_4	XLPE	C_2H_4	1.98	55%	23%	22%
Cable 7	Instrument	Copper	0.5	37	XLPE	C_2H_4	XLPE	C_2H_4	1.98	55%	23%	22%
Cable 8	Instrument	Copper	0.5	37	XLPE	C_2H_4	XLPE	C_2H_4	1.98	55%	23%	22%

Step 3: Convert the cable conductor, insulation, and jacket percentage mass fractions to mass per unit length, expressed in Kg/m and compute the elemental mass fractions.

CABLE BASELINE ELEMENTAL MASS FRACTIONS									
Tray Number	Cable Number	Mass/Length (kg/m)	Conductor (kg/m)	Insulation (kg/m)	Jacket (kg/m)	Copper 63/63	Carbon 24/28	Hydrogen 4/28	Metal Diff Factor
S013	Cable 1	1.25	0.650	0.288	0.313	0.650	0.514	0.086	0.80%
S013	Cable 2	1.25	0.650	0.288	0.313	0.650	0.514	0.086	0.80%
S013	Cable 3	1.25	0.650	0.288	0.313	0.650	0.514	0.086	0.80%
S013	Cable 4	1.25	0.650	0.288	0.313	0.650	0.514	0.086	0.80%
S013	Cable 5	1.98	1.089	0.455	0.436	1.089	0.764	0.127	1.05%
S013	Cable 6	1.98	1.089	0.455	0.436	1.089	0.764	0.127	1.05%
S013	Cable 7	1.98	1.089	0.455	0.436	1.089	0.764	0.127	1.05%
S013	Cable 8	1.98	1.089	0.455	0.436	1.089	0.764	0.127	1.05%
S013	**All**	**12.92**	**6.96**	**2.97**	**2.99**	**6.96**	**5.11**	**0.85**	

Step 4: Calculate the elemental fractions for combustion particles.

COMBUSTION PRODUCT YIELDS						
Soot (.05 g/g)		Char (25%)		Gas (CO, CO2, H2O)		Metal
C (72/78)	H (6/78)	C (12/12)	H (0/0)	C	H	Cu
0.0277	0.0023	0.1500	0.0000	0.3366	0.0834	5.20E-03
0.0277	0.0023	0.1500	0.0000	0.3366	0.0834	5.20E-03
0.0277	0.0023	0.1500	0.0000	0.3366	0.0834	5.20E-03
0.0277	0.0023	0.1500	0.0000	0.3366	0.0834	5.20E-03
0.0411	0.0034	0.2228	0.0000	0.4998	0.1239	1.14E-02
0.0411	0.0034	0.2228	0.0000	0.4998	0.1239	1.14E-02
0.0411	0.0034	0.2228	0.0000	0.4998	0.1239	1.14E-02
0.0411	0.0034	0.2228	0.0000	0.4998	0.1239	1.14E-02
0.2753	**0.0229**	**1.4910**	**0.0000**	**3.3457**	**0.8291**	**0.0665**

Step 5: Obtain the activation levels for the material isotopes of interest.

RADIONUCLIDE ACTIVATION LEVELS FOR OPERATING MODES									
Cable	Chemical	Radionuclide Characterization				Activity (Bq/g)			
Material	Formula	Isotope	Atomic No	Atomic Wt	Half Life	Baseline	Beam On	Cooldown	Shutdown
XLPE & PE	C_2H_4	C-11	6	11.011	20.36 min	7.29E+03	7.29E+03	0.00	0.00
		H-3	1	3.016	12.35 yr	1.45E+04	1.45E+04	1.45E+04	1.42E+04
Copper	CU	Cu-66	29	65.93	5.12 min	1.67E+07	1.67E+07	0.00	0.00
		Cu-64	29	63.93	12.70 hr	8.20E+07	8.20E+07	1.68E+02	0.00
		Cu-67	29	66.93	61.9 hr	3.85E+04	3.85E+04	2.62E+03	0.00
		Cu-61	29	61.93	1.65 hr	4.26E+03	4.26E+03	0.00	0.00
		Ni-66	28	65.93	54.8 hr	5.63E+02	5.63E+02	2.70.E+01	0.00

Step 6: The final step is to calculate based on per unit length the estimated activity levels of each radionuclide.

RADIONUCLIDE RELEASE - MODE: BEAM ON									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	5.112	7.29E+06	3.73E+07	0.27526	2.01E+06	3.34574	2.44E+07	0.00	0.00
H-3	0.852	1.45E+07	1.24E+07	0.02294	3.33E+05	0.82906	1.20E+07	0.00	0.00
Cu-66	0.06654	1.67E+10	1.11E+09	0.00	0.00	0.00	0.00	0.03327	5.56E+08
Cu-64	0.06654	8.20E+10	5.46E+09	0.00	0.00	0.00	0.00	0.03327	2.73E+09
Cu-67	0.06654	3.85E+07	2.56E+06	0.00	0.00	0.00	0.00	0.03327	1.28E+06
Cu-61	0.06654	4.26E+06	2.83E+05	0.00	0.00	0.00	0.00	0.03327	1.42E+05
Ni-63	0.06654	5.63E+05	3.75E+04	0.00	0.00	0.00	0.00	0.03327	1.87E+04

RADIONUCLIDE RELEASE - MODE: COOLDOWN (10 days after shutdown)									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	5.112	0.00	0.00	0.27526	0.00	3.34574	0.00	0.00	0.00
H-3	0.852	1.45E+07	1.23E+07	0.02294	3.32E+05	0.82906	1.20E+07	0.00	0.00
Cu-66	0.06654	0.00	0.00	0.00	0.00	0.00	0.00	0.03327	0.00
Cu-64	0.06654	1.68E+05	1.12E+04	0.00	0.00	0.00	0.00	0.03327	5.59E+03
Cu-67	0.06654	2.62E+06	1.74E+05	0.00	0.00	0.00	0.00	0.03327	8.72E+04
Cu-61	0.06654	0.00	0.00	0.00	0.00	0.00	0.00	0.03327	0.00
Ni-63	0.06654	2.70E+04	1.80E+03	0.00	0.00	0.00	0.00	0.03327	9.00E+02

RADIONUCLIDE RELEASE - MODE: SHUTDOWN (120 days after shutdown)									
Isotope	Baseline Activity		Pre-Fire	Soot (C6H6)		Gas - CO, CO2, H2O		Airborne Metal (50%)	
	Mass (Kg/m)	Activity (Bq/Kg)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)	Mass (Kg/m)	Activity (Bq/m)
C-11	5.112	0.00	0.00	0.27526	0.00	3.34574	0.00	0.00	0.00
H-3	0.852	1.42E+07	1.21E+07	0.02294	3.27E+05	0.82906	1.18E+07	0.00	0.00
Cu-66	0.06654	0.00	0.00	0.00	0.00	0.00	0.00	0.03327	0.00
Cu-64	0.06654	0.00	0.00	0.00	0.00	0.00	0.00	0.03327	0.00
Cu-67	0.06654	0.00	0.00	0.00	0.00	0.00	0.00	0.03327	0.00
Cu-61	0.06654	0.00	0.00	0.00	0.00	0.00	0.00	0.03327	0.00
Ni-63	0.06654	0.00	0.00	0.00	0.00	0.00	0.00	0.03327	0.00