Use of Physical Modeling Tools in the Design of Fire-Protection Systems for an Electric Transformer in an Underground Hydroelectric Power Plant

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Resumen

Uso de herramientas de simulación computacional de modelos físicos para el diseño de sistemas de protección contra incendios de un transformador de potencia en una central de generación hidroeléctrica subterránea

Los diseños de los sistemas de protección contra incendios en las centrales de generación subterráneas van más allá de lo netamente prescriptivo. Lo anterior se debe a que, adicional a los riesgos de la operación de los equipos rotativos y eléctricos, existe una dificultad para evaluar el tiempo necesario para la evacuación del personal debido a las largas distancias entre el portal de acceso y la casa de máquinas. Por lo tanto, se hace necesario realizar diseños basados en desempeño con el propósito de disminuir el nivel de incertidumbre que dejan los diseños prescriptivos y verificar que el personal pueda evacuar de manera adecuada.

En este trabajo de grado se analizaron tres diferentes herramientas de modelación física: Fire Dynamics Simulator (FDS), Consolidated Model of Fire Growth and Smoke (CFAST) y ANSYS-FLUENT, en un caso de aplicación de un incendio de un transformador de potencia refrigerado por aceite con una tasa de liberación de calor estimada de 8746 kW, para el cual se analizaron cinco escenarios de incendios diferentes.

Inicialmente se caracterizó con base en el método prescriptivo un sistema de protección y de riesgos contra incendios en centrales hidroeléctricas, específicamente en lo relacionado con el transformador eléctrico. Esta caracterización permitió el diseño de un sistema protector contra incendios a partir de recomendaciones prescriptivas. Se simularon cinco escenarios de incendios que consideraban sistemas confinados (la celda del transformador) o no confinados (la celda del transformador y el pasillo aledaño) así como la disponibilidad de extractores de humo y sistemas de diluvio. Los resultados de las simulaciones de todas las herramientas de modelación física se compararon, especialmente aquellos relacionados con la temperatura del humo y la velocidad de liberación de calor (HRR, Heat Release Rate).

Inicialmente, los tiempos de evacuación disponibles (ASET) calculados por métodos computacionales para niveles de riesgo relacionados con los cambios en la temperatura, la concentración de monóxido de carbono, dióxido de carbono y oxígeno y la radiación térmica se compararon con el tiempo de evacuación requerido (RSET) calculado por método prescriptivo. Se identificó que el tiempo requerido para la evacuación del personal es menor al tiempo disponible, por lo cual, el personal puede evacuar a una zona segura.

Posterior a esto, se compararon los resultados de las temperaturas de la capa de humo reportadas por las herramientas de simulación física con las calculadas por el método prescriptivo para la definición del sistema de extracción de humos.

Finalmente, se evaluó la funcionalidad de cada una de las herramientas de modelación física para adaptarse a los escenarios propuestos. FDS permitió simular los cinco escenarios; con CFAST fue necesario de forma artificial ajustar la HRR para representar el sistema de extinción por diluvio. En el caso de FLUENT solo fue posible simular, dentro de un tiempo de cómputo similar al de FDS y en un computador personal, dos escenarios que se presentaban en estado estable. Si bien CFAST es la herramienta de modelación física más fácil de usar, FDS se ratificó como el estándar de uso en la simulación de incendios pues la complejidad de su desarrollo matemático le permite una mejor caracterización del incendio. Si bien FLUENT tiene potencial para simular un incendio, su aplicación por parte de profesionales especializados en el área de seguridad contra incendios se limita a simulaciones en estado estable dentro de la capacidad de cómputo normalmente disponible para este tipo de análisis en la industria.

PALABRAS CLAVES: Tasa de liberación de calor, centrales de generación hidroeléctrica, extracción de humos, diseños basados en desempeño, evacuación.

Abstract

Use of physical modeling tools in the design of fire-protection systems for an electrical transformer in an underground hydroelectric power plant

The design of fire protection systems in underground power plants goes beyond what is solely prescriptive. This is because, in addition to the risks of the operation of rotating and electrical equipment, there is difficulty in evaluating the time required for the evacuation of personnel due to the long distances between the access portal and the power plant. Therefore, it is necessary to carry out performance-based designs to reduce the level of uncertainty left by prescriptive designs and verify that personnel can evacuate properly.

In this monograph, three different physical modeling tools (PMTs) were analyzed: Fire Dynamics simulator (FDS), Consolidated Model of Fire Growth and Smoke (CFAST) and ANSYS-FLUENT, in a case of application of fire in an oil-insulated transformer with an estimate heat release rate of 8746 kW, for which five different fire scenarios were analyzed.

A prescription-based approach to the characterization of a fire protection system and a fire risk analysis in hydroelectric power plants was initially undertaken. This part was particularly devoted to a fire in an electric transformer and lead to the design of a fire protection system exclusively based on prescriptive recommendations. Five fire scenarios that considered either a confined system (the transformer cell) or an unconfined system (the transformer cell and the adjacent hallway) as well as the availability of smoke evacuation and water deluge protection were then modeled with all the three PMTs. The results from all the PMTs simulations were compared, particularly those related with smoke temperature and predicted Heat Release Rate (HRR).

The available evacuation times (ASET) calculated by the PMTs and associated to risks related to changes in temperature, concentration of carbon monoxide, carbon dioxide and oxygen and thermal radiation were compared with the required evacuation time (RSET) calculated by the prescriptive method. It was identified that the time required for the evacuation of personnel is less than the time available.

The results of the smoke layer temperatures reported by the PMTs were compared with those calculated by the prescriptive method for the definition of the smoke extraction system.

Finally, the functionality of each PMT to model the proposed fire scenarios was evaluated. FDS could be used simulate the five proposed scenarios. CFAST demanded to artificially adjust the HRR to represent the deluge extinguishing system. Even though a more detailed representation of the geometry was possible with FLUENT, only the steady-state cases could be modeled in a similar computational time frame that of FDS and with a personal computer. Even though CFAST was deemed as the easiest to use PMT, FDS was confirmed as the standard to use when modeling fires as its mathematical complexity allows for a more reliable fire representation. Although FLUENT has potential for fire simulation, its application by fire safety engineering (FSE) practitioner would be limited to steady state simulations if the simulations are to be carried out in the time frame and with the typical computational facilities available in industry.

KEYWORDS: heat release rate, hydroelectric power plant, smoke extraction, performance-based design, evacuation.

Content

List of figures

Pág.

List of tables

Pág.

Introduction

Fire Safety Engineering (FSE) uses prescriptive and performance-based design methods to prevent fires, save lives, and minimize property damage. While the prescriptive methodology has been used for more than half a century, the performance-based approach has, arguably, been available just in the last two decades. For systems, such a “type” power transformer, located in an underground hydroelectric plant, the availability of prescriptive methods is scarce. The use of performance-based methods is, then, very attractive. However, the practitioner in FSE has limited resources when applying performance-based engineering to these systems.

One area of performance-based design is the physical modeling tools (PMT) available to the FSE practitioner. Not only it is important to select the right tools from those available, but to correctly use them. This monograph reviews different modeling tools in the assessment of a fire event in a "type" power transformer, which is in an underground hydroelectric power plant. The plant under study includes six transformer cells, separated by fire walls and a metallic fire-resistant enclosure on the front that communicates with the access hallway to the transformer area and serves also as an evacuation route for personnel, which is a typical configuration of this type of units in transformer cells (Working Group A2.33, 2013).

Experts dedicated to the investigation of fires in transformers estimate that there are around 400000 power transformers in the world, which will present failures at a rate of 0.02 per year (Berg & Fritze, 2012). Most failures are due to component degradation, corrosion, and lack of maintenance.

This document indicates how smoke production and fire dispersion can be analyzed by three physical modelling tools: FDS, CFAST, and FLUENT. It compares the results obtained from the physical modeling tools (PMTs) with those obtained with basic hand calculations suggested in prescriptive codes.

1.1 Problem Statement

The design of fire protection systems in underground hydropower plants has traditionally been developed according to a prescriptive analysis that follows pre-established standards (FM Global, 2020; IEEE, 2012; National Fire Protection Association, 2020). However, these standards, conceived with a general character, do not consider the particularities of each installation. Given that each hydroelectric power plant is built depending on the particularities of the terrain, the location and atmospheric conditions, and the hydraulic potential, it is highly probable that the prescriptive regulations have been made based on systems that are different from those that exist in a particular hydroelectric plant.

Fires in hydroelectric plants are less frequent than those that occur in hotels, buildings, and entertainment centers. Furthermore, it is uncommon that data from a fire in a hydroelectric power becomes public, since fire investigations mostly focus on identifying if the insurance coverage is applicable, which gives the final report on the incident a confidential nature (Chi et al., 2011; Lucas, 2009; Roberson & Stambaugh, 2002).

Fire protection in Colombia is framed within the Colombian Earthquake Resistant Construction Regulation of 2010 - NSR-10 (Asociación Colombiana de Ingeniería Sísmica, 2010) and its subsequent updates, which prescribes some fire protection requirements in its chapters J and K. The inclusion of fire regulations in a construction-based code stems from the fact that in a fire event, structures could collapse due to high temperatures. A section related to fire protection systems was then included in NSR-10, so that it was possible to comply with the objective of the code, which is the protection of people's lives.

In Colombia, a standard exclusively dedicated to protection against fires does not exist. In fact, the fire protection recommendations for power plants in the NSR-10 standard are very general and only include power generation plants within the classification of “industrial installations”; a distant area from the underground hydroelectric power plant that this work deals with. Furthermore, there is no regulatory framework in Colombia for the use of physical modelling tools for the design of fire protection (Mariño & Muñoz, 2016). It is considered that performance design using computer tools could particularize fire protection design in such a way that resources are optimized, and costs are reduced. However, the lack of legislation and the absence of appropriate technical guidelines regarding this issue have led to the recommendation in Latin America of prescriptive design over performance design (Tavares, 2009).

The situation in Latin America contrasts with what happens, for example, in the United States, where the National Fire Protection Association – NFPA, in NFPA 101, corresponding to human safety (National Fire Protection Association, 2021c), indicates that the designer of fire protection systems can make use of physical modelling tools to complement and validate the designs made in a prescriptive manner, with the purpose of evaluating their adequate performance under operating conditions and determining possible improvements if it is the case. Despite the existence of this recommendation by the NFPA, questions arise such as: what physical modeling tools can be used? What methodology should be followed when conducting performance design for fire prevention using physical modeling tools? How different can the results of the physical modeling tools be from the calculations made according to the prescriptive standards? These questions have not yet been clearly answered and motivate this study.

1.2 Scope and Research Aim

1.2.1 Scope

In this study, the use of physical fire modeling tools is considered as a complement for the prescriptive design of fire protection systems for five case studies with two different configurations in a "type" underground hydroelectric power plant. The design is first conducted in the traditional manner, considering the recommendations and regulatory requirements for this class of power plants. Subsequently, computer simulations were carried out with three physical modeling tools: FDS (K. McGrattan et al., 2020), CFAST (Peacock et al., 2015a), and FLUENT (ANSYS, 2020a).

For the basic hand calculations, the equations established by the regulatory framework of the NFPA are used to estimate the Heat Release Rate (HRR), the volume and temperature of smoke produced, and the location of the exhaust system. Additionally, the pressure and flow of the nozzles of the deluge system are determined.

To evaluate the three physical modeling tools available for the representation of a fire, the different fire scenario studies were simulated, and the characteristics of each physical modelling tool were compared.

The case studies involve two fire scenarios in the transformer cells: a confined fire in the transformer cell and an unconfined fire in the transformer cell.

1.2.2 General Objective

Evaluate the use of physical modeling tools for the design of fire protection systems for an electrical transformer in underground hydroelectric power plant.

1.2.3 Specific Objectives

- Identify the technical characteristics of the different technological tools used for the computational simulation of fires and smoke extraction.
- Evaluate the functionality of at least three (3) fire computer simulation programs in the performance-based design of a fire protection system for an electrical transformer of underground power plant.
- Compare the design procedure and the results of the prescriptive and performance methods for a fire protection system for an electrical transformer of underground power plant.
- Define a procedure for the implementation of performance-based designs in accordance with the requirements presented in the standards and recommendations.

1.3 Document Outline

This document is divided in six chapters. Chapter 1 describes the case study, introduced the problem and the objectives. Chapter 2 presents an introduction to fire protection systems as well as risk analysis in hydroelectric power plants as well as the characterization of the different fire scenarios that occur in underground hydroelectric power plants.

The design, based on recommendations from prescription-design codes, of the smoke-extraction and fire extinguishing-systems for an electrical transformer is presented in Chapter 3. In Chapter 4, the simulation setups in the three different physical modeling tools used in this study are presented and identified.

In Chapter 5 the results of the simulations with the different physical modeling tools are compared. Chapter 6 contains the conclusions of the study carried out and the recommendations for future associated studies.

2 Characterization of Fire Protection Systems and Fire Risk analysis in Hydroelectric Power Plants – A Prescription-based approach

This chapter firstly describes fire protection systems for hydroelectric power plants. A second section presents a simplified fire risk analysis of an electric transformer, that includes a description of the case studies that are analyzed in the simulations.

2.1 Fire Protection in Hydroelectric Power Plants

For a fire of a power plant to take place, four components (the fire tetrahedron) must be present: combustible material, usually lubricant oil, refrigerant oil or cover plastics from cables; an oxidizing substance, usually air; high temperature to facilitate the evaporation process, caused by rotating equipment or electrical components, and a chain reaction that generates the propagation of the reaction.

Fire protection devices are classified, depending on their purpose and application, as passive and active. Those in the first category guarantee the evacuation of people and confine the fire to a certain area, in such a way that the firefighters can better carry out subsequent extinction tasks. These passive protection systems include compartmentation by fire-resistant walls and doors, emergency signals that indicate the available evacuation routes, and emergency lighting that guarantees visibility in high-smoke conditions.

Active protection fire systems have the purpose to protect the assets. Typical components of active protection are the fire detection systems, which use smoke and temperature detectors that constantly monitor site conditions and strobe sirens and alarm bells that notify people when it is time to evacuate. Additional components of active protection systems are extinguishing systems (water, water-foam, inert gases, or hybrid systems), that have the purpose to control and extinguish the fire. Smoke control, pressurization and extraction systems are also active protection systems that are responsible for directing the combustion gases towards a safe area so that a safe evacuation is guaranteed. These systems enhance the fire protection effort.

2.1.1 Design methodologies for fire protection systems

There are different methods to design a fire protection system; the prescriptive design method is based on the use and compliance with regulatory recommendations. This method uses the correlations described in standards and technical documents to determine the fire protection system. These recommendations are generated by expert committees and are periodically updated.

On the other hand, with the increase and improvement of different technologies such as physical modeling tools, Performance-Based Design (PBD) has become available to the FSE community.

In PBD the fire behavior can be represented in several ways. The first is by recreating the real conditions of the fire in a controlled scenario (Liu et al., 2020; Roberson & Stambaugh, 2002). A second approach makes use of scale models that maintain the same behavior conditions as the real fire (Huang et al., 2019). The third approach is based on physical modelling tools (Chi et al., 2011; Lucas, 2009). Simulation by means of physical models is perhaps the most widely used due to its versatility in generating different scenarios and the relative low cost when compared to the other two approaches.

The main difference between these two types of design methods is that prescriptive design focuses on covering different types of risks, without focusing on one. Contrary, performance design represents the design objective, sometimes from its very conception and allows optimization or improvement of protection systems (Duarte, 2004).

An important advantage of prescriptive design is that it does not require great expertise at the engineering level since it does not demand a deep analysis of the results. Furthermore, the need to validate performance-based designs gives prescriptive designs some advantage since they are assumed to be valid for any building and application (Hadjisophocleous & Benichou, 1999). This also makes performance-based designs inherently bound by the prescriptive codes (Maluk et al., 2017).

2.1.2 Fire sources in hydroelectric power plants

A hydroelectric power converts the potential energy that results from the difference in height of the water column between the reservoir and the turbine into kinetic energy through the rotation of a turbine. This kinetic energy is transformed into electrical energy by means of an electrical generator.

According to official data (XM, 2022), Colombia has about 12 GW of installed hydroelectric power capacity of which 11 GW tare centrally dispatched and represent 68% of the Colombian energy basket. Part of this energy (10 GW) is supplied by twenty hydroelectric plants with an effective capacity greater than 50 MW, all with underground power plants. Additionally, these hydroelectric plants have an average life span of 30 years from their start-up, which is why a process of modernization of these plants has been carried out in recent years, a process that has included the design of new fire protection systems.

As **Table 2-1** shows, Colombia registered three out of ten incidents related to fires in underground hydroelectric power plants that were identified worldwide in the refereed literature. Without being a thorough review, **Table 2-1** gives an idea that fire-related incidents are not uncommon in hydroelectric power plants and that fire prevention should be very important in these facilities.

Table 2-1: Compilation of fire accidents in hydroelectric power plants

Country	Power Plant	Year	Description	Victims
Colombia	Central de generación Termosierra del grupo EPM (166 MW)	2021	Battery bank failure. Although the fire did not take place in the hydroelectric generation plant, it is relevant because of the presence of these battery banks in hydroelectric plants (Betancur, 2021).	0
India	Srisailam power plant (900 MW)	2020	Fire due to a short circuit in the generator panels that spread to the generation units (Roushan, 2020)	9 deaths
Colombia	Central hidroeléctrica de Playas de EPM (204 MW)	2017	Fire in the transformer cells that spread to the power plant that kept the plant out of service for almost four months (Cárdenas, 2017)	0
Colombia	Central hidroeléctrica de Guatapé de EPM (560 MW)	2016	Fire in the cable tunnel during splice welding (Arias, 2016)	0
Jaan	JPowers (82 MW)	2015	Fire in communication cables to the dam, which spread to the dam control room (Yasuda & Watanabe, 2017).	Not identified
USA	PSPP (84 MW)	2012	Fire on a cable in the control room that spread to the rest of the control room (Yasuda & Watanabe, 2017).	0
USA	Not identified (100 MW)	2007	A misspecified lightning rod was installed and caused a ground fault. The operator inadvertently recharged the faulty circuit without checking the fault and caused a fire (Yasuda & Watanabe, 2017)	Not identified
USA	Watts Bar power plant (175 MW)	2002	Fire in the vertical cable tunnel that spread to the control building (Yasuda & Watanabe, 2017)	0

Country	Power Plant	Year	Description	Victims
Norway	Not identified (140 MW)	1999	A light fixture in the portal building had a fire that spread to the ceiling and walls (Yasuda & Watanabe, 2017)	Not identified
Taiwan	Dajia-River hydroelectric power plant (234 MW)	1993	Fire in the transformer enclosure that spread to the rest of the power (plant (Chi et al., 2011)	6 deaths and 26 wounded

Figure 2-1 presents the most important fire risks in the powerplant process diagram. The turbine movement is converted to electricity in the generator and transformers and leaves the power plant through the cable trays. The presence of insulation, oil control units, bearings, and battery banks represent fire risk throughout the system.

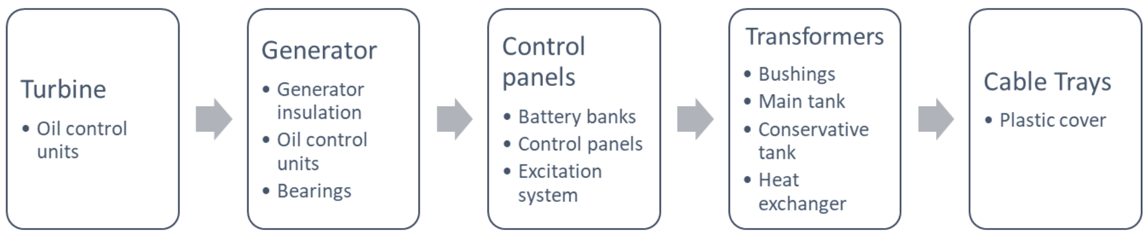


Figure 2-1: Process diagram and fire risk equipment in a power plant

- **Oil control units**

The function of the oil control units is to control the opening and closing systems of the turbine inlet valves and, additionally, to control the braking and synchronization of the generator. Due to the high friction between the generator shaft and the braking systems, this equipment must work at high oil pressures that can generate an increase in temperature and gas production that can cause fire.

- **Generator**

The electric generator converts the kinetic energy of the rotation of the turbine into electrical energy by electrical induction. Since the equipment presents high speeds of rotation, it can present overheating in the windings because of friction and heating in the bearing tanks. Although the cores of modern stators are made of noncombustible materials, the old generators had cardboard portables coated with dielectric oil which were highly combustible.

- **Electrical equipment**

Electrical equipment such as power panels, exciters and power bars serve to carry electrical power from the generator to the transformer. Its greatest risk of fire is related to overheating of components due to an electric arc. These parts are currently manufactured with flame retardant components.

- **Battery banks**

The function of the battery banks is to maintain the charge in the equipment during an emergency to facilitate the correct shutdown of the generation process. The highest risk in this type of device is related to the generation of vapors and hydrogen that that result from an undesired increase in temperature, which can be ignited by a spark inside the room. An electric arc can also be generated that facilitates the fire when the batteries are worn out when completing their charge cycles or due to connection problems in the terminal blocks (Lucas, 2009).

- **Transformers**

Power transformers are responsible for converting the electrical power of generators to facilitate electricity transport. Usually, transformers are insulated in oil and have a water-oil radiator that keeps the equipment cool. Oil is the most critical component in a power plant fire event, due to the high smoke production in a fire of this type and the high volume of fuel to be burned (Duarte, 2004; Lucas, 2009) and this is the reason why this fire event was analyzed in this study (Duarte, 2004; Lucas, 2009).

- **Cable Trays**

The power cables are responsible for carrying the power from the power plant transformers to the substation. Because electrical power is correlated with temperature because of increased resistance, power cables can be susceptible to fire as their coating wears away (Yasuda & Watanabe, 2017).
In older hydroelectric plants, the power cables are covered with oil insulation, which increases the probability of fire as it is a highly combustible element.

2.2 Fire Risk Analysis for an Electric Transformer

The methodology to identify fire scenarios and make the fire risk analysis was adapted from the ISO/T16733 and is shown in **Table 2-2**:

Table 2-2: Methodology to determine fire scenarios

Steps of ISO/TS 16733		Comments
1	Location of fire	Characterize the space in which fire begins as well as the specific location within the space.
2	Type of fire	Characterize the ignition, initial intensity, and growth of potential fires.
3	Potential fire hazards	Identify fire scenarios that could arise from fire hazards associated with the intended use of the property or the design.
4	Systems impacting on fire	Identify the fire safety systems and features that are likely to have a significant impact on the course of the fire or development of untenable conditions. Characterize the initial status of each system or feature.
5	Occupant response	Identify actions that people take that can have significant impact, favorable or otherwise, on the course of the fire or the movement of smoke.
6	Event tree	Construct an event tree that represents alternative event sequences from fire ignition to outcome associated with fire scenarios.

Source: Adapted from SPFE Fire Protection Handbook, 5th Ed. table 38.1 (Hurley, 2015)

2.2.1 Location of fire

The analysis is for a hydroelectric underground power plant that produces 560 MW of electricity with eight units of generation, each one with Vertical axle Pelton turbine and twelve single-phase power transformers. In this work, only half of the transformer cells are shown because the plant is separated in two stages. This plant is representative of others that are active in Colombia and is similar to the ones analyzed in the studies by Liu et al. (Liu et al., 2020) and Huang et al. (Huang et al., 2019).

The plant is located at a height of 1055 meters above sea level (atmospheric pressure of 89278 Pa), with a 2 km-long access tunnel and a level difference of approximately 200 m from the access portal to the power plant. The ambient temperature inside the plant is 35°C when the air conditioning system is off, which is the case in a fire event, and its relative humidity is 55%.

The fire source is assumed to be a power transformer located in a transformer cell. Since all the cells have the same configuration inside, the cell farthest from the extraction system was used for this study, as it is considered to be the most extreme condition for the hallway extraction system. **Figure 2-2** presents a top view of the location of fire and highlights the transformer cell that was assumed to be the fire source. **Figures 2-3** and **2-4** detail the relevant dimensions in the system.

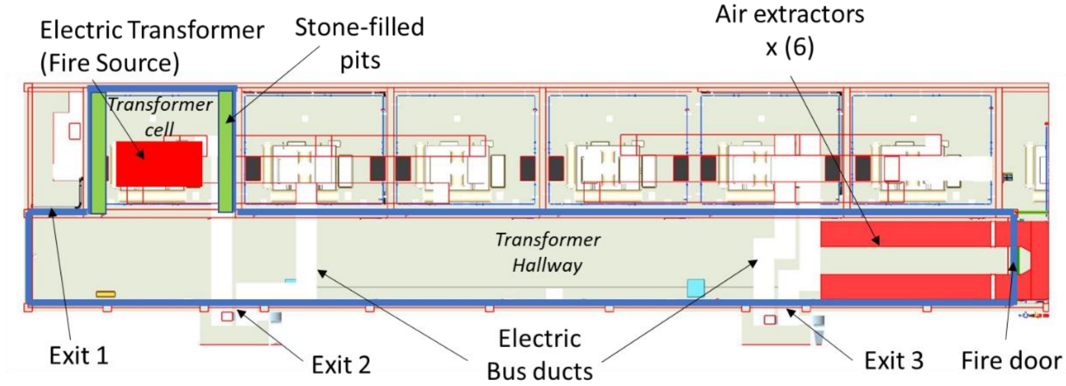


Figure 2-2: General layout of the study scenario - Top view

Figure 2-3: Dimensions of the study scenario – Front View

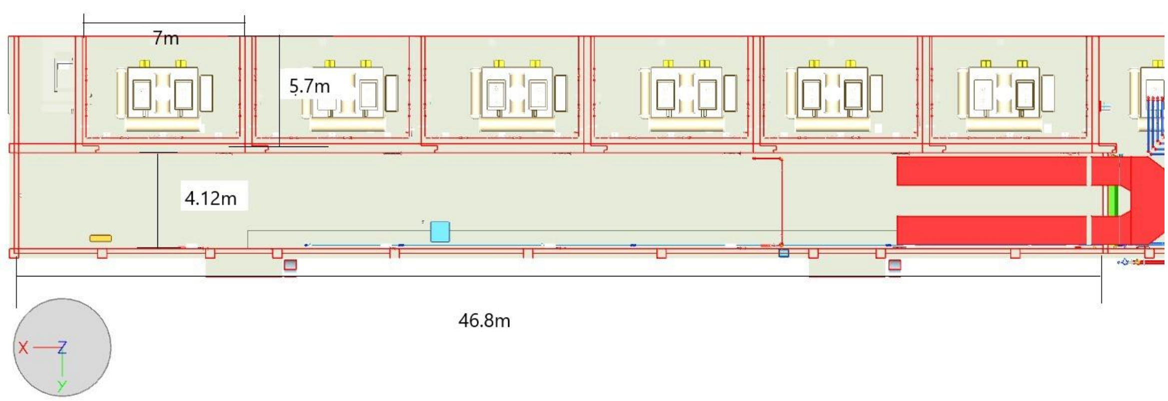


Figure 2-4: Dimensions of the study scenario – Top View

Each transformer cell has concrete fire walls, a metal fire barrier on the front for the transformer entrance, and a fire door for personnel entry. There is an air intake damper above the fire door and on the ceiling of the cell there is a smoke extraction grille, as illustrated in **Figure 2-5**.

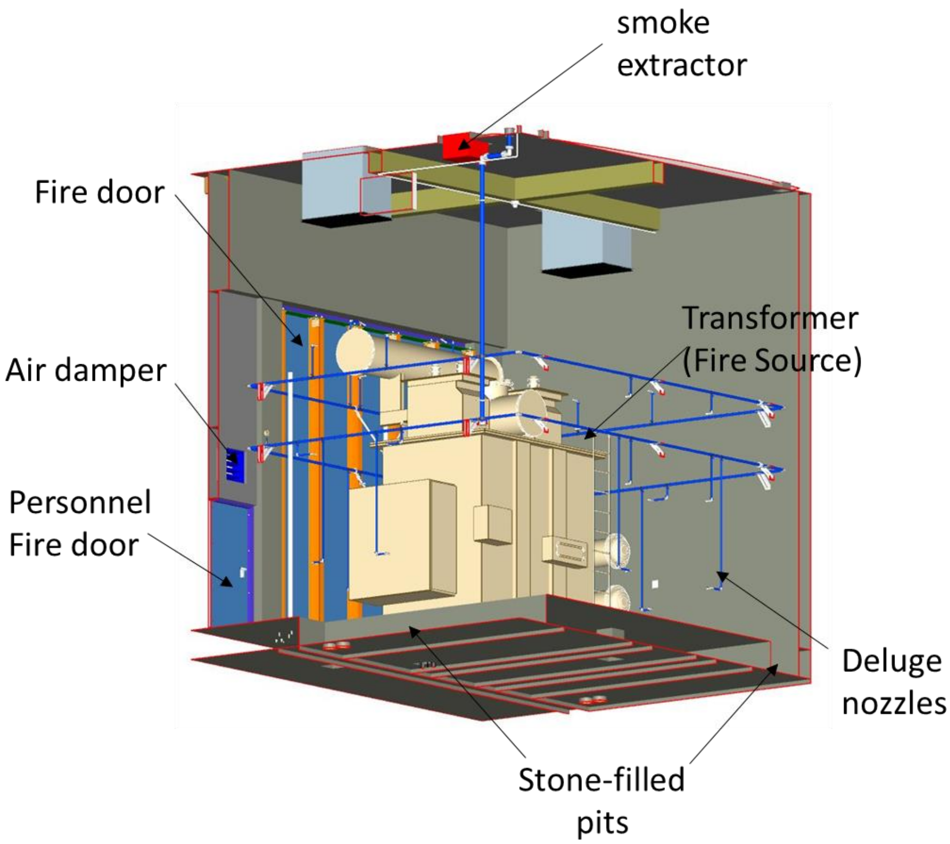


Figure 2-5: Transformer cell configuration

The transformer hallway, as depicted in **Figures 2-6** and **2-7** is confined by concrete walls and ceiling and a fire-resistant roll-up door for the entrance of the equipment. The hallway has three possible evacuation routes, each one with fresh air intake dampers (Exits 1, 2 and 3 in **Figure 2-7**), which open during a fire event in coordination with the extraction system. The first evacuation route (Exit 1) includes three dampers with dimensions Height × Width of 1 m × 1 m, 1.6 m × 0.85 m and 1.1 m × 1 m. Exit 2 contains one damper of 0.5 m × 2.5 m. Finally, Exit 3 is equipped with one damper of 0.5m × 2.5m. The available area of renewal air is 6.6 m^2.

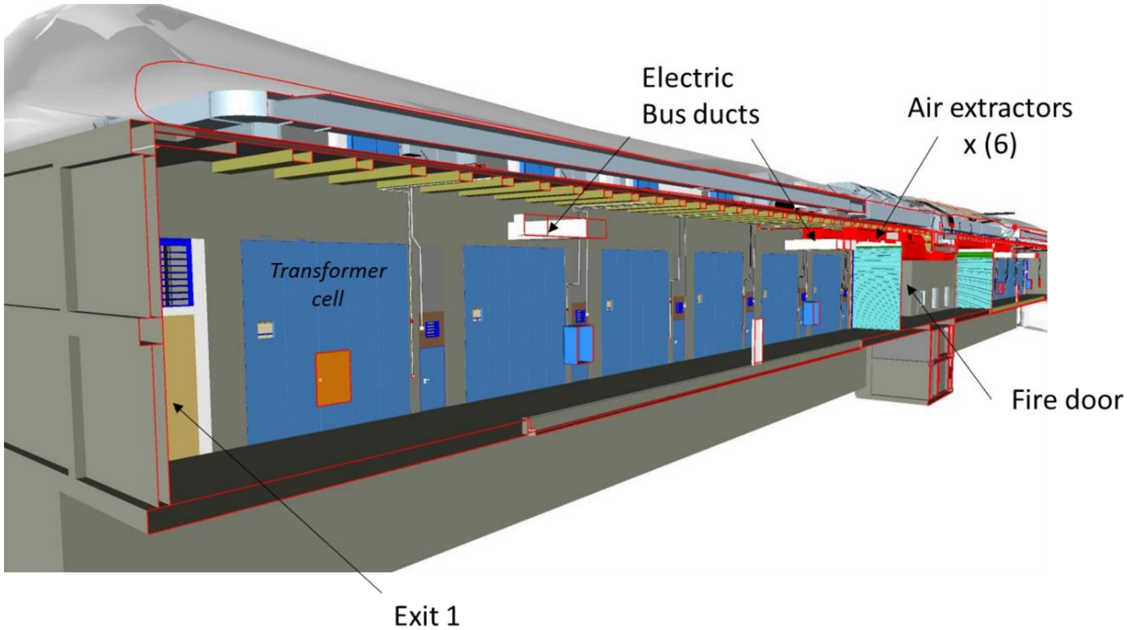


Figure 2-6: Transformer hallway configuration back view

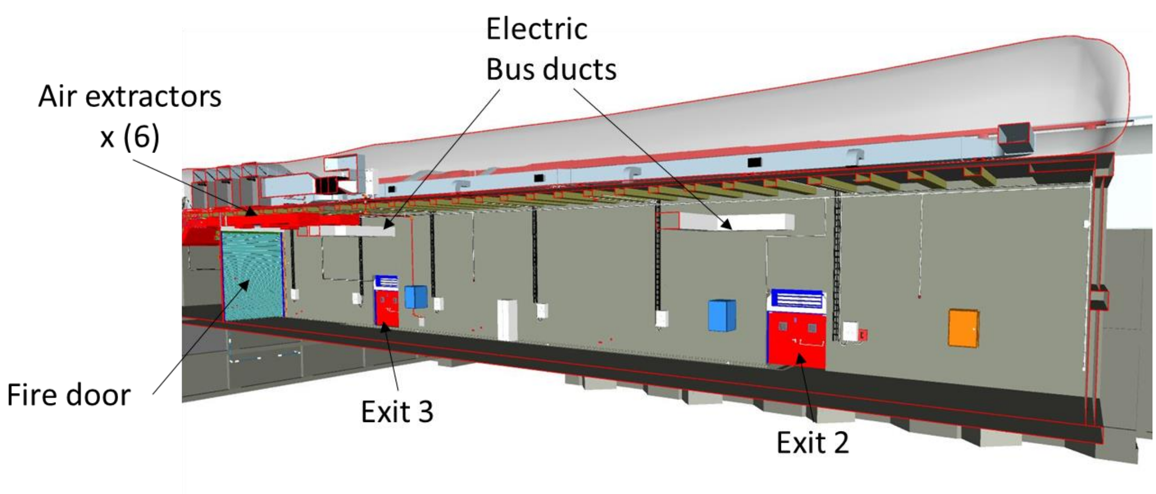


Figure 2-7: Transformer hallway configuration front view

2.2.2 Type of fire

Different fire scenarios have been documented in transformers that may involve pool fires, spray fires or vapor fire clouds, depending on whether there is a rupture of the tank, an overpressure in the relief lines or a release of oil vapors. For this work the fire is considered as a large-scale pool fire, characterized by buoyancy-driven turbulent flames, which is confined to the area of the top cover of the transformer (Darnaculleta, 2019). This is considered as a worst-case scenario as these transformers have a stone-fill pit around the transformer that can suppress the flaming combustion of mineral oil by lowering the flame temperature and controlling the combustion air, that should convert the fire to a vapor fire cloud with a lower intensity (IEEE, 2012) (Working Group A2.33, 2013).

- **Chemical substances characteristics**

The chemical substance acting as the fire source is the transformer's oil, which is a hydrocarbon that has high smoke production, and that is subject to turbulent flows and radiant thermal feedback (Darnaculleta, 2019). A typical transformer oil is a mixture of naphthenics and pharafinics, with a simplified chemical formula of $\mathbf{C_{14}H_{28}}$ (Cao et al., 2021; Kaplan et al., 2010; Lucas, 2009). **R-1** presents the simplified combustion reaction that was assumed to represent the system.

$$C_{14}H_{28} + 20.86\ (O_2 + 3.76N_2)\ \rightarrow 13.71\ CO_2 + 0.29\ CO + 14\ H_2O + 78.41\ N_2 \qquad \text{(R-1)}$$

- **Ignition source characterization**

Fires in hydroelectric plants are grouped into three broad categories: fires in the power plant, fires caused by equipment with oil immersion, and fires in the generator (Yasuda & Watanabe, 2017). In this case the fire is for an equipment with oil immersion.

If a transformer operates above normal conditions, the deterioration of the oil will increase the generation of gases such as hydrogen, carbon dioxide, and carbon monoxide, which create bubbles of pressurized gas that can rupture the transformer tank. In some cases, the deterioration of the oil and the introduction of water molecules and impurities can cause the insulation of the oil to be lost and an electric breakdown to occur (Bishop & Rodriguez, 2011; Cao et al., 2021; Hoole et al., 2017). This electric breakdown can generate a spark and ignite the released gases.

Another possible source of ignition can be generated by an overvoltage in the connection bushings due to deterioration in their insulation or corrosion. The rupture of this seal produces a discharge of oil outside the transformer, producing a large puddle-type fire.

Mechanical damage can also be generated in the transformer cooling system or in the oil recirculation system, causing the oil to overheat (Duarte, 2012).

Table 2-3 shows the technical characteristics of the typical transformer oil used as reference in work.

Table 2-3: Thermal properties of transformer oil

Parameter	Units	Value
Operation temperature	°C	130 (Polužanski et al., 2021)
Oil mass	kg	14000 (own estimate)
Oil volume	m^3	18.81 (own estimate)
Oil density	g/cm^3	0.885 (Zhu et al., 2017)
Heat of combustion	kJ/kg	46400 (Hurley, 2015)
Flash point	°C	152 (Working Group A2.33, 2013)
Soot yield	kg/kg	0.097 (Hurley, 2015)
Carbon monoxide yield	kg/kg	0.041 (Hurley, 2015)

2.2.3 Potential fire hazard

Two fire scenarios have been defined, which have been divided into five case studies according to the following:

- **Fire Scenario 1: Confined fire**

The fire is confined to the transformer cell. There is no explosion of the transformer, and the smoke remains inside of the cell.

- Case study 1: confined fire, no inlet or outlet of air; and the deluge system does not operate.
- Case study 2: confined fire, with inlet of air through a damper located in front of the cell, and a smoke extraction through a damper connected to the smoke extraction system located upper the cell.
- Case study 3: confined fire with smoke extraction, and the deluge system operates.

- **Fire scenario 2: Unconfined fire in transformer cells**

The fireproof enclosure at the front of the cell does not maintain its structural stability and allows the transformer cell to communicate with the access hallway to the transformers. The corridor is in turn confined by the firebreak enclosures and the concrete structures that prevent the smoke from spreading to other areas of the power plant. For this case study, the protection systems implemented in Fire Scenario 1 are not considered.

- Case study 4: unconfined fire in the transformer cells, which spread to the access corridor from the cells. The smoke propagates in the absence of an extraction system.
- Case study 5: unconfined fire in transformer cells with smoke extraction system. All dampers in the hallway are open to allow air entrance.

For this case, a water deluge or sprinkler protection system was not implemented, due to the difficulty in controlling the spilled water in transformers hallway.

Table 2-4: Summary of case studies

		Security system implemented		
Potential Fire Hazard	**Case study**	**Compartmentation**	**Smoke extraction**	**Water deluge**
Confined Fire	Fire scenario 1	X		
	Fire scenario 2	X	X	
	Fire scenario 3	X	X	X
Unconfined fire	Fire scenario 4	X		
	Fire scenario 5	X	X	

2.2.4 Systems impacting on fire

- **Equipment**

A rupture of the tank has instantaneous effects in the vicinity of the transformer, with a radius of affectation to nearby equipment of more than 18 m (Bishop & Rodriguez, 2011). In this case, it would represent an affectation to the electrical panels and the bus ducts that leave the transformer cell.

- **Environment**

The duration of a transformer fire can last from 4 to 28 hours (Bishop & Rodriguez, 2011; El-Harbawi & Al-Mubaddel, 2020); therefore, smoke could cause great damage to the facilities near the fire. Since the case studies are for an underground plant, it is expected that this smoke production will affect the generation equipment and the power plant, but it will not affect nearby water sources or the environment.

- **Security systems**

Power transformers should have safety systems (Working Group A2.33, 2013) that must be installed in accordance with manufacturing regulatory requirements. However, some of the transformers found in hydroelectric power plants do not have safety systems as they were manufactured before current regulations, so they are more susceptible to generating a fire.

Therefore, in accordance with what is indicated in NFPA 850 (National Fire Protection Association, 2020), the following fire protection systems have been implemented in Fire scenarios 2, 3 and 5 to protect each of the transformers: fire-resistant enclosures have been specified in each of the cells and in the hallway, an extraction system inside the cells and in the hallway, and a deluge system for cooling the transformers.

2.2.5 Occupant response

Below are the characteristics of the personnel occupying the facilities, which were defined in accordance with what is indicated by Life Safety Code® (National Fire Protection Association, 2021c).

- Response characteristics

It is expected that inside the power plant there will be the operations and maintenance personnel of the plant, which is personnel with basic training in attention to incipient fires, with familiarity with the environment of the building, distributed throughout the power plant in tasks Maintenance and inspection of main equipment.

They are distributed in a hierarchical structure by positions and functions, in general they are technical personnel, mostly male, aged between 25 and 50 years.

- Location

The personnel are distributed throughout the power plant, the only area that remains occupied all the time is the control room with 2 operators. For a fire in the transformer cells, it is expected that only maintenance personnel will be in the surrounding areas.

- Number of occupants

The maximum occupancy load of the area is 9 m^2/occupant, according to NSR-10 (Asociación Colombiana de Ingeniería Sísmica, 2010) for industrial installations, which for an area of 231.56 m^2 gives a maximum number of occupants of 25.

- Staff assistance

Although all the personnel have basic training in attention to fire outbreaks, there are personnel who have firefighter and first aid training known as "brigadistas" (brigade personnel). There must be at least one brigade member per work shift.

- Emergency response personnel

In addition to the response of the personnel for the evacuation, the response time of the firefighters must be considered. Because these facilities are typically far from principal cities, municipal fire departments are rarely equipped to deal with large fires such as those that take place in underground power plants. In an emergency, it the nearest fire department is 45 kilometers away from the power plant.

- Off-side conditions

There are no hydrants or bodies of water near the entrance to the powerhouse due to its distance from populated centers.

- Consistency of assumptions

It assumes that in a fire event, the rolling fire doors of the hallway will remain closed as well as the fire doors of the cell, and the extraction and deluge systems would be operating.

2.2.6 Event tree

The event tree in **Figure 2-8** shows the sequence of failures that could occur on each of the analyzed fire scenarios. After the fire starts in the transformer, the tree considers four possibilities depending on whether the automatic deluge extinction, the cell smoke extraction, the fire enclosure, and the hallway smoke extraction operate. The answers to these questions are the origin of the five Fire scenarios previously described.

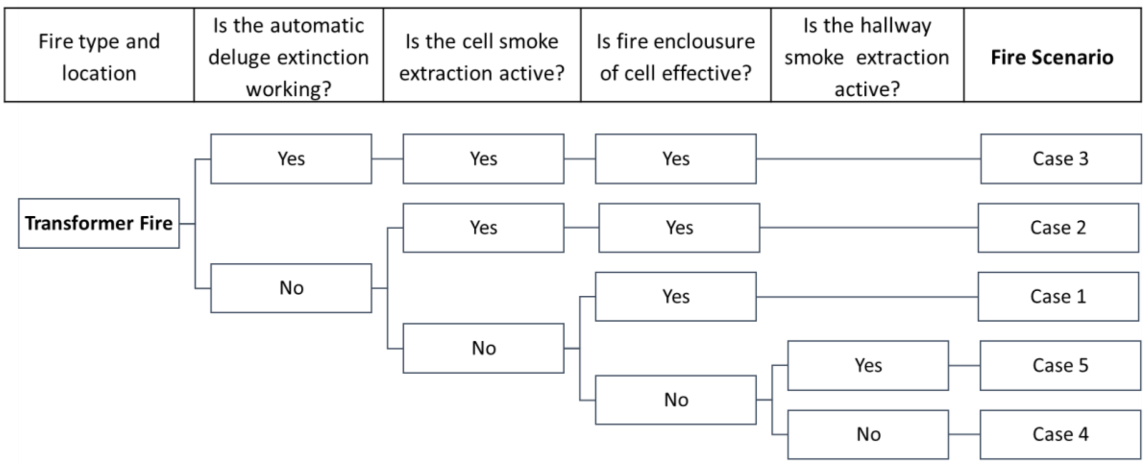


Figure 2-8: Event tree of transformer fire

Source: Own elaboration, adapted from Figure 38.2 Handbook SFPE (Hurley, 2015)

3 Fire Protection Design - Prescriptive Method

This chapter presents the methodology used to carry out the design of the fire protection system through the traditional prescriptive method. As indicated above, the prescriptive design method applies standards, whenever possible, to the design fire protection. In this study, prescriptive recommendations were used to perform analytical calculations of the smoke extraction, deluge fire suppression systems, and evacuation. It is important to clarify that the strict implementation of a prescriptive method calls for the existence of a clear norm in code that can be applied to the design. In the following sections, however, the definition of a prescriptive approach was broadened to include the use of equations and general guidelines present in standardized codes.

The regulatory framework that applies to fire-safety design is determined by each country according to its needs. In the case of Colombia, the regulations corresponding to fire protection systems are framed in NSR 10 that is based on the International Building Code (IBC®) of the United States. However, it has been adjusted according to the needs of the national market.

In this chapter, the calculation of the smoke layer temperatures for a confined fire and an unconfined fire in the transformer cells is carried out and the smoke production rate of the fire source is also calculated, to determine the operative conditions of the smoke extraction system. The operating conditions of the deluge extinguishing system for the transformers are also determined and, finally, the minimum alarm levels are determined and the Required Safe Egress Time (RSET) of personnel is calculated. The goal of this calculation is to compare these predictions with the results obtained from physical modeling tools, as those described below.

Although correlations that describe different fire behaviors, such as those described below, give an approximate result and are not applicable to all fires, they are considered accepted worldwide because they were reviewed by a panel of experts from different disciplines that are part of the National Fire Protection Association of the United States (NFPA) (National Fire Protection Association, 2018), which accredit that these equations can be included for this purpose within NFPA Recommended Practices. These correlations are presented in the same way in the Fire Protection Handbook by the Society of Fire Protection Engineers (SFPE) of the United States (Hurley, 2015), that in addition to this publication has others that are also of interest for this work.

Some associations such as the Institute of Electrical and Electronic Engineers (IEEE) (IEEE, 2012) also carry out studies corresponding to fire protection in the electrical sector industry and have specific standards for their sector. Insurance companies such as the Global Asset Protection (GAP) (GAPS, 2015) and Factory Mutual Insurance Company (FM Global) (FM Global, 2020) , oversee research that creates standards so that their customers improve the security conditions of their assets and thus reduce insurance claims. As these are private recommendations, the following study centered on the NFPA recommendations as those tend to be more universal.

3.1 Applicable Regulations

In Colombia, the applicable standard for the design of fire protection systems is the 2010 Earthquake resistant building code known as NSR-10. This document presents a guide for evacuation and fire protection, it was elaborated and published by the Asociación de Ingeniería Sísmica – AIS (Seismic Engineering Association). Interestingly, the NSR-10 standard does not define a calculation method for the design of the smoke extraction or for fire extinguishing systems. Having been developed in 2010, it does not come as a surprise that the NSR-10 does not consider the use of physical modeling tools in the design of fire protection systems.

The implementation of the requirements of the NSR-10 standard is carried out through the Normas Técnicas Colombianas – NTC (Colombian technical standards) (ICONTEC, 1982, 2009, 2009, 2011) which are identical copies of the NFPA standards. However, they are not updated with the same regularity as the NFPA, so it is usual to go directly to international standards to characterize each of the systems that must be implemented.

The NSR-10 characterizes a hydroelectric plant as an occupation group of the manufacturing and industrial type (F1), for which the installation of automatic sprinklers is exempted as long as the areas between fire walls do not exceed 1000 m^2. Therefore, automatic sprinklers do not need to be installed either in the transformer cell or in the hallway. The NSR-10, however, required that hose outlets and automatic fire extinguishers are distributed throughout the power plant as indicated in NFPA 14 (National Fire Protection Association, 2019) and NFPA 10 (National Fire Protection Association, 2022), respectively.

Regarding the NFPA, the requirements of NFPA 101 (National Fire Protection Association, 2021c) corresponding to human safety are identified, which characterizes the occupation as a Special Purpose Occupation to the Industrial occupancies that are characterized by a relatively low density of employee population, with much of the area occupied by machinery or equipment. Additionally, indicates that it should see recommendations of fire protection in NFPA 850 (National Fire Protection Association, 2020).

According to NFPA 850 (National Fire Protection Association, 2020), oil-filled electrical transformers must be separated from adjacent areas with fire barriers with a fire resistance rating of 3 hours, unless they are protected with an automatic fire suppression system, for which the fire resistance rating can be reduced to 1 hour. Additionally, it is recommended that oil filled electrical equipment should be protected by an automatic extinguishing system such as Automatic sprinkler, foam-water spray, water spray, and compressed air foam systems.

To choose the appropriate extinguishing agent, the following considerations must be considered: type of risk to protect, effect of the discharge in space, and health risks; therefore, it is considered that the most appropriate extinguishing system for this risk is a water deluge system. This is due to, fires in transformers presents high rates of heat and smoke release, which can be reduced more effectively with water than other gaseous agents; also, that a confined space is not required to carry out the discharge and, finally, since the water does not present risks to people's health.

Additionally, it is required that the ventilation systems of underground plants allow the evacuation of exhaust smoke and chemical fumes that may result from fires or their extinction process.

Table 3-1 and **Table 3-2** present the applicable standards for the design of a fire protection system for a hydroelectric power plant.

Table 3-1: Standards that can be applied in the design of fire protection systems for hydroelectric power plants in Colombia

Designation	Title	Reference
NSR 10	Colombian Regulation of Earthquake Resistant Construction (From spanish Reglamento Colombiano de Construcción Sismorresistente)	(Asociación Colombiana de Ingeniería Sísmica, 2010)
NFPA 101	Life safety code®	(National Fire Protection Association, 2021c)
NFPA 850	Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations	(National Fire Protection Association, 2020)
NFPA 72	National Fire Alarm and Signaling Code®	(National Fire Protection Association, 2022c)
NFPA 15	Standard for Water Spray Fixed Systems for Fire Protection	(National Fire Protection Association, 2022b)
NFPA 204	Standard for Smoke and Heat Venting	(National Fire Protection Association, 2021d)

Designation	Title	Reference
NFPA 92	Standard for Smoke Control Systems	(National Fire Protection Association, 2021b)

Table 3-2: Other recommendations that can be applied in the design of fire protection systems for hydroelectric power plants

Designation	Title	Reference
SFPE Handbook of Fire Protection Engineering	SFPE Handbook of Fire Protection Engineering	(Hurley, 2015)
SFPE Engineering Guide to Human Behavior in Fire	SFPE Engineering Guide: Human Behavior in Fire	(Society of Fire Protection Engineers, 2019)
ASHRAE Handbook of Smoke Control Engineering	ASHRAE Handbook of Smoke Control Engineering	(Klote et al., 2012)
IEEE 979	IEEE Guide for Substation Fire Protection Sponsored by the Substations	(IEEE, 2012)
IEEE 1147	IEEE Guide for the Rehabilitation of Hydroelectric Power Plants	(IEEE, 2005)
GAP 17.12.1	GAPS Guidelines GAP 17.12.1 Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations	(GAPS, 2015b)
GAP 5.9.4	GAPS Guidelines GAP 5.9.4 Transformers Surroundings	(GAPS, 2015a)
FM Global DS 7-101	FM Global 7-101 Fire Protection for Steam Turbines and Electric Generators	(FM Global, 2012)
FM Global DS 5-3	FM Global DS 5-3 Hydroelectric power plants	(FM Global, 2020)

3.2 Purpose of Design

The purpose of design of the fire protection system was, as recommended in Chapter J.1.1. of the NSR-10, to focus on providing the necessary conditions to guarantee the safe evacuation of personnel in a fire event, i.e., it is focused on human safety.

3.3 Goal

To evaluate if the extraction system allows to have safe conditions during the evacuation time.

3.4 Fire Design Curve

NFPA describe the heat release rate (HRR) curve as Fire Design Curve (National Fire Protection Association, 2021b) . There are basically two ways to assess the heat release rate (HRR) in fires: analysis and synthesis of experimental data or modelling and fire simulation (Hietaniemi & Mikkola, 2010).

In this case the heat release rate ($\dot{q}$) was calculated with the Babrauskas correlation shown in equation (3-1) (National Fire Protection Association, 2021b).

$$\dot{q} = \Delta h_c \dot{m}''_\infty \left(1 - e^{-k\beta D}\right) \, A \tag{3-1}$$

where,

$\dot{q}$ = heat release rate (kJ/s)

Δh_c = net heat of combustion (kJ/kg)

$\dot{m}''_\infty$ = mass loss rate per unit of area (kg / s * m^2)

$k\beta$ = experimental constant

D = diameter of fire pool fire (m)

A = area of pool fire (m^2)

It is important to clarify that this correlation was developed for pool fires, which usually have a circular dispersion. Because the top of the transformer is square in shape, its area is approximated to a circular area for the purpose of using this relationship.

The values used to determine the heat release rate were taken from the SFPE handbook of fire protection engineering, Table 26.21 (Hurley, 2015). The properties for a generic transformer oil are: Δh_c = 46400 kJ/kg, $\dot{m}''_\infty$ = 0.039 kg / s * m^2, and -kβ = 0.7 m^{-1}.

These empirical constants were determined experimentally. Particularly for the net heat of combustion, it was determined with an oxygen bomb calorimetry, so it would be appropriate to use the effective heat of combustion to assume some rate of incompleteness. However, because there are no realistic large-scale measurements to determine the effective heat of combustion, in this case is used the net heat of combustion (Hurley, 2015).

The area of the fire (A) was considered as that of the top surface of the transformer (A = 2.00 m × 2.85 m = 5.7 m^2) and an equivalent circular fire source of D = 2.69 m was assumed by having similar areas.

Equation (3-1) indicates that the maximum heat release rate of fire is $\dot{q} = 8745.51\ kW$. This value of HRR per unit of area of 1534.3 kW/m^2 is consistent with HRR's of the transformer oil report by Zang (Zhang et al., 2019), shown in **Figure 3-1**, where the estimate HRR (prescriptive) maintains the same slope as the HRR calculated for 50 kW/m^2 and the maximum value remains between the maximum values for 50 kW/m^2 and 20 kW/m^2.

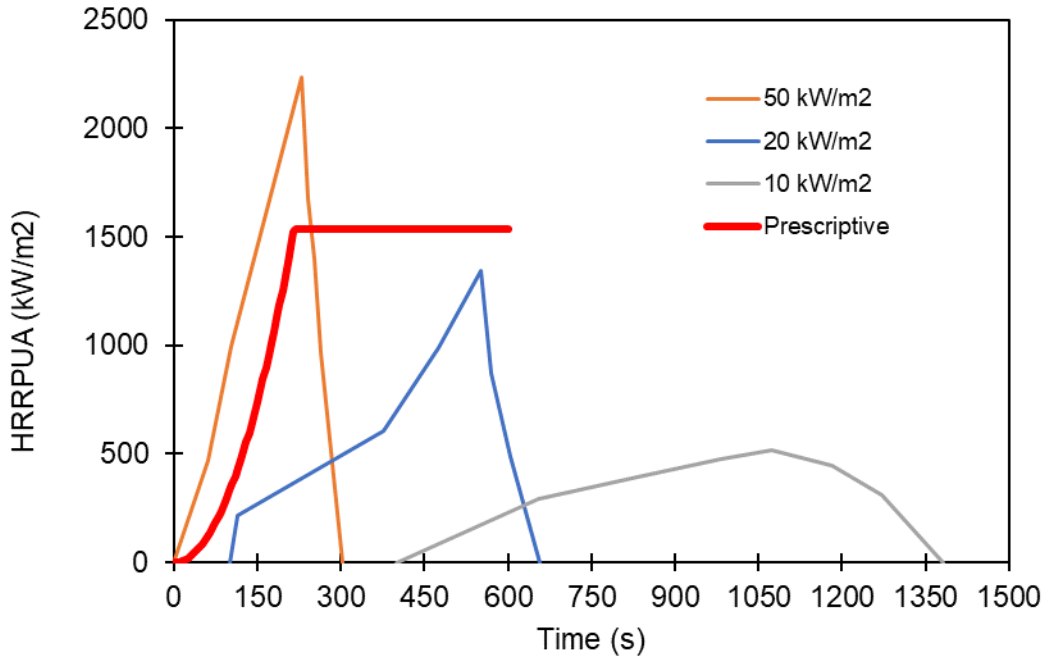


Figure 3-1: Comparison of calculated HRR vs HRR´s of the transformer oils under different external radiative heat fluxes (Zhang et al., 2019)

An unsteady fire model that includes a growth and a steady phase of fire was used to represent the HRR. The growth phase was represented with a t-squared fire growth model as described in Equation (3-2) taken from NFPA 92 (National Fire Protection Association, 2021b), while the value of the HRR for the steady phase region was obtain from Equation (3-1).

$$\dot{q} = 1055 \left(\frac{t}{t_g}\right)^2 \tag{3-2}$$

where:

$\dot{q}$ = heat release rate of design fire (kW)

t = time after effective ignition (s)

t_g = growth time (s)

The growth time (t_g) was 75 s as an oil transformer fire is considered as an ultra-fast fire (National Fire Protection Association, 2021b). The time after effective ignition that is the time to reach the steady state was calculated as t_{ss} = 215.94 s from Equation (3-2).

The duration for the steady phase was estimated from Equation (3-3) (National Fire Protection Association, 2021d):

$$\triangle t = \frac{m * \Delta h_c}{\dot{q}} = 74278\ s = 20.6\ hours \qquad (3\text{-}3)$$

Even though the fire has a very long duration, only the first 10 minutes were analyzed given that, as previously explained, the goal of the fire-control system is guaranteeing the safety of the personnel.

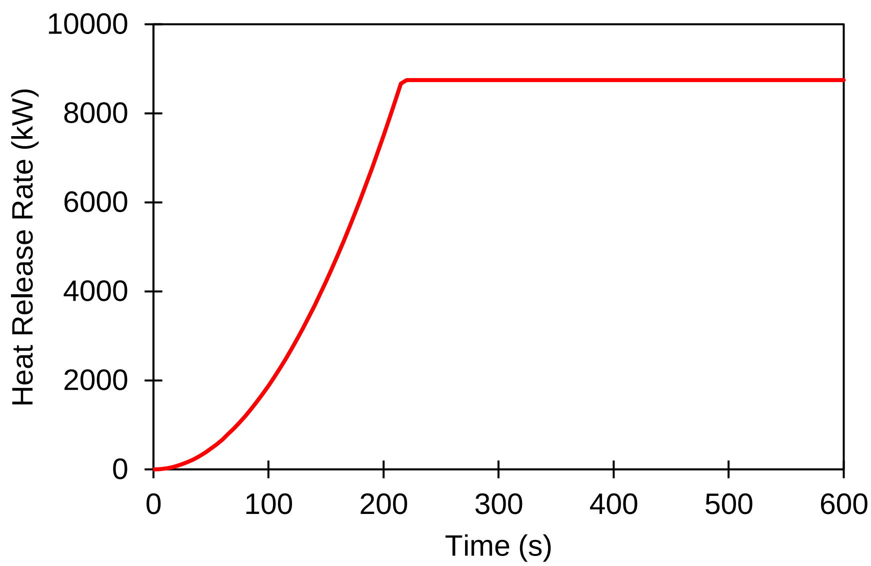


Figure 3-2: Estimated heat release rate for the generic transformer oil used in this work

This case is the most extreme behavior of the fire, which would be considered an unlikely case from the point of view of the behavior of a pool fire in a transformer cell. This is because, as good practice in the electrical industry, for power transformers there is a "bed" of stones around the transformer and under it in some cases, in such a way that in case of a transformer malfunction, e.g., a fire, the oil is directed to it by the effect of gravity (National Fire Protection Association, 2020). This bed of stones has two purposes: the first is to allow the correct drainage of the water from the deluge system, and in the case of the outdoor transformers, to allow the drainage of rainwater. The second purpose is to serve as a support system for extinction of the transformer fire, separating the fuel element (oil) from the oxidizer (oxygen).

Due to the above, an HRR with a lower upper limit than the one shown in this work would be expected. In APPENDIX B, a sensitivity analysis is presented for the fire scenario 2 (confined fire with smoke extraction) in which the variables of the heat release rate per area unit (HRRPUA) and the time in which the maximum value of HRR is reached for a fire of the t-squared type (TAU_Q) were modified. The use of a sensitivity analysis agrees with the recommendations in NFPA 1 (5.7.7), Fire code (National Fire Protection Association, 2021a).

3.5 Smoke Extraction

The goal of the smoke extraction system design is to estimate the mass flow of smoke and its temperature so that a safe exhaust system can be designed. The calculations are different for the confined and unconfined scenarios.

3.5.1 Confined fire

In a confined fire the smoke volume to extract can be easily found from the recommendation of the insurance company Global Asset Protection services – GAP (GAPS, 2015b). GAPS recommends for areas with heavy smoke-generating capability, such as those that include an oil-bearing transformer, a smoke removal system with a capacity of 4 cfm (cubic feet per minute) for each ft^2 of floor area (1.2 m^3/min for each m^2 of floor area), this represents 1.53 m^3/s for the confined scenario. Equation (3-4) can be used to compute the mass of smoke released when the density is assumed as 1.225 kg/m^3 at a temperature of 308 K.

$$\dot{m}_g = \dot{V},ext * \rho,To \tag{3-4}$$

where:

$\dot{m}_g$ = gas flow rate out the opening (kg/s)

$\dot{V},ext$ = volume of extraction

ρ,To = density of smoke layer

$$\dot{m}_g = 1.87425 \left(\frac{kg}{s}\right) \tag{3-5}$$

Equation (3-6) was used to determinate the temperature of the smoke layer in a confined fire (Hurley, 2015):

$$\frac{\triangle T_g}{T_\infty} = 0.63 \left(\frac{\dot{q}}{\dot{m}_g C_p T_\infty}\right)^{0,72} \left(\frac{h_k A_T}{\dot{m}_g C_p}\right)^{-0,36} \tag{3-6}$$

where:

T_g = temperature of the upper gas layer (K)

$\dot{m}_g$= gas flow rate out the opening = 1.87 kg/s

C_p= Specific heat of gas (it was assumed 100% air at 308 K) = 1.005 kJ/kg*K

T_∞= ambient temperature = 308 K

Equation (3-7) (Hurley, 2015) was used to estimate the convective heat transfer coefficient to the walls, h_k:

$$h_k = \left(\frac{k\,\rho\,c}{t}\right)^{1/2} \; for\; t < \; t_p \tag{3-7}$$

where:

ρ = density of the compartment surface = 2400 kg/m^3 for concrete (Hurley, 2015)

c = specific heat of the compartment surface material = 1 kJ/kg*K for concrete (Hurley, 2015)

k = thermal conductivity of compartment surface = 0.0014 kW/m*K for concrete (Hurley, 2015)

t_p = thermal penetration time (s) = $\left(\frac{\rho\, c}{k}\right)\left(\frac{\delta}{2}\right)^2$ (Hurley, 2015)

Because the HRR increases up to a maximum value, the temperature also attains an almost constant value at approximately 200 s. At this point the temperature slowly increases as the value of h_k, in the denominator in Equation (3-6), decreases with time (see Equation(3-7)). This could probably reflect an increase in the wall temperature with time. **Figure 3-3** presents the predicted variation of temperature with time.

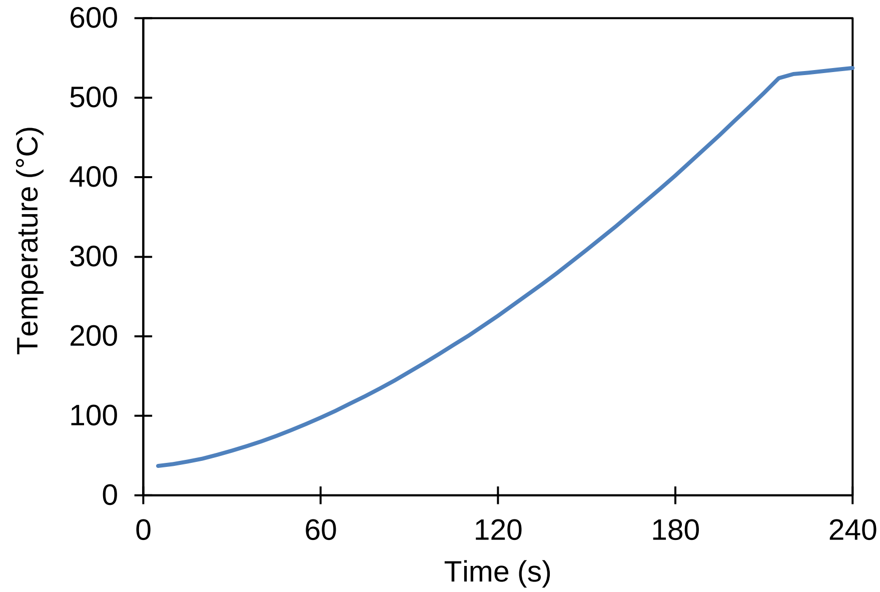


Figure 3-3: Predicted temperature of the smoke gas layer – Confined fire – prescriptive

3.6 Unconfined Fire

An unconfined space requires a different set of equations to predict the smoke-layer temperature and the smoke volume. T_s in Equation (3-8) corresponds to the predicted average temperature of the smoke layer for the unconfined fire that spreads to the transformer hallway (National Fire Protection Association, 2021b).

$$T_s = T_\infty + \frac{K_s \, \dot{q}_c}{\dot{m} \, C_p} \tag{3-8}$$

where,

Ts = smoke layer temperature (°C)

T_∞ = ambient temperature (°C)

K_s = fraction of convective heat released by the smoke layer. This value was assumed as 0.5 based on recommendations in the NFPA 92 (National Fire Protection Association, 2021b) for non plug-holing fires.

$\dot{q}_C$ = convective portion of the heat release rate (kW), was estimated from Equation (3-9).

$\dot{m}$ = mass flow rate of the plume at elevation z (kg/s)

C_p = specific heat of plume gases (it was assumed 100% air at 308 K) = 1.005 kJ/kg*K

$$\dot{q}_C = X\,\dot{q} \tag{3-9}$$

where,

X = convective fraction, approximated as 0.7. (National Fire Protection Association, 2021b)

$\dot{q}$ = heat release rate (kW), taken from Equation (3-1).

Equations (3-10) and (3-11) were used to determinate the mass flow rate in the plume as a function of the distance between the smoke layer and the limiting elevation.

$$When\ z > z_l\ , \qquad \dot{m} = \left(0.071\,\dot{q}_C^{\ 1/3}\,z^{5/3}\right) + 0.0018\dot{q}_C \tag{3-10}$$

$$When\ z < z_l\ , \qquad \dot{m} = 0.032\dot{q}_C^{\ 3/5}\,z \tag{3-11}$$

where,

z_l = limiting elevation (m) = $0.166\dot{q}_C^{\ 2/5}$ (National Fire Protection Association, 2021b)

z = distance above the base of the fire to the smoke layer interface (m) = 2 m.

$\dot{m}$ = mass flow rate of the plume at elevation z (kg/s).

Figure 3-4 shows how the predicted temperature of the smoke layer increases with time. The maximum temperature obtained is around 289°C. As expected, the smoke layer temperature for an unconfined fire is significantly lower than that of the confined fire in **Figure 3-3**.

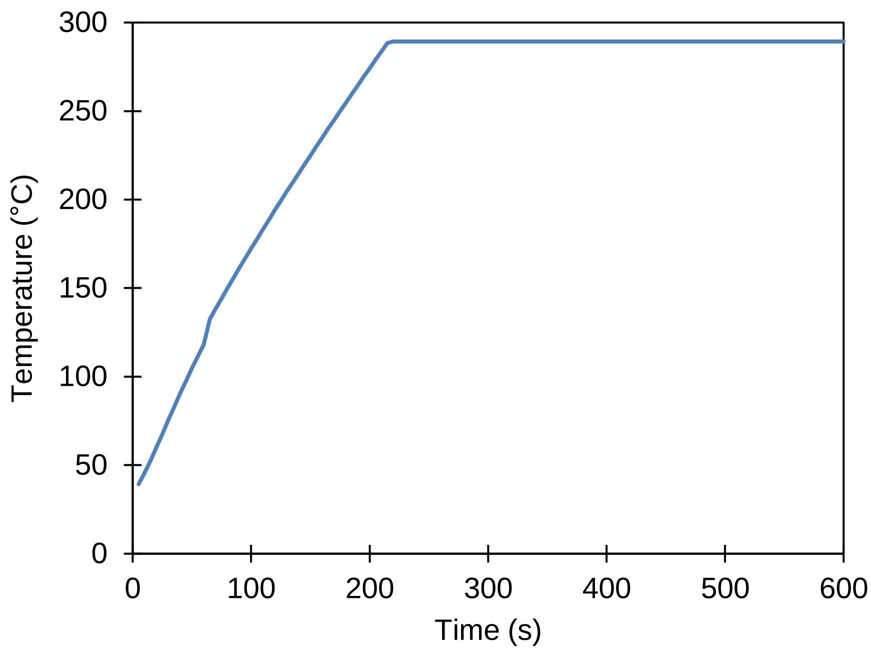


Figure 3-4: Temperature of smoke gas layer – Unconfined fire– prescriptive method

Equation (3-12) relates the volumetric flow to the mass flow. (3-12)

$$\dot{V} = \frac{\dot{m}}{\rho} \quad (3\text{-}12)$$

where,

$\dot{V}$ = volumetric flow rate of smoke exhaust (m^3/s)

$\dot{m}$ = mass flow of smoke exhaust (kg/s), taken from equations (3-10) y (3-11).

ρ = density of smoke (kg/m^3)

The density of smoke was calculated using the ideal gases equation:

$$\rho = \frac{P_{atm}}{R\,T} \quad (3\text{-}13)$$

where,

ρ = density of smoke (kg/m^3)

P_{atm} = atmospheric pressure

R = gas constant (it was assumed 100% air) = 287 Pa m^3/ Kg K

T = Absolute temperature of smoke (K) **Figure 3-4**

Replacing the density value in Equation (3-12), the volumetric flow of smoke for non-confined fire was estimated as $\dot{V}$= 21.61 m^3/s.

To determine the number of extraction dampers to be installed in the hallway, particular attention must be paid to preventing the plug-holing phenomenon from occurring in the area close to extraction. Therefore, the following correlation (National Fire Protection Association, 2021b) was applied for 2, 4 and 6 extraction dampers. The configuration for two and four dampers was discarded because, they exceeded the 2 m separation restriction between the dampers that is in place, to avoid the plug-holing.

$$S_{min} = 0.9\, \dot{V_e}^{1/2} \tag{3-14}$$

where,

S_{min} = minimum Edge-to-edge separation between inlets (m)

$\dot{V_e}$ = volume of flow rate of one exhaust inlet (m^3/s)

According to the above, for the site conditions, the minimum distance between the extraction dampers was estimated as 1.7 m for six extraction dampers (two lines of three dampers).

3.7 Water Fire Suppression

As the NFPA 850 (National Fire Protection Association, 2020) recommends different types of extinguishing systems for electrical transformers, such as automatic sprinkler, foam-water spray, water spray, and compressed air foam systems, has been decided to use a deluge water spray system with open nozzles distributed around the transformer, in such a way that they cover its entirety. The foregoing is due to the fact that its implementation and maintenance cost is lower than the others, it does not require confinement of spaces, and it has a great availability of water in a hydroelectric power plant.

To define the discharge factor K, a commercial nozzle with the following in **Table 3-3** was used:

Table 3-3: Configuration of deluge nozzles for water extinction

Parameter	**Units**	**Value**
Flow rate	L/min	30.28
K-factor	(L/min)/$\sqrt{bar}$	25.9
Orifice diameter	m	0.00635
Spray angle	°	47.5

The time of response of the deluge system was determined based on the NFPA 15 (National Fire Protection Association, 2022b), that under test conditions, the heat detection system, when exposed to a heat source or an open pilot sprinkler line test valve, shall operate the system actuation valve within 40 seconds.

The nozzles were distributed to maintain a discharge rate around the transformer of 10.2 (L/min)/m^2 defined in NFPA 15 (National Fire Protection Association, 2022b).

The heat release rate after the discharge of water deluge system was approximated according to Equation (3-15) (Yu et al., 1994). This equation indicates that decreases of HRR during extinction is function of time and k.

$$\dot{Q}\ (t) = \ \dot{Q}_{,0}\ \exp[-k\ (t - to)] \qquad (3\text{-}15)$$

where,

$\dot{Q}\ (t)$ =total heat release rate at time (t)

$\dot{Q}_{,0}$ = total heat release rate at time (t_0) of water application

k is an empirical parameter that can expressed as follows (Yu et al., 1994):

$$k = \frac{\alpha\left(\dot{m}''_w \ Q_w - \beta \, \dot{m}''_f \, \Delta Hc + \dot{m}''_f Qp\right)}{\rho_f \, C(Tp - T\infty)} \tag{3-16}$$

where,

ρ_f = fuel density (kg/m^3)

C = specific heat of fuel (kJ/kg K)

ΔHc = net heat of combustion (kJ/kg)

T_p = average temperature of layer of the fuel undergoing pyrolysis (K)

T_∞= initial temperature of the fuel (K)

α = ratio of the total burning surface area versus the total volume of fuel under pyrolysis

β= fraction of the total heat release rate transferred to the fuel surface

$\dot{m}''_f$ = average burning rate per unit burning surface area (kg /s m^2)

$\dot{m}''_w$ = average water evaporation per unit burning surface area (kg /s m^2)

Q_w = heat of evaporation of water (kJ/kg)

Qp = heat of pyrolysis (kJ/kg)

As the parameter k depends on many variables that are not readily available, it is normally simplified by Equation (3-17) (Khoat et al., 2020).

$$k\ (t) = E_{COEFFICIENT}\ \dot{m}''_w\ (t) \tag{3-17}$$

where,

$E_{COEFFICIENT}$ = extinguishing coefficient (m^2/(kg s)

$\dot{m}''_w\ (t)$ = local water mass flow per unit area. (kg/m^2)

As previously identified, the extinction coefficient depends not only on the fuel properties and geometry, but also on the water droplet size, spray angle, and initial velocity. While the value for $E_{COEFFICIENT}$ can be as high as 16.4 m^2/(kg·s) (Lee, 2019) and as low as 0.5 m^2/(kg·s) (Khoat et al., 2020) a more common value is 1 m^2/(kg.s) (Hamins & Mcgrattan, 2003; K. McGrattan et al., 2020). Therefore, given the high extinction properties of deluge nozzles the extinction coefficient used was 1.

3.8 Human Safety

3.8.1 Levels of alarm in fire events

In underground plants, most deaths are related to toxic smoke, rather than fire. This happens because of the low availability and long distance of the evacuation routes (Liu et al., 2020). Therefore, the effects to personnel because of the fire must be considered.

There are some conditions that compromise the safety of humans in fire events. These conditions depend both on thermal conditions such as fire temperature and radiation, and on combustion products. **Table 3-4** presents values where the risk is evident for human safety. An air temperature over 60°C is the highest temperature at which 100% water-vapor saturated air can be breathed. Low levels of oxygen O_2 can cause hypoxia, a concentration lower than 14% oxygen can cause an increase in ventilation/heart rate. CO_2 stimulates breathing, a concentration up to 6% increases approximately 3 times the respiratory rate; this causes the person to enter more combustion pollutants such as CO and HCN into the body. High concentrations of CO_2 can also displace oxygen and cause hypoxia. Carbon monoxide combines with hemoglobin in the blood to form carboxyhemoglobin (COHb), which results in toxic asphyxia. A concentration of CO greater than 3000 ppm can cause asphyxia during the first 5 minutes. Higher CO concentrations are lethal in shorter periods of time.

Finally, a radiative heat flux of 2.5 kW/m^2 causes on people a tolerable intensity for first 5 minutes or severe pain above 5 minutes of exposure.

Table 3-4: Alarm values to human safety

Description	**Designation**	**Risk Level**	**Source**
Temperature	T	> 60 °C	(Society of Fire Protection Engineers, 2019)
Oxygen	O_2	< 14%	(Society of Fire Protection Engineers, 2019)
Carbon dioxide	CO_2	> 5 %	(Hurley, 2015)

Description	Designation	Risk Level	Source
Carbon Monoxide	CO	> 3000 ppm	(Society of Fire Protection Engineers, 2019)
Radiative heat	Q,r	> 2.5 kW/m2	(Chi et al., 2011)

3.8.2 Evacuation time

The values presented in the previous numeral must be considered to determine the available safe exit time (ASET) which will be calculated by the physical model tools in Chapter 4. ASET presents the following relationship:

$$\mathrm{ASET} > \mathrm{F\ x\ RSET} \tag{3-18}$$

where,

ASET = time available for an individual occupant to escape or move to a safe location

RSET = time required for an individual occupant to escape or move to a safe location.

F = safety factor = 2 (Hadjisophocleous & Benichou, 1999)

The required Safe Egress Time (RSET) was calculated using Equation (3-19) (Hurley & Rosenbaum, 2015):

$$\mathrm{RSET} = \mathrm{td} + \mathrm{ta} + \mathrm{to} + \mathrm{ti} + \mathrm{te} \tag{3-19}$$

where,

td = time from fire ignition to detection

ta = time from detection to notification

to = time to notification until occupants decide to take action

ti = time from decision to take action until evacuation commences

te = time from the start of evacuation until it is complete.

According to the SFPE Handbook of Fire Protection Engineering (Hurley, 2015), this equation can be simplified as:

$$\mathrm{RSET} = \mathrm{t}_{p-e} + \mathrm{t}_{e} \tag{3-20}$$

where,

t_{p-e}= time in pre-evacuation phase

t_{e}= time in evacuation phase

Ronchi (Ronchi et al., 2019) determined the evacuation time of an underground physics research facility and used a speed of 1 m/s to estimate the evacuation time because these locations do not involve children nor older adults. The same authors estimate the pre-evacuation time as 180 s (Ronchi et al., 2019). Leonita (Leonita et al., 2017) recommended for evacuation through stairs in high buildings a maximum scape velocity of 0.75 m/s to calculate the time of pre-evacuation, Equation (3-21), as presented by Chi (Chi et al., 2011), was used.

$$\mathrm{t}_{p-e} = \frac{\sqrt{\sum A_{area}}}{30} = \frac{\sqrt{A_{cell} + A_{hallway}}}{30} \tag{3-21}$$

where,

A_{area} =total area of evacuation zone

A_{cell} = total area of transformer cell

$A_{hallway}$ =total area of transformer’s hallway

Figure 3-5 presents the most critical evacuation route for the fire event presented in this work. This path was used to calculate the distances and areas relevant in equations (3-20) and (3-21).

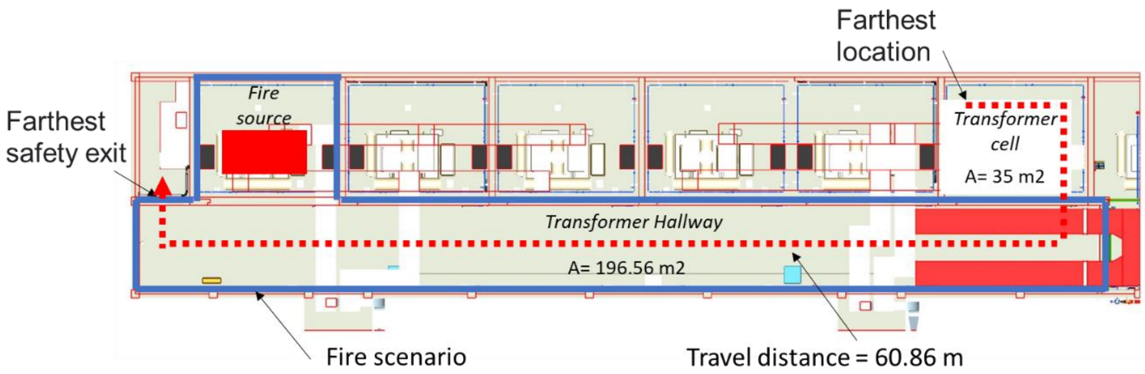


Figure 3-5: Proposed evacuation route for the RSET calculation

According to **Figure 3-5**, the area of the transformer cell is 35 m^2 and the area of transformer's hallway is 196.56 m^2, for a time in pre-evacuation phase (t_{p-e}) of 0.5 min (30 s), according to Equation (3-21).

The evacuation time (t_e) was estimated with Equation (3-22).

$$t_e = \frac{l}{S} \tag{3-22}$$

where,

t_e= time in evacuation phase

S = speed along the line of travel

l = travel distance of **Figure 3-5**

The speed is calculated with Equation (3-23):

$$S = k\,D \tag{3-23}$$

where,

S = speed along the line of travel

D = population density in persons per unit of area = 0.11 p/m^2 (Table K.3.3-1 -NSR10)

k = constant = 1.4 for corridor (table 59.2 Handbook Fire protection SFPE)

The calculated speed along the line of travel was 1.19 m/s. and the time to evacuee (t_e) as 51 s.

The required Safe Egress Time (RSET) was estimated as 81 from Equation (3-20) and considering a safety factor F=2 (Hadjisophocleous & Benichou, 1999), the minimum Available Safe Egress Time (ASET) should be over 162 s from Equation (3-18).

4 Application of Physical Modeling Tools to fire protection design

Physical modelling tools (PMT) can represent very different fire events as they allow changes in fire power, environmental conditions, number of control volume entrances and exits, rate of smoke extraction, and type of extinguishing systems. The PMT used for fire simulation can be divided in those based on computational fluid dynamics (CFD) such as the Fire Dynamics Simulator (FDS)(K. McGrattan et al., 2020), and JASMINE (BRE-Group, 2019), and zone models such as the Consolidated Fire and Smoke Transport (CFAST) (Peacock et al., 2015a) and B-RISK (BRANZ, 2023)(formerly BRANZfire) from the Building Research Association of New Zealand. It is also possible to model fires with traditional CFD models such as Open Foam (WiKi, 2021), ANSYS FLUENT (ANSYS, 2020a) or Star-CD (3dcadportal.com, 2014).

Vallejo-Molina presents a detailed review of the different physical simulation tools available for modeling fires and explosions (Vallejo, 2023). Other authors have also compared different PMTs, to address, mainly, the differences between general CFD codes and FDS (Binbin, 2011; Edin & Ström, 2019; Hui Zhong & Tunku Abdul Rahman, 2013).

While it would be interesting to test all available PMT for fire modeling, that is an impossible task for the timeframe of this monograph, this study focuses on three PMTs: (1) CFAST as an archetypical zone model, (2) FDS as it is, arguably, the most used software for fire simulation, and (3) ANSYS-FLUENT as an example of how general CFD tools can be used to represent a fire.

Appendix A shows the variables and materials that have been used in the computational calculations.

4.1 Fire simulation with FDS

The simulations carried out used the version FDS 6.7.9 of Fire Dynamics Simulator. This is an open-source code developed by the National Institute of Standards and Technology (NIST) of the United States. It is a CFD (Computational Fluid Dynamics) fire model that solves the equations of Navier-Stokes of mass balance and energy by the method of finite elements with emphasis on heat and smoke transport for fires. It solves the turbulence model by Large-Eddy Simulation (LES) for low-speed flows, by default. FDS uses a structured mesh in which it is possible to use multiple meshes.

FDS involves the use of the Smokeview (SMW) program (Forney, 2022), version 6.7.21, also developed by NIST, as a results viewer.

Equations (4-1) to (4-4) present the conservation equations used by FDS (K. B. McGrattan, 2006a).

- Mass continuity

$$\frac{\partial \rho}{\partial t} + \nabla * (\rho u) = \dot{m}_b''' \tag{4-1}$$

Where $\dot{m}_b'''$ is the production rate of species

- Species concentration (mass fraction)

$$\frac{\partial \rho Y_\alpha}{\partial t} + \nabla * (\rho Y_\alpha u) = \nabla * (\rho D_\alpha \nabla Y_\alpha) + \dot{m}_\alpha''' + \dot{m}_{b,\alpha}''' \tag{4-2}$$

- Momentum transport

$$\frac{\partial \rho u}{\partial t} + \nabla * (\rho \mathrm{uu}) = -\nabla \tilde{p} - \nabla * \tau + (\rho - \rho_0) g \tag{4-3}$$

- Sensible enthalpy transport

$$\frac{\partial \rho h_s}{\partial t} + \nabla(\rho h_s u) = \frac{D\bar{p}}{Dt} + \dot{q}''' - \nabla * \dot{q}'' \tag{4-4}$$

Combustion (Equation (4-5)) and radiation (Equation (4-6)) are introduced into the governing equations via source terms, $\dot{q}'''$and $\dot{q_r}'''$ into the energy transport equation.

$$\dot{q}''' = -\sum_{\propto} \dot{m}_{\propto}''' \Delta h_{f,\alpha} \tag{4-5}$$

The heat release rate per unit of volume is defined by summing the lumped species mass production rates time their respective heat of formation.

$$\dot{q}_r''' = k(x)[U(x) - 4\pi I_b(x)] \quad ; \quad U(x) = \int_{4\pi} I(x, z')ds' \tag{4-6}$$

- Ideal gases

$$\bar{p} = \frac{\rho T R}{\overline{W}} \tag{4-7}$$

4.1.1 Simulation constraints

The following considerations were required to carry out the simulations with FDS:

- The fire is confined to the limits of the fire cell and hallway.
- The transformer oil is the only fuel in the transformer cell.
- The air extraction speed remains constant throughout the simulation.
- The deluge system, this is automatically activated 40 s after the start of the fire and all the nozzles start the discharge of water simultaneously as indicates in NFPA 15 (National Fire Protection Association, 2022b).
- The physical and chemical properties of the transformer oil were assumed to be those of $C_{14}H_{28}$, from Equation (R-1)

4.1.2 Geometry

- **Fire scenario 1**

In this case the outer geometry of the cell was represented as a cube of dimensions of 5.75 m × 7 m × 7 m with adiabatic walls. The fire source was established at the top of a cube that represents the transformer tank. The transformer conservator tank was also added to the model as part of the possible interference that may occur.

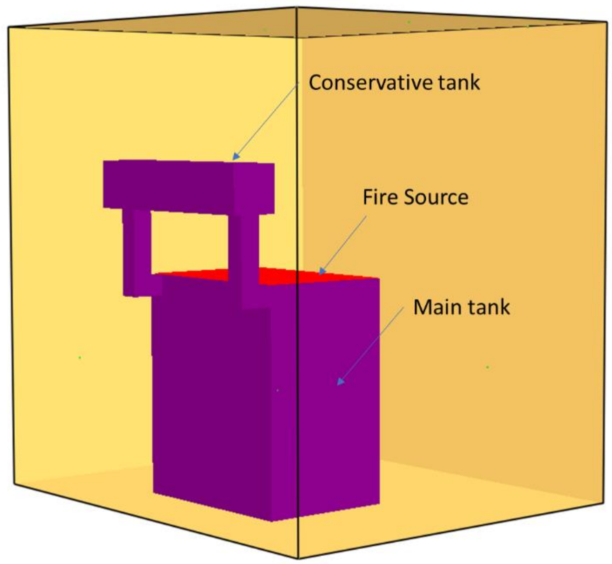


Figure 4-1: Geometry for the FDS simulation of the Fire scenario 1 – Confined fire

- **Fire scenario 2**

In this scenario a smoke extraction window was added to the geometry in Fire scenario 1 at the top (50 cm × 50 cm) and an air passage at the front to represent the air intake damper (50 cm × 50 cm) the model was extended to the outside of the cell to allow calculation of the intake air. Additionally, fire doors were added to the front of the cell, to which the properties of steel were assigned.

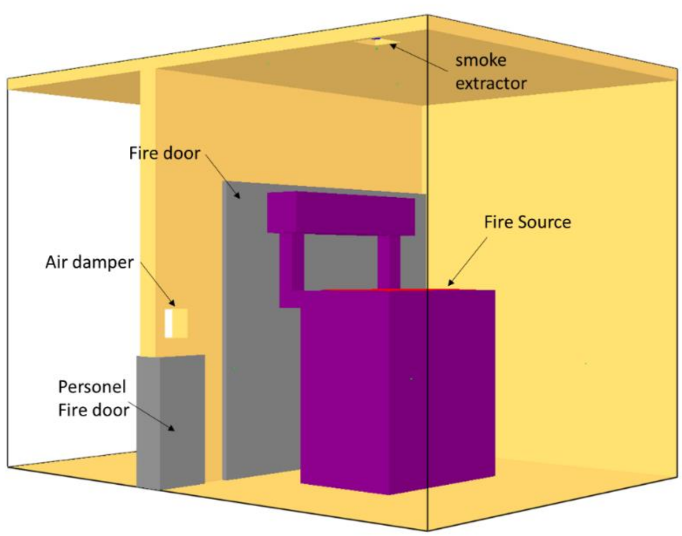


Figure 4-2: Geometry for the FDS – Fire scenario 2 – Confined fire with smoke extraction

- **Fire scenario 3**

This fire scenario adds to Fire scenario 2 the nozzles corresponding to the deluge system which are programmed in the FDS to be displayed in the SMV as small nozzles.

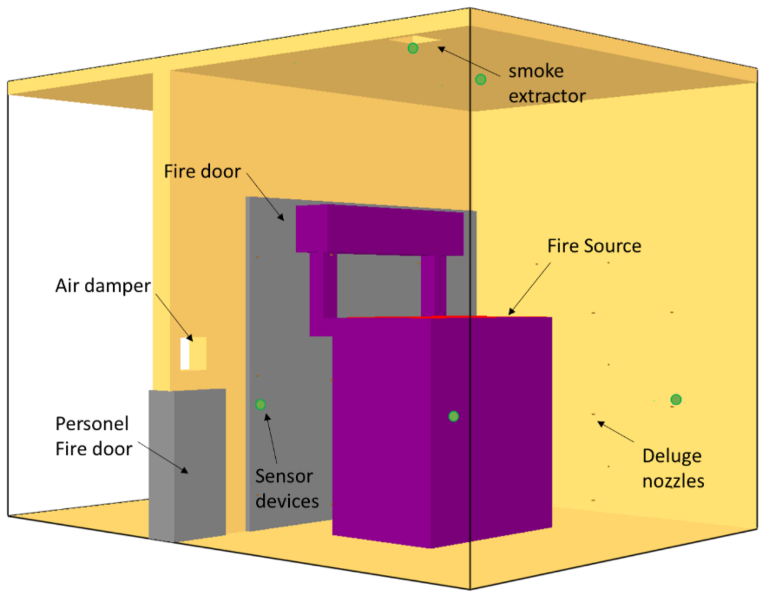


Figure 4-3: Geometry for the FDS Fire scenario 3 – Confined fire, smoke extraction and deluge

- **Fire scenario 4**

The fire scenario 4 corresponds to a fire that is not confined to the transformer cell, but spreads to the hallway. The geometry of the transformer cell was the same as in scenarios 1 to 3 but the fire door was left opened.

As in the previous cases, the fire source was established over a cube that resembles the transformer's tank. The cell extraction system was not modeled, nor was the air inlet damper to the cell, because their effect would be negligible when compared to that of the opened fire door.

The hallway was represented as adiabatic walls and floors. The electric bus ducts were added in the upper part because they interfere with the transport of the smoke from the fire source to extraction. In this scenario the extraction ducts were parameterized with an extraction velocity of 0 m/s.

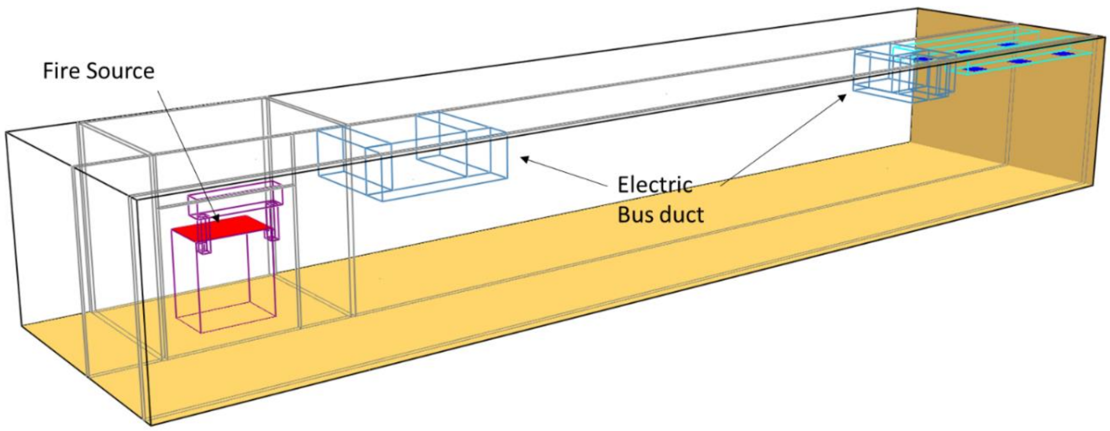


Figure 4-4: Geometry for the FDS – Fire scenario 4 – Unconfined fire.

- **Fire scenario 5**

In the Fire scenario 5, the operation of the smoke extraction system for Fire scenario 4was evaluated, for which the extraction system was modeled with six extraction dampers (1 m x 0.5 m, each) at 2 m apart, all with the same air extraction velocity. In addition, the fresh air intake dampers were included, located in the three available evacuation routes, whose equivalent area is equal to the area of the extraction dampers. The hallway and the source of the fire were modeled in the same way as in the Fire scenario 4.

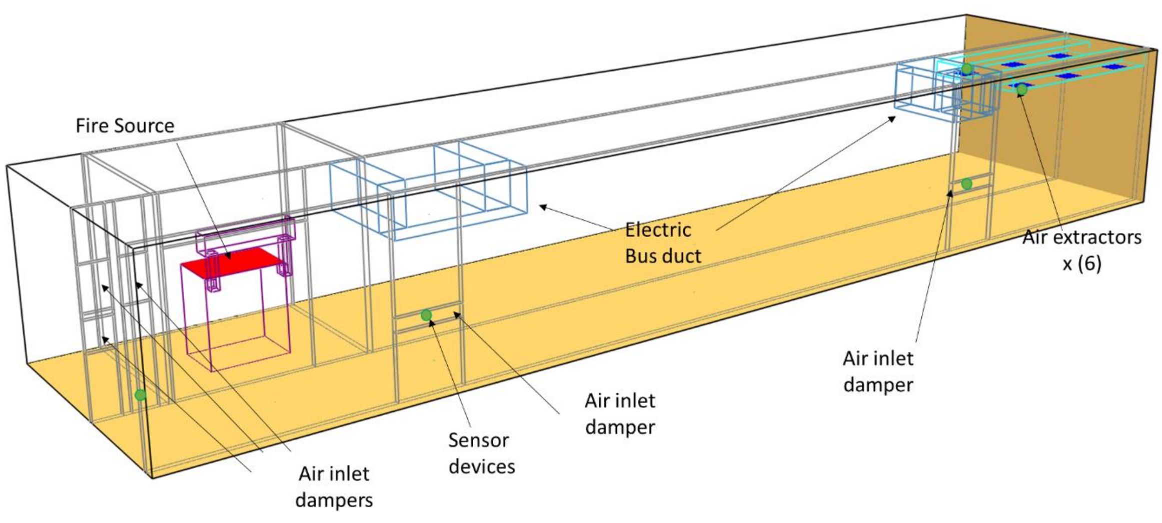


Figure 4-5: Geometry representation for the FDS – Fire scenario 5 – unconfined fire with smoke extraction

4.1.3 Mesh definition

To discretize the control volume, a structured mesh with equal size in its dimensions has been constructed. The FDS Verification guide recommends, to guarantee good mesh resolution and a reasonable computational cost (Johansson, 2021), to maintain the relation $5 < D^*/\delta x < 10$, where D* is the characteristic fire diameter and is computed from Equation (4-8) and δx is the cell size (K. B. McGrattan, 2006b).

$$D^* = \left(\frac{\dot{q}}{\rho_\infty * \ C_p * \ T_\infty * \ \sqrt{g}}\right)^{2/5} \tag{4-8}$$

where,

$\rho_\infty =$ air density at 308 K and 89278 Pa

C_p = specific heat capacity of air = 1.005 kJ / kg K

T_∞ = ambient temperature = 35 °C

g = acceleration of gravity = 9.8 m/s^2

As D* was computed to be 2.4 m, the recommended cell size, δx. should vary between 0.5 m and 0.25 m. As some parts of the model are smaller than 0.25 m, a value of 0.2 m was finally used as the cell size.

4.1.4 Boundary conditions and other important FDS parameters

As the objective of this study was to evaluate the use of physical modeling tools in the design of fire protection systems, there was not a devoted effort to optimize every simulation setup. However, for each PMT, care was taken that the simulation successfully proceeded until completion. This practice is similar to what actual practitioners do in real life.

The following list illustrates the boundary conditions and most important parameters for the FDS simulations.

1) The simulation time was 240 s for the confined fire scenarios and 600 s for the unconfined fire scenarios.
2) The ambient temperature was considered to be 35°C.
3) The walls of the compartments were defined as concrete and the electric bus ducts as steel. The material properties of concrete are presented in APPENDIX A.
4) The fire source was defined with a HRR with an increasing curve of the t-squared type with a time to stabilization (TAU_Q) of 216 s and a heat release rate per unit of area (HRRPUA) of 1534.3 kW/m^2. Additionally, a soot yield of 0.097 and CO yield of 0.041 were added. The heat of combustion used was 46400 kJ/kg. The radiative fraction was 0.35 (default value of FDS).

5) The smoke extraction damper was defined with a volume of flow of 3.63 m^3/s for unconfined fire and a velocity of 6.1 m/s for confined fire.
6) The areas of the air inlet dampers were considered as open boundary.
7) For the water deluge simulation (Fire scenario 3), the extinction coefficient was defined as 1 as previously explained.

The configuration of the FDS software is shown in the APENDIX C.

4.1.5 Sensor devices

The amount of data that a transient, 3D CFD code, such as FDS, generates can be very difficult to navigate and may imply storage capacities well above those of typical computers. To get around this problem, FDS allows the user to define locations in the simulation domain where the variation of certain variables with time can be recorded. In the case of the confined fire, the temperatures at the roof of the transformer cell and on the extraction damper were registered.

In the unconfined fire scenario, to measure the risk indices, sensors were installed in each of the emergency exits, in the center of the corridor, at a height of 2 m. Additionally, measurement sensors were installed in the extraction dampers. **Figure 4-3** and **Figure 4-5** show the location of the sensor devices. In the unconfined simulations, in addition to temperature, this device registered the concentration of the major combustion species as well as that of soot.

4.2 Fire Simulation with CFAST

The Consolidated model Fire and Smoke Transport (CFAST) is a physical modelling tool developed by the National Institute of Standards and Technology (NIST) in the United States. This study makes use of CFAST 7.7.2 (Peacock et al., 2015a) and the results were analyzed in Smokeview (SMW) (Forney, 2022).

CFAST is a Zone Model that divides the control volume into two zones: a hot layer and a cold layer. Differential equations are used to describe the mass and energy balances, and to determine the temperatures and concentrations of the combustion gases.

CFAST, as was the case for FDS, simplifies the pyrolysis model of fire using a HRR imposed by the user.

Equation (4-9) represents the transient state mass balance.

$$\frac{dm_i}{dt} = \dot{m_\iota} \tag{4-9}$$

where the rate of change of the mass layer i is equal to the sum of the mass source terms ($\dot{m_\iota}$) that include plume mass entrainment and supply/exhaust ventilation.

Equation (4-10) describes the energy balance.

$$\frac{d(C_v m_i T_i)}{dt} = \dot{q_\iota} - P\frac{dV_i}{dt} \tag{4-10}$$

The rate of change in the layer´s internal energy $(C_v m_i T_i)$ is equal to the sum of heat source terms ($\dot{q_\iota}$) minus the work associated with expansion or contraction of the layer ($P\frac{dV_i}{dt}$).

The heat source terms ($\dot{q_\iota}$) include the heat release rate, convective losses to walls, and radiation exchange.

The temperature, mass, and volume of each compartment are related to the pressure through the ideal gases law, Equation (4-11).

$$P\,V_i = m_i R T_i \tag{4-11}$$

Equations (4-9) to (4-11) can be combined to obtain equations (4-12) to (4-15) that are actually solved to yield the pressure, volume of the upper layer and temperature of the upper and lower layer, respectively.

$$\frac{dP}{dt} = \frac{\gamma - 1}{V}(\dot{q_1} + \dot{q_u}) \tag{4-12}$$

$$\frac{dV_u}{dt} = \frac{1}{P\gamma}\left[(\gamma - 1)\dot{q_u} - V_u\frac{dP}{dt}\right] \tag{4-13}$$

$$\frac{dT_u}{dt} = \frac{1}{C_p m_u}\left[\dot{q_u} - C_p \dot{m_u} T_u + V_u\frac{dP}{dt}\right] \tag{4-14}$$

$$\frac{dT_1}{dt} = \frac{1}{C_p m_1}\left[\dot{q_1} - C_p \dot{m_1} T_1 + V_1\frac{dP}{dt}\right] \tag{4-15}$$

An additional set of equations, (4-16) to (4-17), represents the heat balance on the walls.

$$\dot{q}'' + k\frac{\partial T_w(0,t)}{\partial x} = 0 \qquad (4\text{-}16)$$

Where $\frac{\partial T_w(0,t)}{\partial x}$ is the temperature gradient at the wall surface, $\dot{q}''$ is the net radiative and convective heat from the adjacent gas layer and $T_w(x,t)$ is the temperature wall profile. The temperature gradient is evaluated in Equation (4-17) with a constant temperature boundary condition $T_w(0,t) = T_w$.

$$\frac{\partial T_w}{\partial t} = \frac{k}{c\rho}\frac{\partial^2 T_w}{\partial x^2} \qquad (4\text{-}17)$$

4.2.1 Simulation constraints

The following are the assumptions that were considered for the simulations in the CFAST software:

- The fire is confined to the limits of the model.
- The transformer's oil is the only combustible material.
- The fire is extinguished when the oxygen concentration is below 15%.

For Fire scenario 3, which corresponds to the analysis of the behavior of the extinction system by deluge in the case of a confined fire, the HRR curve was modified to simulate the effect that the extinction system would have on the fire. This was done to overcome the fact that CFAST does not simulate extinction systems by deluge, only extinction by automatic sprinklers activated by temperature. Therefore, the HRR curve of the fire for fire scenario 3 of the FDS simulation, in **Figure 4-6** was therefore imposed to the CFAST simulation.

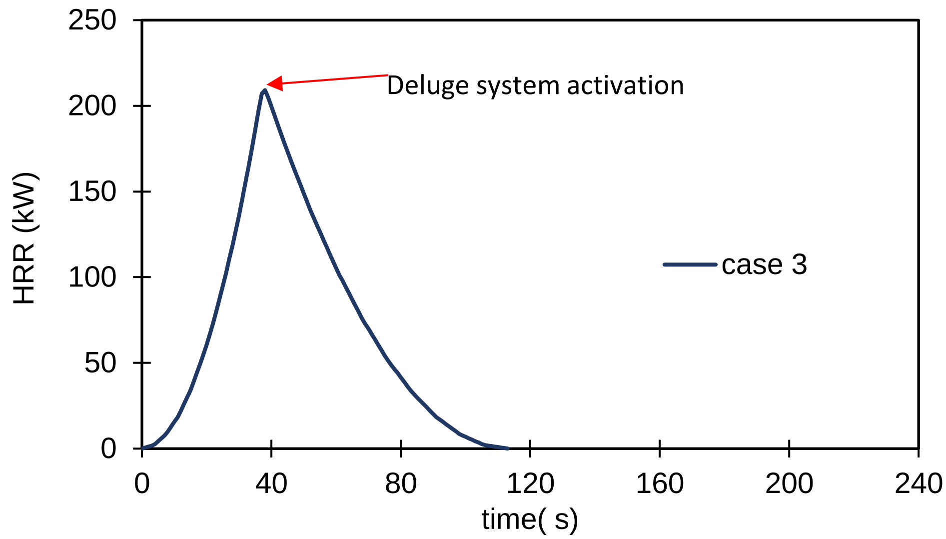


Figure 4-6: Modified HRR to account for the deluge system action in the CFAST simulation of Fire scenario 3

4.2.2 Geometry

- **Fire scenario 1**

For a fire confined to the transformer cell, the volume was simplified to a cube with the dimensions of the cell. The fire source was in the center of the cell, where the center of the transformer would be.

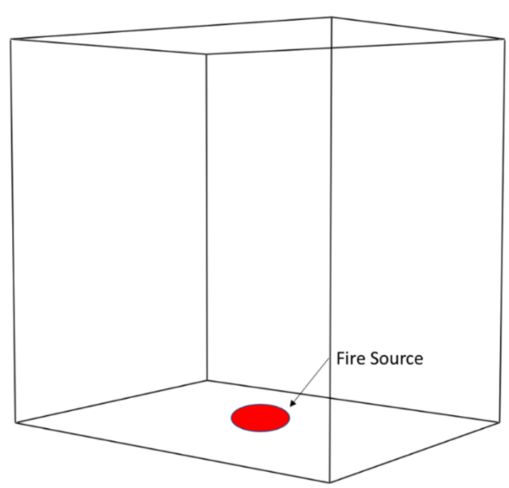


Figure 4-7: Geometry for the CFAST Fire scenario 1 - Confined

- **Fire scenario 2**

This scenario adds to Fire scenario 1 an opening for air inlet and a smoke extraction at the top of the cell.

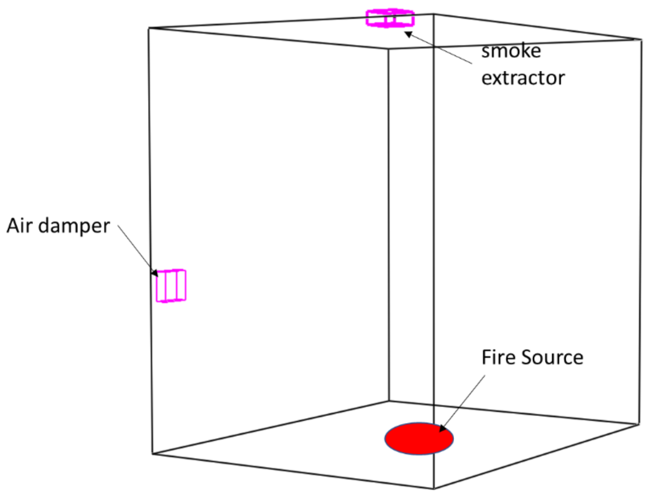


Figure 4-8: Geometry for the CFAST Fire scenario 2 – Confined fire with smoke extraction

- **Fire scenario 3**

This case uses the same geometry as Fire scenario 2 but the HRR curve, as indicated above, was modified to represent a deluge system.

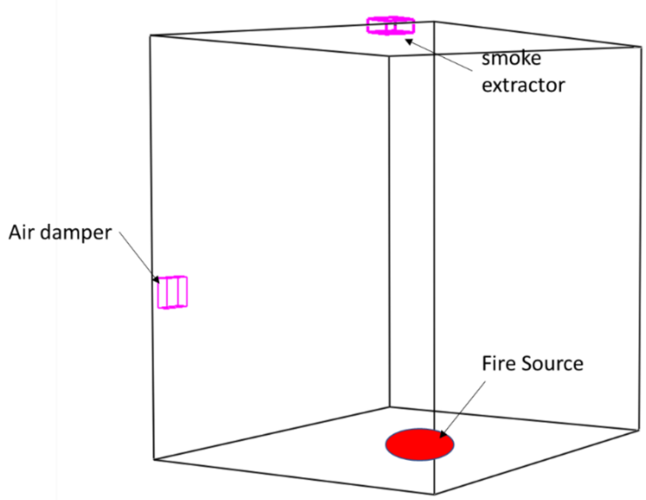


Figure 4-9: Geometry for the CFAST Fire scenario 3 – Confined fire with smoke extraction and deluge.

- **Fire scenario 4**

While the representation of a hallway as long as that in Fire scenario 4 is beyond the spaces for which CFAST was designed, it is possible to represent the geometry by adding several volumes or “rooms”, which communicate with "doors" of the height of each volume and the width of the hallway. The space for the entrance of the transformer, over which the smoke from the cell is passed to the corridor, was also modeled as a “door.” To model the bar ducts, the rooms were modified with the length and height of the bar ducts and with doors on both sides that communicate with the other rooms. The fire source was kept inside the cell in the area of the floor, as it was modeled in the previous case.

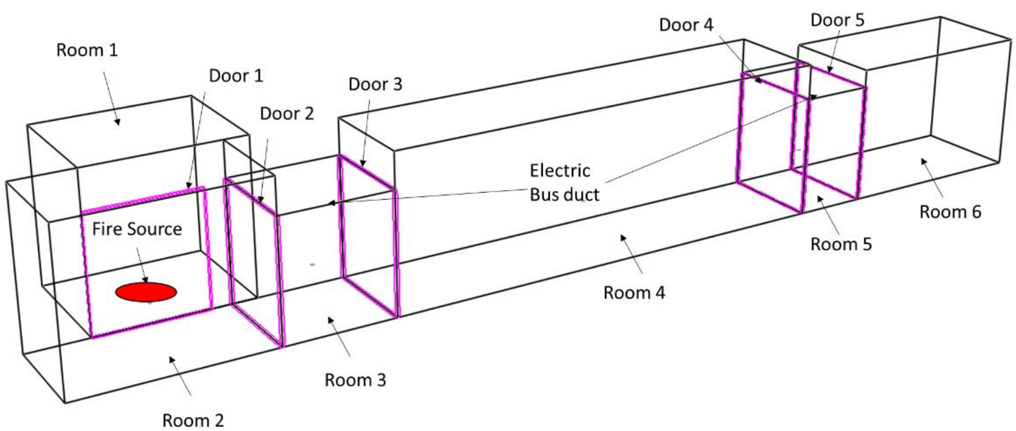


Figure 4-10: Geometry for the CFAST Fire scenario 4 – unconfined fire. The figure shows the 6 rooms and the 5 doors that were used to represent the hallway

- **Fire scenario 5**

To model the smoke extraction system and the fresh air intake dampers and windows were added to the geometry of Fire scenario 4 in each of the damper areas of the evacuation routes, for the fresh air to enter. For smoke extraction, six dampers were modelled in the upper part of the corresponding volume or enclosure, since CFAST limited their installation to one of the surfaces of the volume of the enclosure. To maintain the height of the smoke extraction ducts, the height of the enclosure was lowered to the height where the extraction dampers would be below the duct.

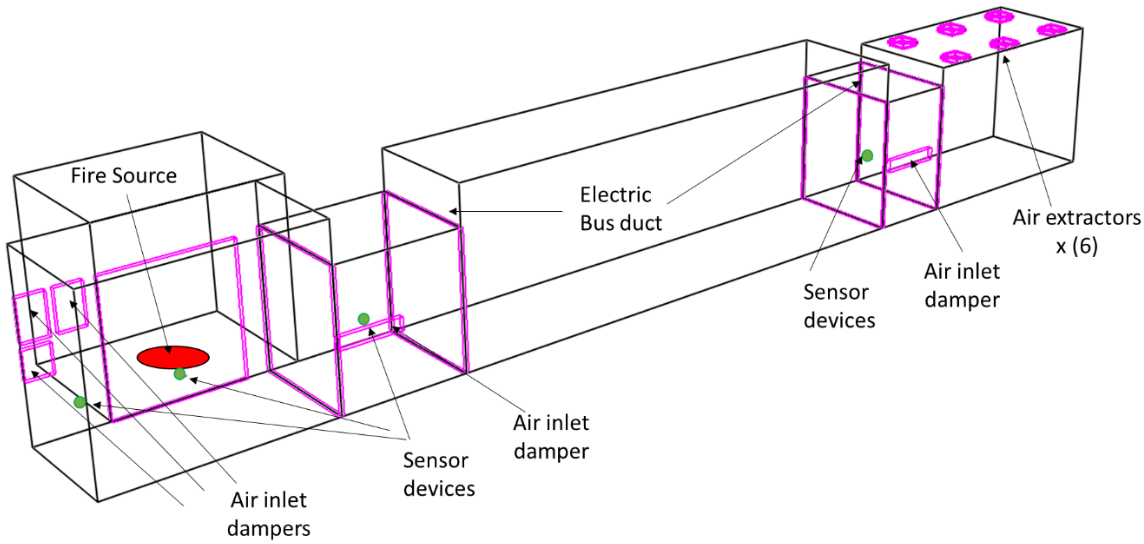


Figure 4-11: Geometry for the CFAST Fire scenario 5 – unconfined fire with extraction.

4.2.3 Boundary conditions and other important CFAST parameters

When possible, the boundary conditions were the same as those used with FDS. The only exception to this norm were:

1) The minimum oxygen level to sustain the fire was defined at 15%. This parameter is also used in FDS, however being a default value, it does not need to be included in the input file. The value for the simulations in FDS was 13.5%.
2) The walls of the compartments were defined as concrete. The material properties of concrete are presented in APPENDIX A.
3) Because CFAST only allows the fire source to be defined on the floor area, the fire source was located just below the site where the transformer is located.
4) The source of the fire was defined with an HRR of 8745 kW and a t-squared type curve with a rise time to steady state of 216 s, see **Figure 3-2**. The radiative fraction was 0.35 (default value of CFAST).
5) For the extraction of the case of confined fire, one extractor was added in the upper part of the cell with an area of 0.25 m^2 and a Flow rate of 1.53 m^3/s. The damper area is the same as that used in FDS, however, while in FDS the damper dimensions must be defined, in CFAST the cross-section must be defined.
6) For the extraction of the unconfined fire, six (extractors were added, each one with an area of 0.7 m^2 and a Flow rate of 3.63 m^3/s.

APPENDIX D includes the inputs files used in the CFAST simulations.

4.2.4 Sensor devices

Contrary to FDS where data from each cell is available in time, CFAST only presents results for the hot and cold layers of the fire. For this reason, the temperature predictions for the temperature in the hot layer where those used to determine the capacity of the smoke extraction system for the confined fire.

For the evaluation of human safety in the unconfined fire scenarios, **Figure 4-11** shows the four sensor devices (known as “targets” for C-FAST) which were defined located in the center of the corridor at a height of 2 m in each of the three emergency exits and on the outside of the transformer cell. The target is an approximation to the measurement devices of the FDS, it is an object in the simulation that can heat up via radiative and convective heat transfer, it was configured as one of plate type and constructed by the same properties as concrete.

4.3 Fire Simulation with FLUENT

FLUENT (ANSYS, 2020a) is a general fluid simulation software that is part of the ANSYS suite, which uses the finite volume method (FVM) to solve the Navier-Stokes equations of balance.

This program is not solely dedicated to the simulation of fires but, given that a fire is fundamentally a reactive fluid, FLUENT could be used to simulate a fire. In fact, there are several examples of its use for the analysis of fires and explosions (Cherbański et al., 2022; Guo et al., 2022).

FLUENT allows the use of an unstructured mesh that can be adjusted according to the designer's requirements, paying particular attention to the areas where more accurate results are required. This process is known as mesh refinement.

FLUENT solves the continuity (Equation (4-18)), momentum (Equation (4-19)), and energy (Equation (4-20)) balance equations along with some additional equations that depend on the nature of the problem such as those related to turbulence (e.g., equations (4-21) and (4-22) for the $\kappa - \epsilon$ model), the species transport model (Equation (4-23)) or a radiation model (e.g., Equation (4-24) the Discrete Ordinate model) .

- Mass balance:

$$\frac{\partial \rho}{\partial t} + \nabla * (\rho \vec{v}) = S_m \tag{4-18}$$

- Momentum balance:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla * (\rho \vec{v} \vec{v}) = -\nabla p + \nabla * \left(\bar{\bar{\tau}}\right) + \rho \vec{g} + \vec{F} \tag{4-19}$$

- Energy balance:

$$\frac{\partial}{\partial t}(\rho E) + \nabla * [\vec{v}(\rho E + p)] = \nabla\left[k_{eff}\nabla T - \sum_j h_j\vec{J_j} + \left(\bar{\bar{\tau}}_{eff} * \vec{v}\right)\right] + S_h \qquad (4\text{-}20)$$

For turbulence model turbulence model is used the K-**ε** model and RANS (Reynolds-averaged Navier–Stokes equations) in which the variables are averaged with respect to time. FDS uses Large Eddy Simulation (LES) turbulence model where the variables are spatially averaged.

- Turbulence – Kinetic energy (K)

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(u + \frac{u_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\epsilon - Y_M + S_k \qquad (4\text{-}21)$$

- Turbulence – Dissipation Rate (ε)

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_j}(\rho\epsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(u + \frac{u_t}{\sigma_\epsilon}\right)\frac{\partial\epsilon}{\partial x_j}\right] + \rho C_1 S_\epsilon - \rho C_2\frac{\epsilon^2}{k + \sqrt{v\epsilon}} + C_{1\epsilon}\frac{\epsilon}{k}C_{3\epsilon}G_b + S_\epsilon \qquad (4\text{-}22)$$

- Species transport

The species transport model is activated to model mixing and transport of chemical species:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho\vec{v}Y_i) = -\nabla * \vec{J_i} + R_i + S_i \qquad (4\text{-}23)$$

- Radiation

The radiation model is used DO Discrete Ordinates:

$$\nabla * [I(\vec{r},\vec{s})\vec{s}] + (a + \sigma_s)I(\vec{r},\vec{s}) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s}')\Phi(\vec{s},\vec{s}')\, d\Omega' \qquad (4\text{-}24)$$

4.3.1 Simulation constraints

- In addition to the assumptions in **4.1.14.1.1**, the following was assumed for the CFD simulations: The fire is limited to the upper part of the transformer with an area of 5.7 m^2.
- There are no reactions in the smoke plume
- The fire was inputted as a constant heat source of 8745.51 kW, as indicates in **Figure 3-2** for steady state.

The possibility to carry out the simulation in FLUENT in a transitory state, as is the case in FDS and CFAST, was initially considered. However, the computational time required to model 600 s of the fire was too high if a time step short enough was used to obtain a stable solution. The fact that most FLUENT studies related to fires have been carried out at steady state is indicative of the difficulties associated with modeling the dynamics of complex fires with general CFD tools. It is possible that a fire simulation can take place in FLUENT in big computer clusters, however that approach was out of the scope of this study that was centered on what an actual practitioner can accomplish with typical computational tools.

The simulation was, therefore, carried out in a stable state which constrained the analysis to fire scenarios with continuous flow, such as fire scenarios 2 and 5. Even in this case it was difficult to obtain convergence, as it was required to iterate from relative low temperatures up to high temperatures for the initial conditions. Convergence also demanded the variation of relaxation factors.

4.3.2 Geometry

- **Fire scenario 2**

The geometry of the stage was taken directly from the CAD as a negative to verify possible interferences. The geometry includes an air inlet that simulates the air inlet damper and an air extractor at the top where it connects to the smoke extractor. The fire source was in the top cover of the transformer.

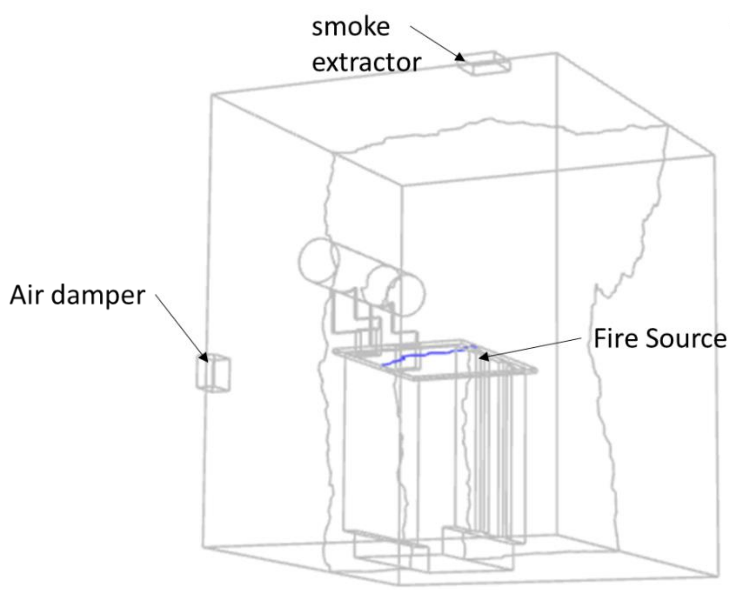


Figure 4-12: Geometry for the FLUENT simulation of the Fire scenario 2 – Confined fire with extraction

- **Fire scenario 5**

The geometry of the transformer and the site was simplified with respect to that presented in the CAD, to allow for the meshing process. A "Boolean" was made to extract the geometry. In this case, three fresh air intake zones were established, which were in the dampers above the emergency exits.

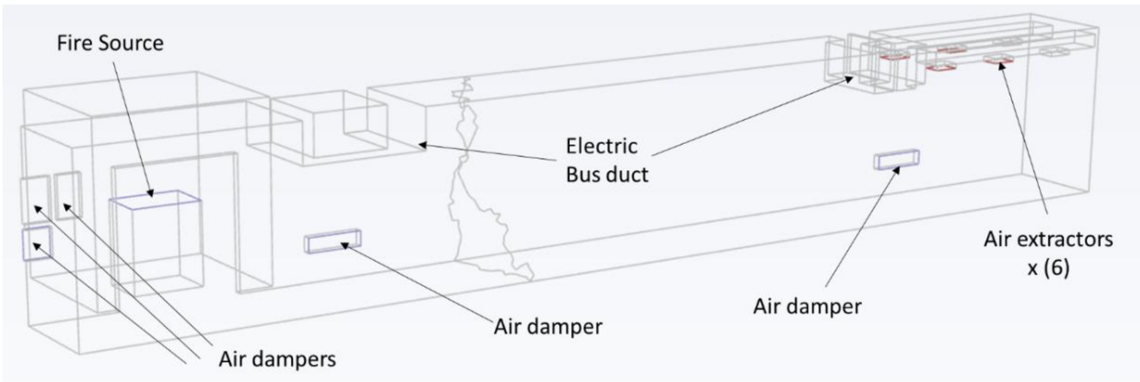


Figure 4-13: Geometry for the FLUENT simulation of the – Fire scenario 5 – Unconfined fire with smoke extraction.

4.3.3 Mesh

The mesh for the confined fire had a maximum size of 0.1 m and 51200 elements, was unstructured and based on tetrahedral elements. Cells with less than 0.1 mm significantly increased the computational cost beyond the time allowed for this study. To verify the quality of the mesh, comparisons of the skewness and aspect ratio factors were made, which were within the ranges recommended by ANSYS (ANSYS, 2020a).

4.3.4 Boundary conditions and other important CFD parameters

The fire source was placed on the upper part of the transformer and was defined as a MASS INLET, with a mass flow that was defined by Equation (4-25).

$$\dot{m} = \dot{q}/\Delta h_c \qquad (4\text{-}25)$$

where,

$\dot{m}$ = rate of mass consumption by the fire

Δh_c= net heat of combustion =46400 kJ/kg

$\dot{q}$ = max heat release rate = 8745.5 kW

Therefore, the source of the fire was defined as a constant mass flow input of 0.188 kg/s entering the control volume at a temperature of 1200 °C that is common for a fire of transformer's oil (El-Harbawi & Al-Mubaddel, 2020).

The products of the reaction that represent the fire are considered as the species that enter the control volume. (See (R-1)). Therefore, the mass fraction of the combustion products was: CO_2: 0.197; CO: 0.003; H2O: 0.082; and N_2: 0.718.

The air inlets through the dampers were defined as PRESSURE INLET for which a pressure of 0 Pa and a re-entry temperature of 35 °C were determined.

The air outlets, represent the smoke extraction system and were defined as an EXHAUST FAN, for which the negative pressures (leaving the control volume) that represent the suction pressure carried out by the extraction fans in the room were determined. The pressure difference from the room to the exhaust system was estimated from Equation (4-26).

$$\mathrm{V} = \mathrm{C} * \mathrm{A} * \sqrt{\frac{2\,\Delta P}{\rho}} \tag{4-26}$$

where,

C = 0.57, is an empirical constant (Klote et al., 2012)
V = volume of air = 1.53 m^3/s for Fire scenario 2 and 3.63 m^3/s for Fire scenario 5
ρ = air density = 1.225 kg/m^3 at a temperature of 308 K
A = area of damper = 0.25 m^2 for Fire scenario 2 and 0.7 m^2 for Fire scenario 5

The pressure difference in damper was estimated as (ΔP) is 25.6 Pa for Fire scenario 2 and 18.6 Pa for Fire scenario 5.

The walls were considered to have no heat flow through them.

The other conditions and parameters of the fire scenario are presented in APENDIX A. APPENDIX E shows the full configurations of FLUENT simulations.

4.3.5 Sensor devices

The idea of "sensor devices" is proper from fire physical modeling tools. Typical CFD programs allow the user to have access to all the data. However, in order to compare the results with those from FDS and CFD, the data used form comparison were those in one of the extraction dampers, the closest to the source of the fire.

5 Results and Analysis

This chapter discusses the results of simulations. The first part shows the verification and validation of the simulations of the analyzed fire scenarios. Then the results from FDS; CFAST and FLUENT are compared with those obtained from recommendations from the prescriptive codes with emphasis on the fire simulation and on the time for evacuation.

In the last part, the results obtained from the three PMTs are compared among them.

5.1 Verification and Validation of Fire Scenario

The purpose of verification is to guarantee that a particular PMTs correctly solving the governing equations, and that is properly representing the fire scenario.

For the FDS simulations, the assumption is made that if the model does not diverge, it is because the program is solving the equations properly. A similar consideration was made for CFAST. Regarding those carried out in FLUENT, the program presents a report of residuals with which it is possible to observe the convergence in the results as the simulation calculations are carried out. Furthermore, care was taken to guarantee that the mass and energy balances closes within 1% and 10%, respectively. It is possible as well to argue that the three PMTs in this study have been extensively used in the last decades and have shown that they correctly solve the balance equations that describe fires, for FDS and CFAST, or a reactive fluid movement, for FLUENT.

The ideal way to verify if the fire scenario planned in the simulations represents a fire scenario in the real world is to validate with experimental results (Cadena & Muñoz, 2014). All three MPTs studied here have been extensively validated either for fires, as is the case for FDS (K. B. McGrattan, 2006c) and CFAST (Peacock et al., 2015b), or for general CFD analysis, as is the case for FLUENT (ANSYS, 2020b).

5.2 FDS

5.2.1 Fire scenario 1

While **Figure 5-1** only indicates that the smoke has completely engulfed the entire room, as discussed below, other variables such as HRR and temperature also indicate that at 240 s the fire is reducing intensity.

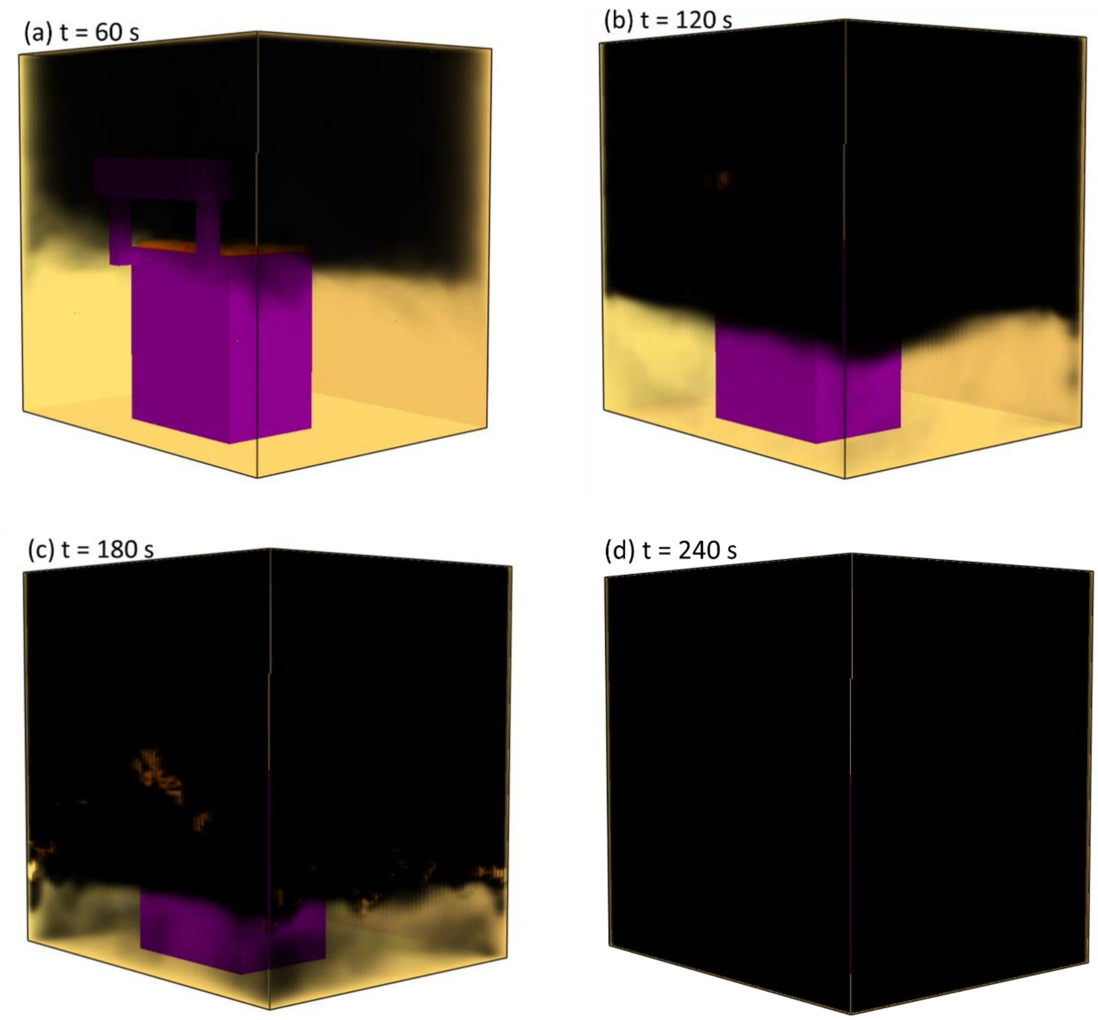


Figure 5-1: Variation of the smoke and flame as predicted with FDS for Fire scenario 1 -with time (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 240 s.

Figure 5-2 show that around 120 s there is evidence of temperatures of the order of those reported for a flashover. Drysdale has commented that it has been observed that in a flashover the radiation is about 20 kW/m^2 at floor level and a ceiling temperature of approximately 600 °C (Drysdale, 2011). However, as discussed below, the radiation to the floor remains lower than 20 kW/m^2 through the fire. The fact that a flashover scenario is not reached does not come as a surprised given that the only fuel in the room is the transformer's oil.

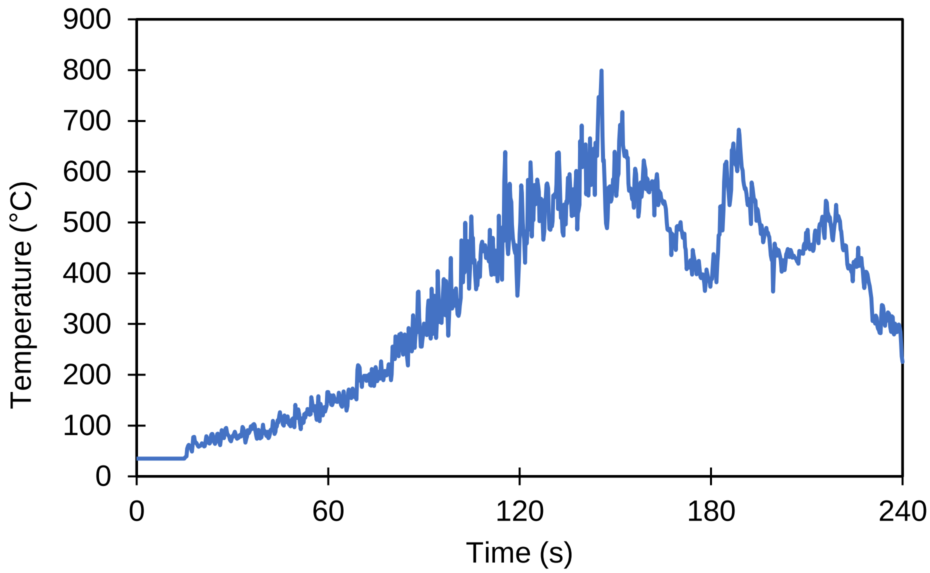


Figure 5-2: Variation of the temperature at ceiling level as predicted by FDS for Fire scenario 2

From 150 s until the end of the simulation, some fluctuations of increases and decreases in temperature were observed, which decrease in intensity as the oxygen in the room is limited. The increases occur, particularly, when all the available oxygen in the lower part of the room is burned and decreases until the oxygen is completely consumed.

Regarding the radiation heat flux on the ground surface, **Figure 5-3** shows that at 190 s the radiation heat flux on the walls as a result of the increase in temperature is more than 20 kW/m^2, but on the ground surface the radiation heat flux is only 6 kW/m^2. This radiation heat flux keeps increasing and at 220 s, there is a spot on the floor where a value as high as 20 kW/m^2 is found (See **Figure 5-3**). The high temperatures at ceiling and high radiative heat flux on floor are akin to those observed in a flashover process and give evidence of the high intensity of the fire.

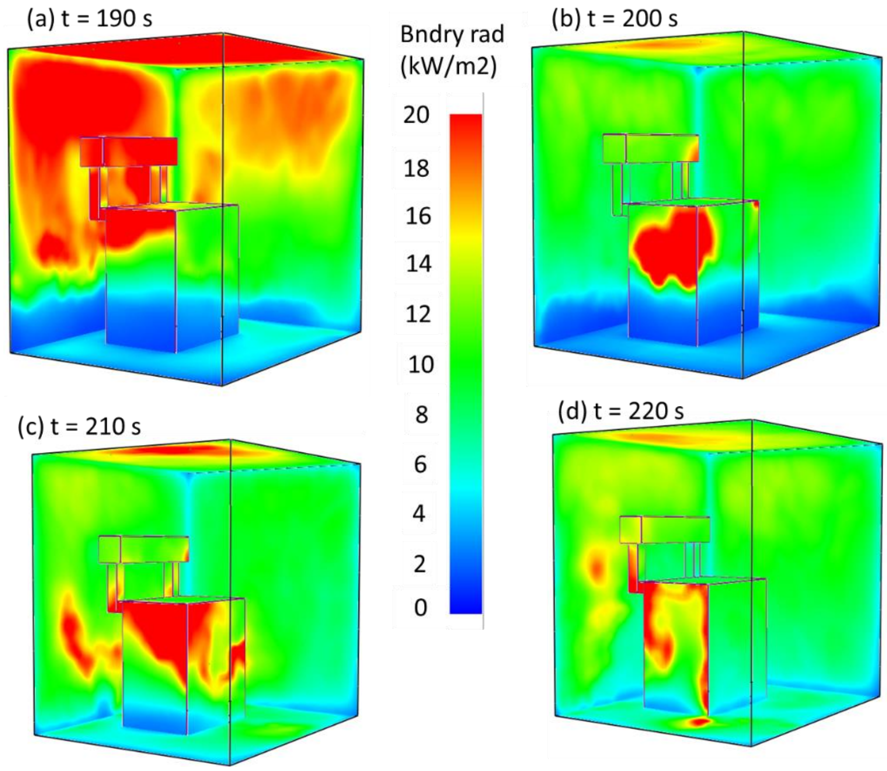
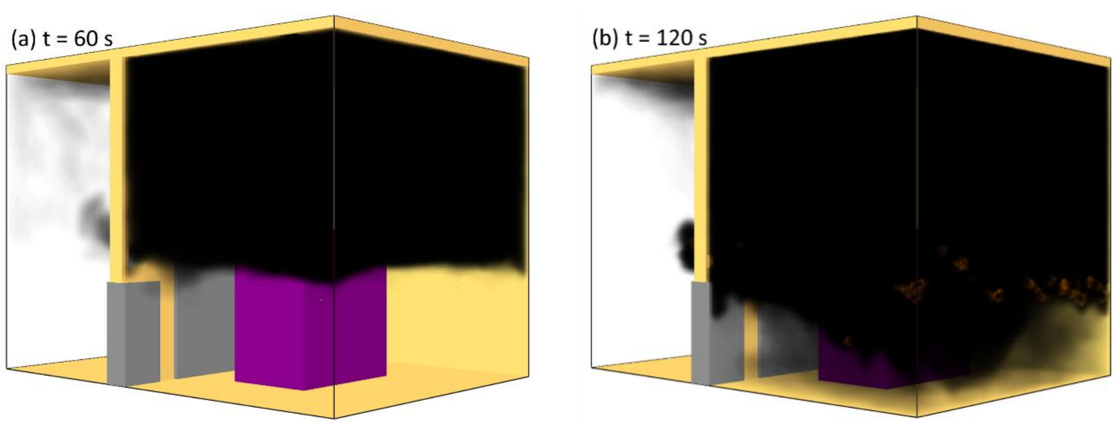


Figure 5-3: Variation of the radiative heat flux on the floor as predicted by FDS for Fire scenario 1 (a) t = 190 s, (b) t = 200 s, (c) t = 210 s, (d) t = 220 s.

5.2.2 Fire scenario 2

Figure 5-4 presents the smoke and flame representation of the simulation of Fire scenario 2 when carried out in the FDS tool, for a confined fire which has a fresh air intake at the front and an extraction at the top of the room.



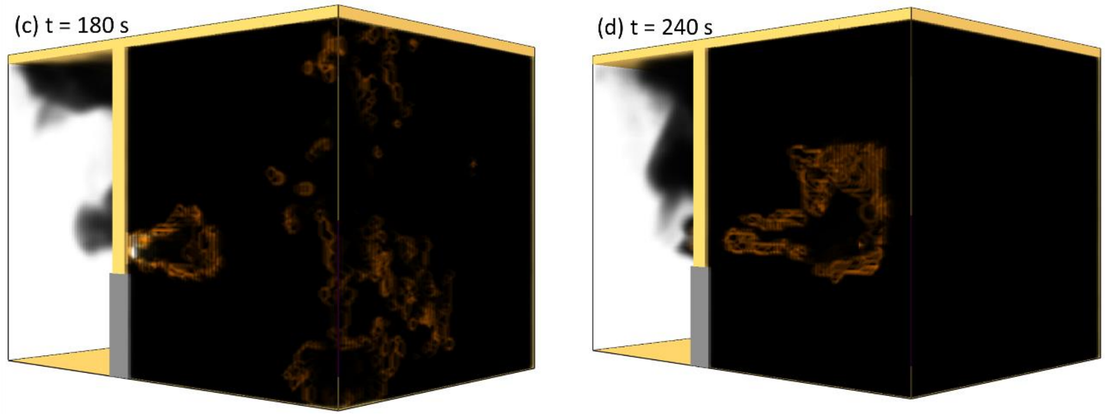


Figure 5-4: Variation of the smoke and flame as predicted by FDS for Fire scenario FDS Test – Fire scenario 2 - (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 240 s.

While the results for this scenario are similar to those for Fire scenario 1 in **Figure 5-1**, after 180 s, certain “burning" of the unburned fuel that ignites due to the entry of air through the front damper is observed. Because the FDS Technical Reference Guide (K. B. McGrattan, 2006a) indicates that in oxygen-starved compartments, such as that in this case, the entrance of air can lead to ”spurious burning”, care was taken to impose an autoignition temperature of 270°C that agrees with an autoignition temperature of 543 K for $C_{14}H_{28}$ (1 - tetradecene), (Hurley, 2015).

Figure 5-5 compares the HRR predicted by FDS when the AIT was 0 K (default) and when it is 540 K. A value of AIT = 0 K indicates that there will always be ignition when oxygen is in contact with fuel. Although there are some differences between both lines, the trend is basically the same.

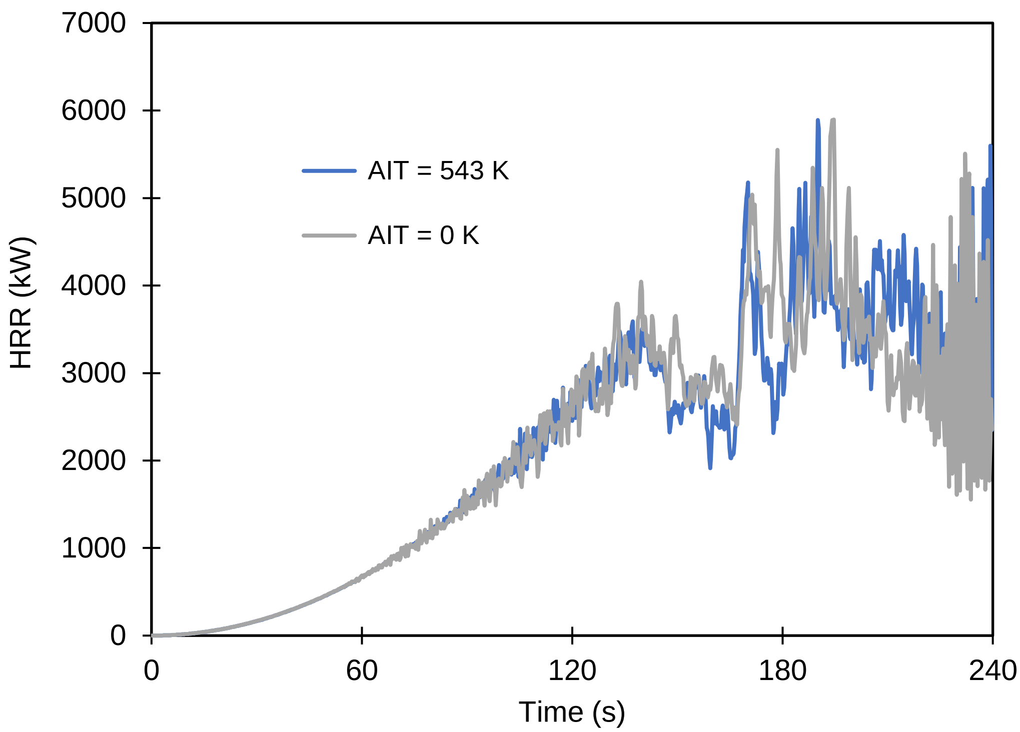


Figure 5-5: Variation of the HRR as predicted by FDS for Fire scenario 2 – Results are for AIT 0 K and 543 K

From 130 s, oscillations were observed in **Figure 5-5** for HRR produced by the entry of air into the cell through the front damper, which temporarily increases the available oxygen in the room, which leads to the reignition of the fuel. Said behavior was previously presented for the temperature measured inside the room, see **Figure 5-2**.

Given that the results in **Figure 5-5** are for HRR and may not detect any spurious burning, **Figure 5-6** and **Figure 5-6** present details of the oxygen and temperature during one of such events. In **Figure 5-6** and **Figure 5-7**, both figures indicate that the region where spurious burning is suspected, has an oxygen concentration like that of air and a temperature in the interface of the order of 1000 K where ignition and combustion of the fuel is rather possible.

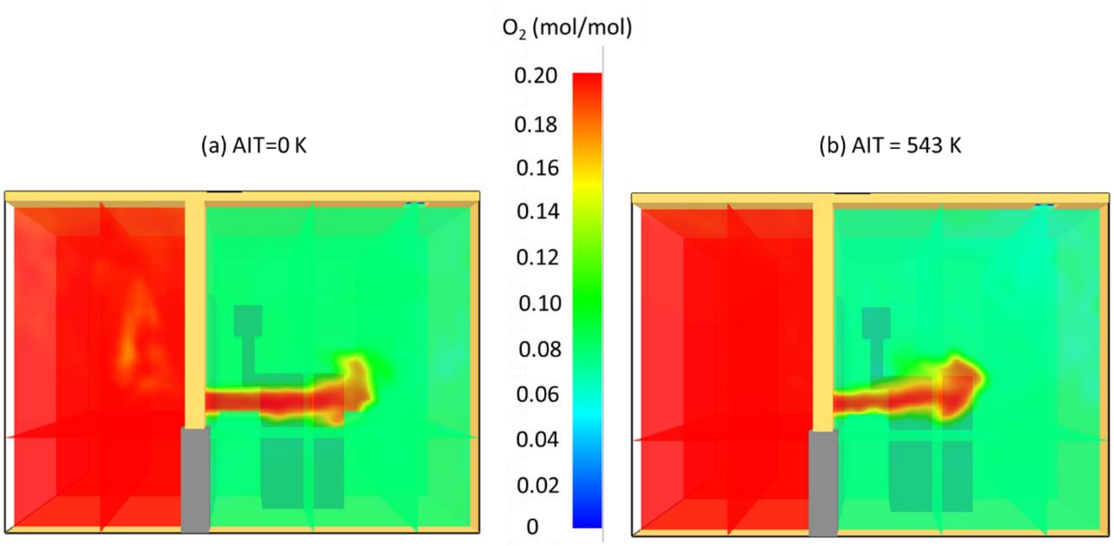


Figure 5-6: Predicted oxygen concentration presented as isocontours of the oxygen mole fraction by FDS Fire scenario 2 – (a): AIT = 0 K; and (b) AIT = 543 K

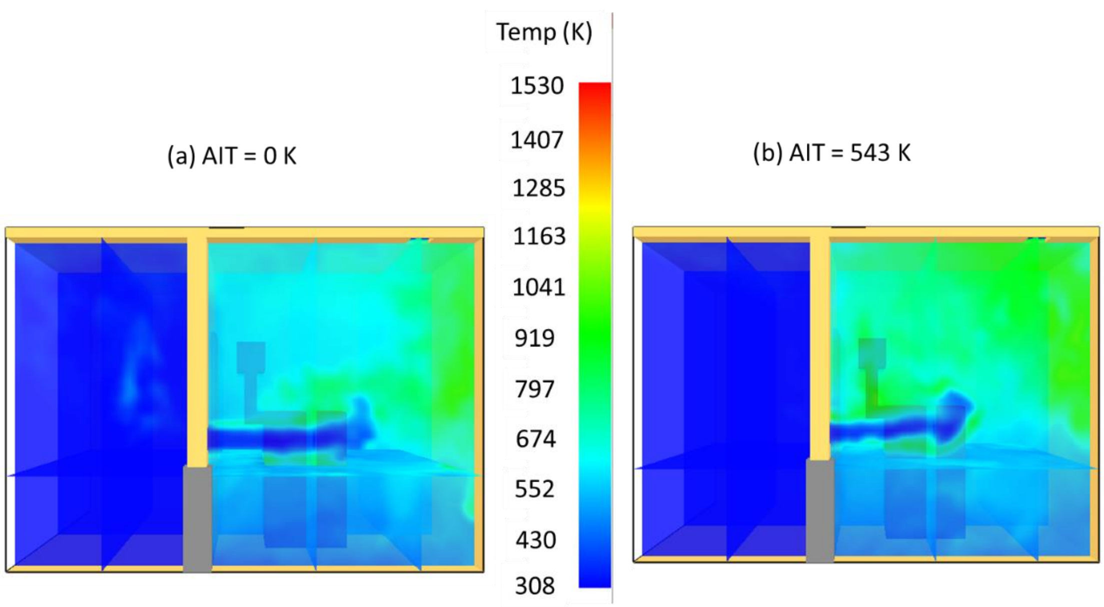


Figure 5-7: Predicted temperature presented as isocontours by FDS Fire scenario 2 – (a): AIT = 0 K; and (b) AIT = 543 K.

5.2.3 Fire scenario 3

Figure 5-8 shows how the deluge system interacts with the smoke and the flame in Fire scenario 3 for a confined fire in which the extinguishing system is activated by deluge of water from the transformers and the cell extraction system.

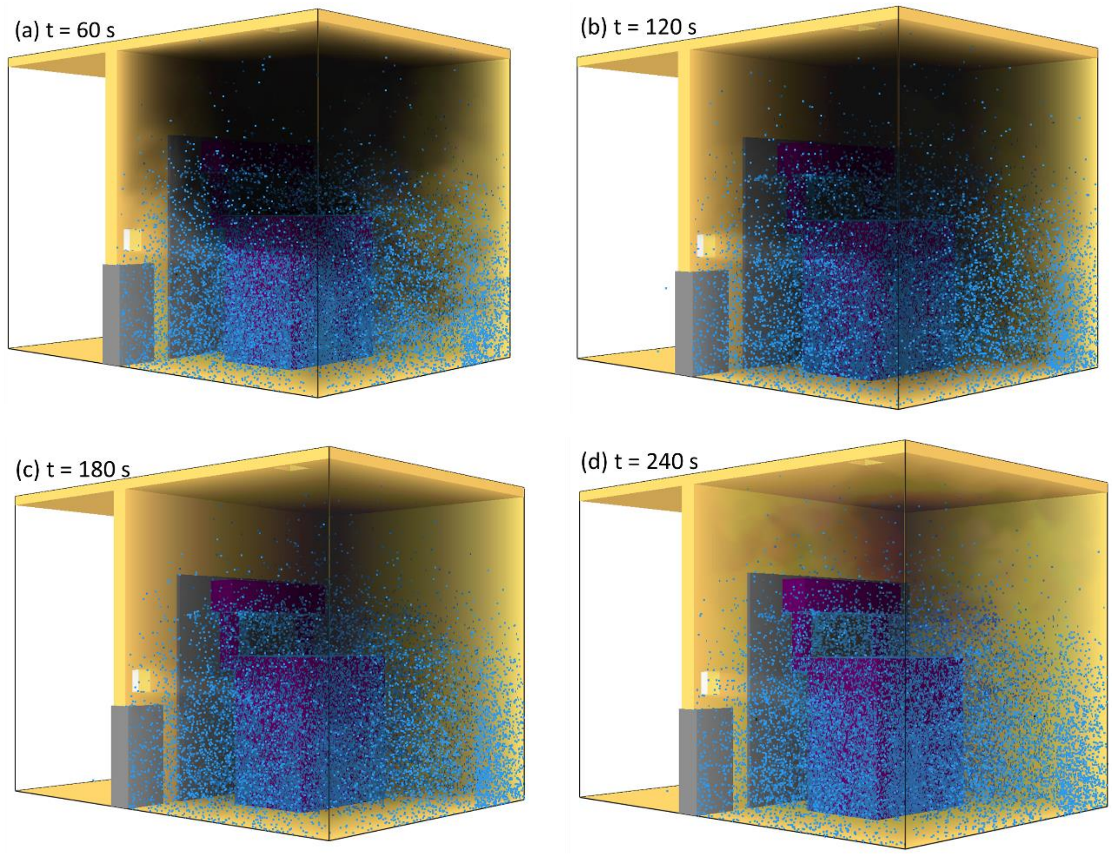


Figure 5-8: Variation of the smoke and flame as predicted by FDS for Fire scenario 3. (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 240 s. The figure also illustrates the presence of water as blue dots

It is evident in **Figure 5-8** that the deluge system extinguishes the fire and that the concentration of smoke that is in the upper part of the cell is extracted through the damper located in the upper part. Additionally, from the moment the deluge system is activated (t = 40 s) the fire is controlled, and the smoke production is reduced until the fire is extinguished **Figure 5-8**.

This fire scenario is the most ideal regarding the behavior of the fire protection system because it demonstrates how different fire protection systems can combine to extinguish a fire.

5.2.4 Fire scenario 4

The results of the FDS simulation for Fire scenario 4 in **Figure 5-9** indicate that the fire generates a layer of stratified smoke in the upper part of the space, that almost completely fills the room after just 300 s. While not shown, after this time, the available oxygen begins to gradually decrease until the fire is extinguished by suffocation.

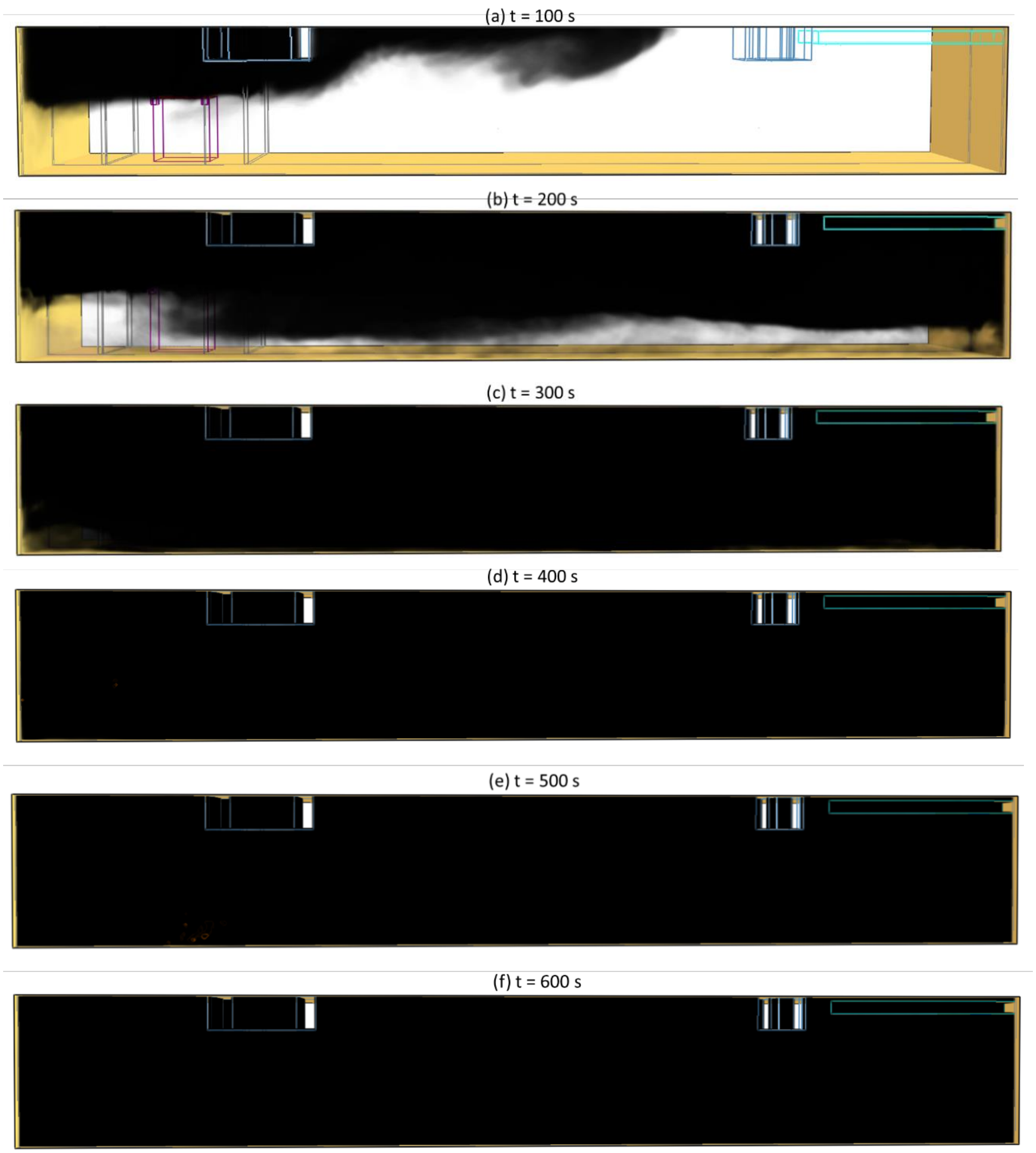


Figure 5-9: Variation of the smoke and flame as predicted by FDS for Fire scenario 4. (a) t = 100 s, (b) t = 200 s, (c) t = 300 s, (d) t = 400 s, (e) t = 500 s. (f) t = 600 s.

5.2.5 Fire scenario 5

Figure 5-10 presents the results of the FDS simulation after the addition of a smoke extraction system to Fire scenario 4.

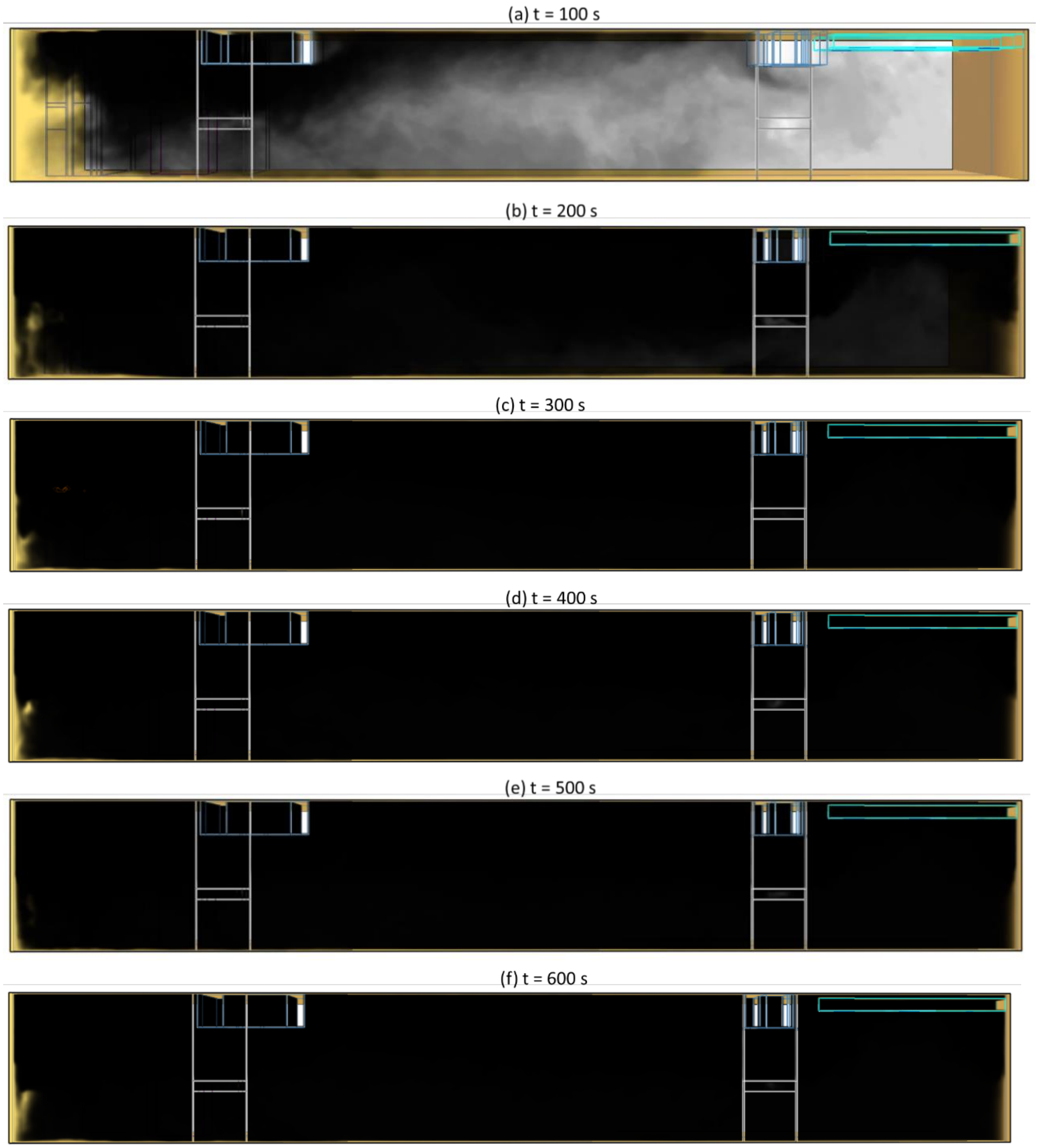


Figure 5-10: Variation of the smoke and flame as predicted by FDS for Fire scenario 5. (a) t = 100 s, (b) t = 200 s, (c) t = 300 s, (d) t = 400 s, (e) t = 500 s. (f) t = 600 s.

It is apparent in **Figure 5-10** that the presence of smoke has increased just after 200 s, when compared to **Figure 5-9**. This probably occurs as the extractor disturbs the smoke layer and induces mixing between both layers.

5.2.6 Comparison of the FDS simulations for the five fire scenarios

Figure 5-11 compares the HRR curves of the different fire scenarios simulated with FDS with those by the prescriptive method. All the cases follow the same trend on the first instances of the fire, as expected given that all had the same prescriptive HRR rate. However, they differ on the predicted steady state HRR as well as on when the fire is extinguished.

The most favorable scenario for the fire protection system is Fire scenario 3 in which the deluge system and the extraction system are activated, and the fire does not develop. In any case, the confined fire does not reach the steady state HRR because, as was described above, the fire extinguishes due to suffocation. Interestingly, the predictions for Fire scenarios 1 and 2 are similar, although the exhaust system tends to prevent large values of HRR that are evident in Fire scenario 1, before extinction.

For the unconfined fire that spreads to the corridor, it is observed in Fire scenario 4 that when the available oxygen is about to run out, there is a sudden increase in the HRR. For Fire scenario 5, it is observed that the HRR maintains the trend of the HRR that was calculated in Chapter 4.

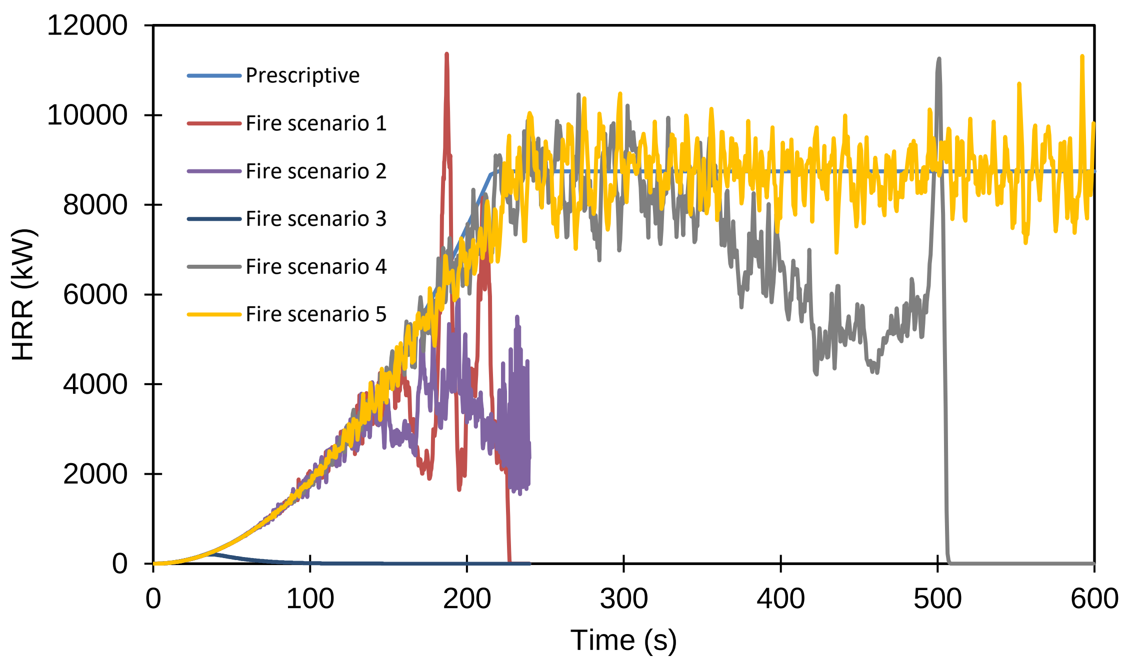


Figure 5-11: Comparison of the predicted HRR for fire scenarios 1 to 5 with FDS. The figure also includes, for comparison, results by the prescriptive method described in Chapter 4

5.3 CFAST

5.3.1 Fire scenario 1

Figure 5-12 present the results from CFAST for Fire scenario 1, a confined fire.: The simulation indicates that the fire increases to a maximum size after around 120 s for which the temperature of the upper layer gets up to around 340 °C. Although not shown, the fire is extinguished because of low oxygen concentration.

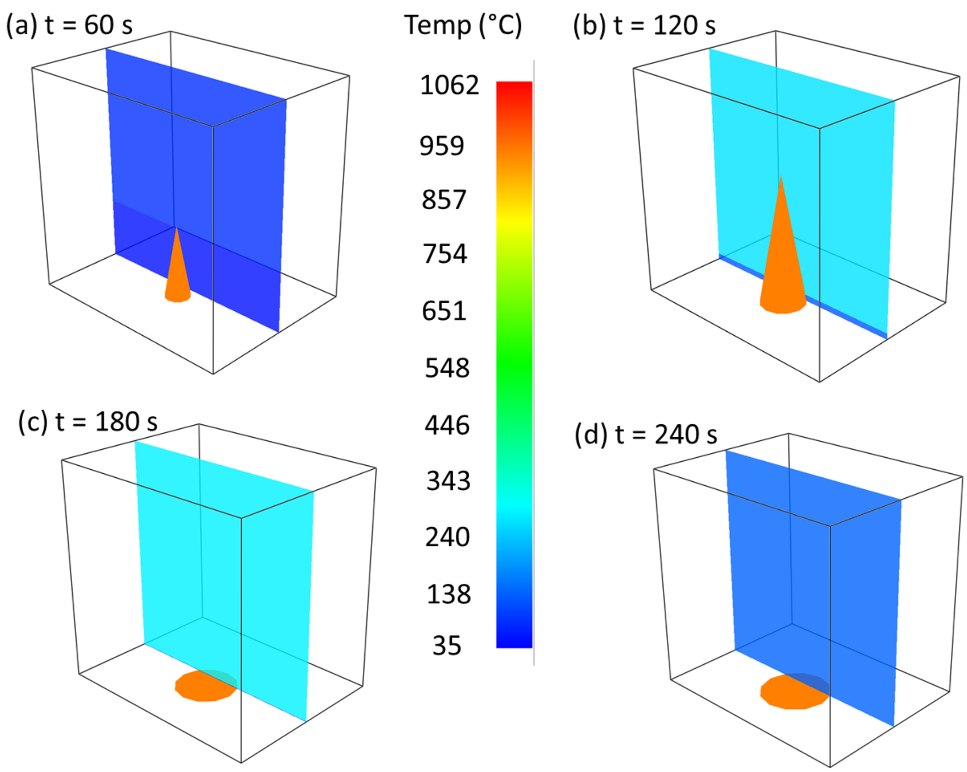


Figure 5-12: Variation of the temperature predicted by CFAST for Fire scenario 1 - (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 240 s.

5.3.2 Fire scenario 2

For Fire scenario 2, CFAST predicts a longer duration of the fire, when compared to Fire scenario 1, as **Figure 5-13** shows. Apparently, the inflow of air dictates that the fire does not suffocate, even after 240 s.

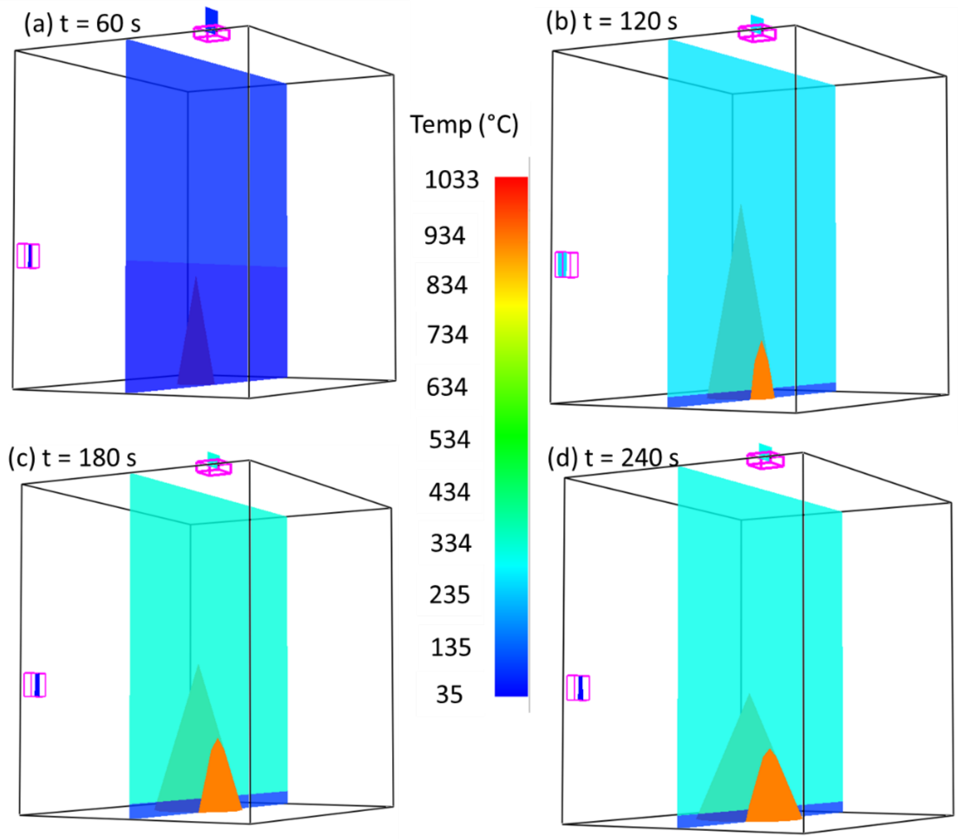


Figure 5-13: Variation of the temperature predicted by CFAST for Fire scenario 2 – (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 240 s.

5.3.3 Fire scenario 3

For this fire scenario, the effect that a deluge extinguishing system would have on the fire confined to the cell is presented. As noted above, CFAST does not include the option to automatically setup a deluge suppression system. Therefore, the HRR curve was decreased to represent the effect of this system on the fire.

Figure 5-14 illustrates how the fire is of much lower intensity, as prescribed by the reduced HRR and that the temperatures in the hot zone never increase above about 100 °C. While **Figure 5-14** does not show all the detail that the FDS simulation had, it conveys a similar message that indicates that the deluge system, if activated, would prevent the fire to grow.

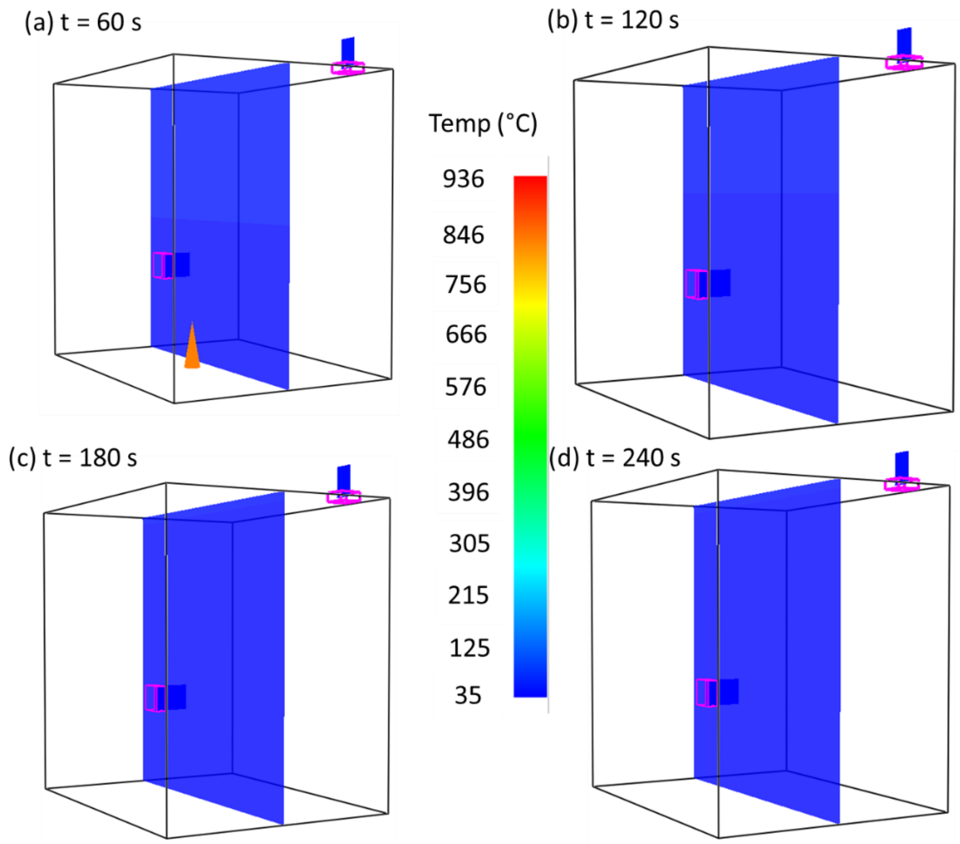


Figure 5-14: Variation of the temperature predicted by CFAST for Fire scenario 3 (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 240 s.

5.3.4 Fire scenario 4

For the unconfined fire in **Figure 5-15**, CFAST indicates that the temperature remains low along the hallway. From the figure it is not clear how smoke sparces. However, it is evident that after about 400 s the fire extinguishes, probably due to lack of oxygen concentration.

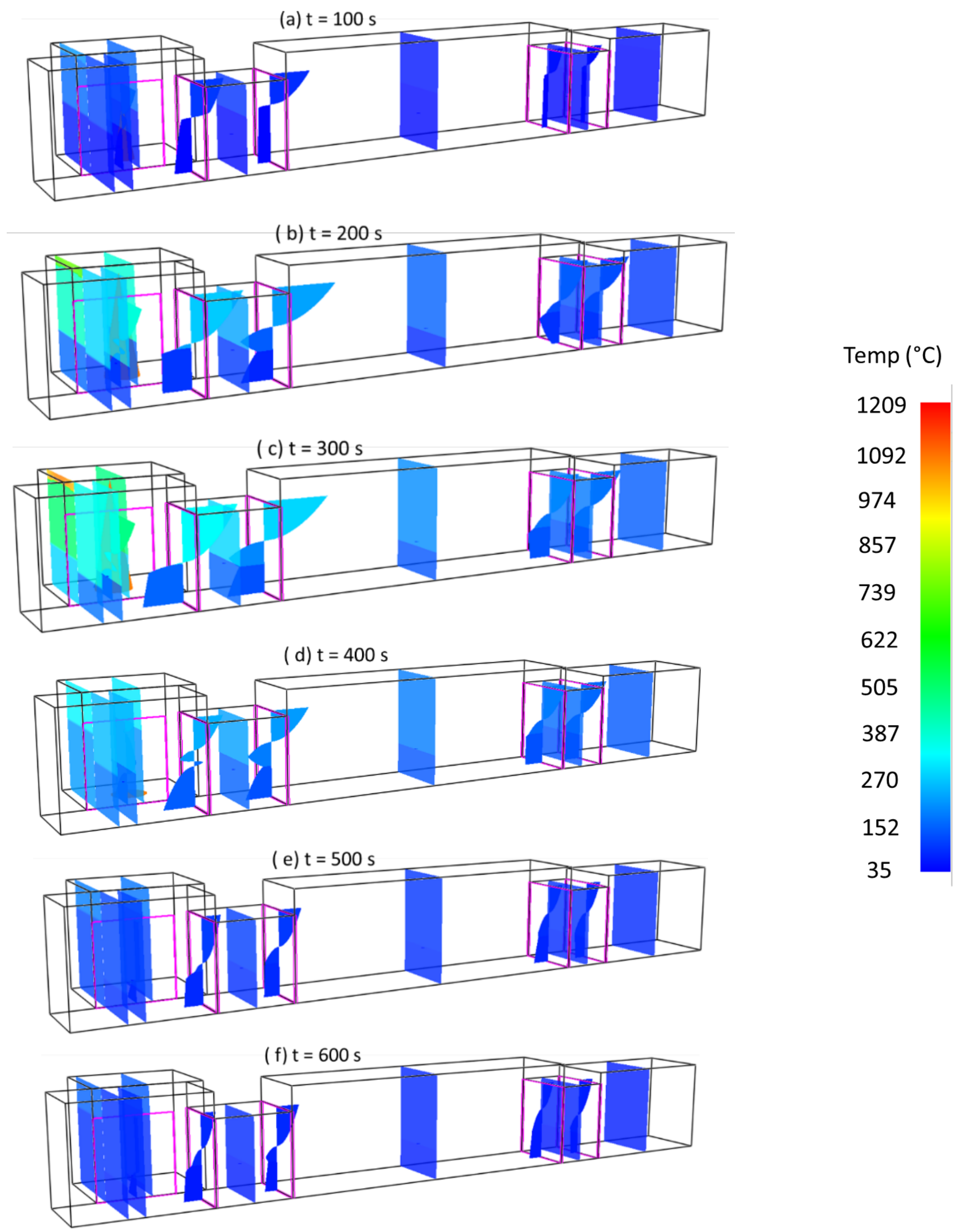


Figure 5-15: Variation of the temperature predicted by CFAST for Fire scenario 4 – (a) t = 100 s, (b) t = 200 s, (c) t = 300 s, (d) t = 400 s, (e) t = 500 s. (f) t = 600 s.

5.3.5 Fire scenario 5

Figure 5-16 shows the results of the CFAST simulations when smoke extraction is applied to Fire scenario 4. The most interesting result in **Figure 5-16** is that, according to CFAST, the extraction system can maintain a stable hot zone up to 400 s. This would facilitate the evacuation effort.

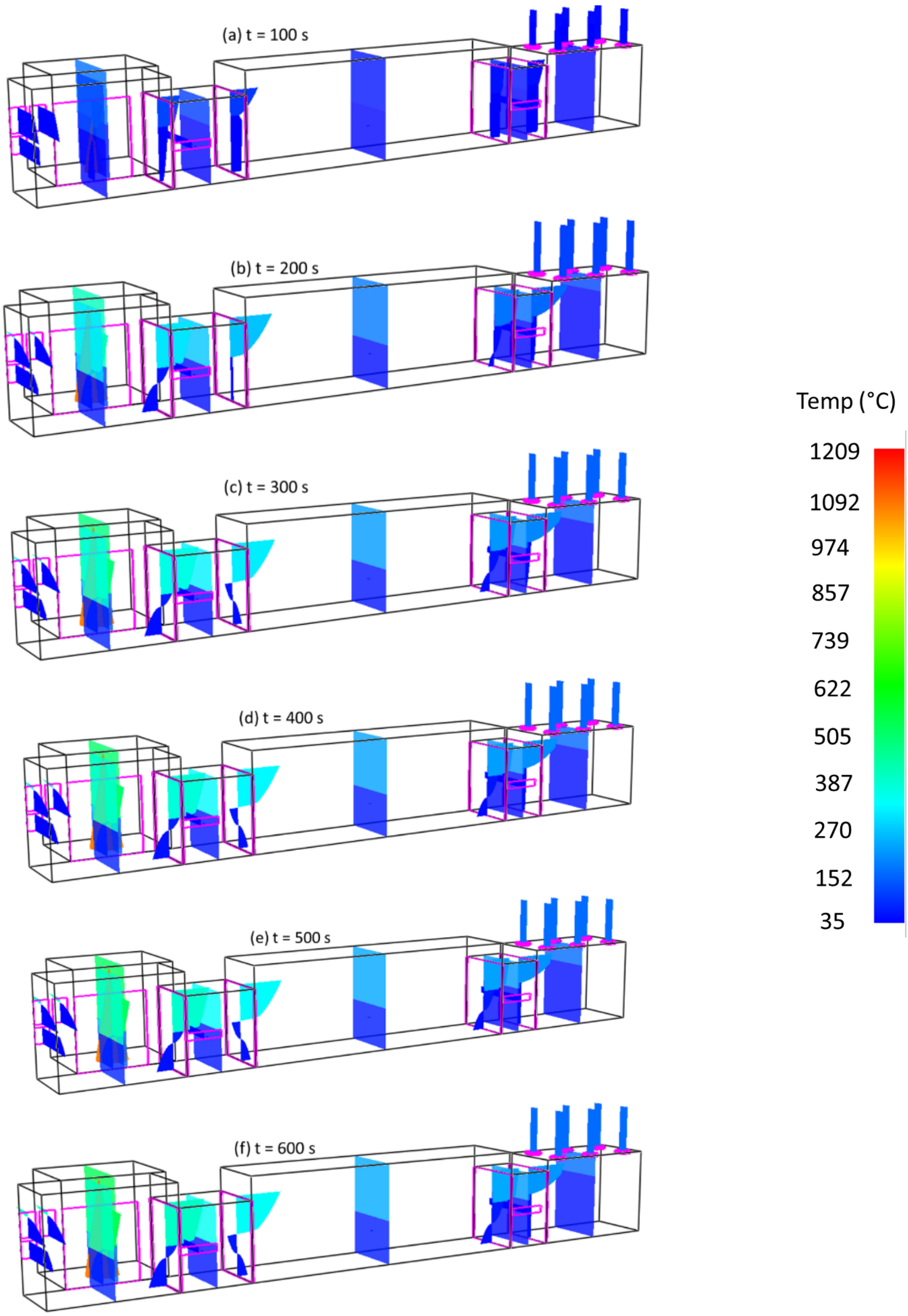


Figure 5-16: Variation of the temperature predicted by CFAST for Fire scenario 5 - (a) t = 100 s, (b) t = 200 s, (c) t = 300 s, (d) t = 400 s, (e) t = 500 s. (f) t = 600 s.

5.3.6 Comparison of the CFAST simulations for the five fire scenarios

Figure 5-17 compares the HRR curve for the five fire scenarios analyzed in CFAST. The figure also includes, for comparison, the HRR used in the prescriptive case. This prescriptive curve is covered by Fire scenarios 4 and 5. As initially observed, in Fire scenario 1 the fire is extinguished by suffocation after about 150 s. For Fire scenario 2, CFAST indicates that the air inlet can maintain the fire for a longer time period than was the case for Fire scenario 1. Fire scenario 3 follows the prescribed HRR. It is interesting to note that the HRR calculated by CFAST does not show the low-frequency variations with time that were predicted by FDS. This is due to the use of turbulence in the FDS code, something that is not considered in the CFAST simulations.

For Fire scenario 4, the predictions indicate that fire follows the prescribed HRR up to 380 s when it is extinguished due to suffocation. For Fire scenario 5, the HRR curve remains the same as that calculated by the analytical method.

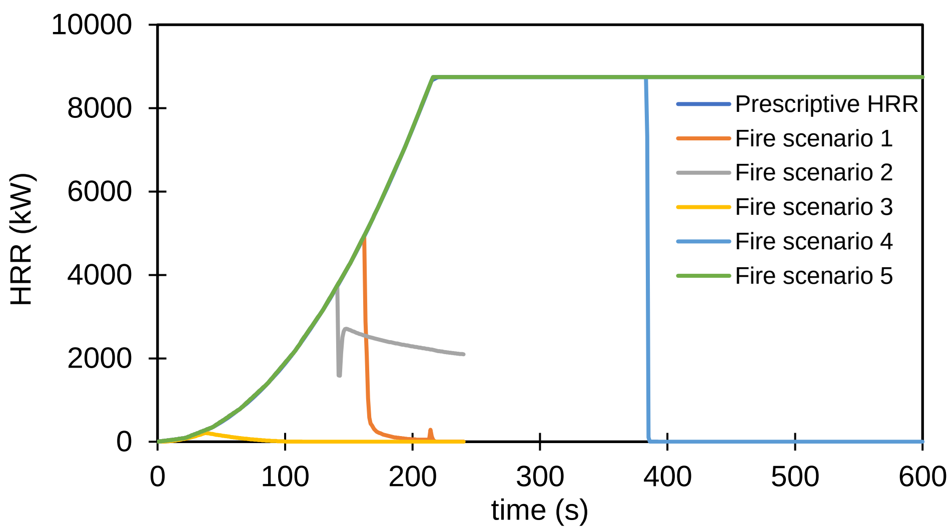


Figure 5-17: Comparison of the predicted HRR for fire scenarios 1 to 5 with CFAST. The figure also includes, for comparison, results by the prescriptive method described in Chapter 4.

5.4 FLUENT

In this section, the results of the fire simulations carried out in the FLUENT are presented. As explained above, the results of these simulations are presented in a steady state, therefore, only Fire scenario 2 and Fire scenario 5 were carried out, since they had an air inlet and outlet that allowed the stable flow to be maintained in the control volume.

5.4.1 Fire scenario 2

Due to the fact that the simulations in FLUENT were carried out assuming the products of combustion and the complexity of modeling the physical properties of the smoke, the results of the fire scenarios are presented as the dispersion of CO_2 in the room. **Figure 5-18** present iso-surfaces of the CO_2 mass fraction concentration. As this is a steady state simulation where the fuel is constantly consumed, it is not surprising that part of the CO_2 that mixes with the incoming cold air flows to the colder lower part of the cell. A significant fraction of CO_2 flows to the top and exists through the extraction system.

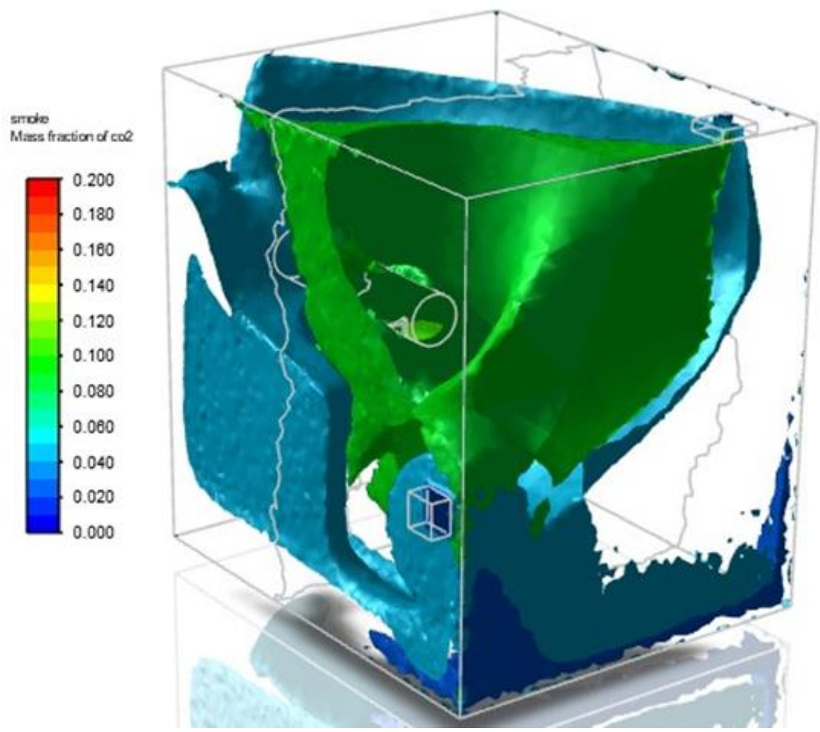


Figure 5-18: Results of the simulation for CO_2 mass fraction of Fire scenario 2 with FLUENT

The results in **Figure 5-18** give little information regarding the spread of the fire. Furthermore, it somehow contradicts the results in **Figures 5-5** and **5-6** that indicate that the air coming from the port at the wall does mix with the combustion gases and does not go down, as the FLUENT simulation suggests. It is possible that the interaction between unburned fuel and incoming gas can only be captured when a truly dynamic simulation is considered.

5.4.2 Fire scenario 5

The simulation of Fire Scenario 5 with FLUENT yields the CO_2 mass fraction iso-contours in **Figure 5-19**. The predicted highest concentration of CO_2 takes place at the source of the fire, with a maximum mass fraction of 19.7% of CO_2 in the upper part of the cell. This steady state simulation indicates that the CO_2 is dispersed along the hallway and that the upper layer is disturbed due to the presence of the exhaust system.

As was the case for Fire scenario 4, little information is gained with this CFD simulation as it is evident that the dynamic of the fire is important when understanding the flow of combustion gases in the system.

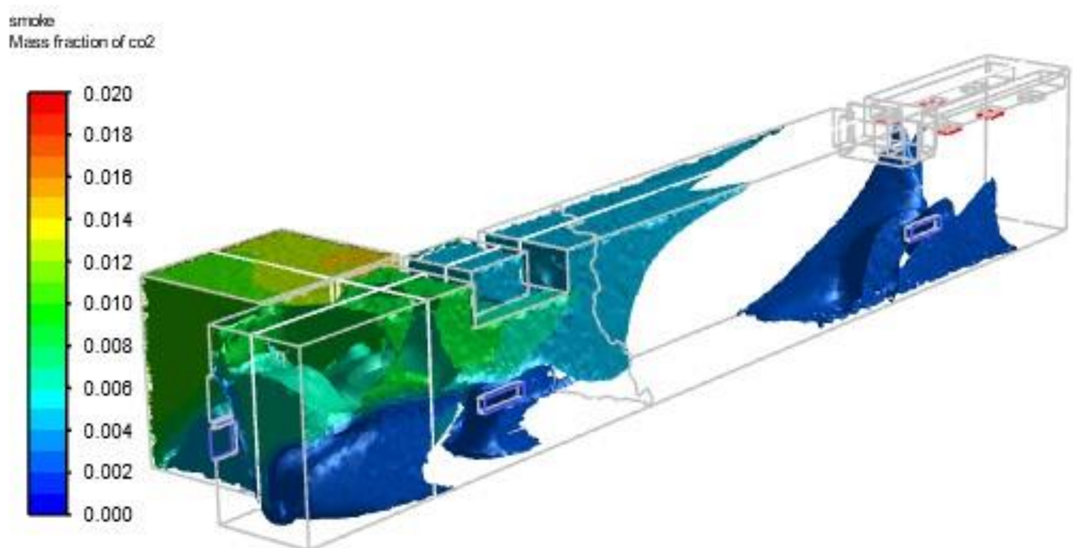


Figure 5-19: Results of the simulation for CO_2 mass fraction of Fire scenario 5

5.5 Comparison of FDS, CFAST and FLUENT Simulations

While the theory behind FDS, CFAST and FLUENT is very different, any fire-safety practitioner would demand a comparison of the predictions obtained from the three PMTs. As this study pursues more an understanding of the functionality of the PMTs, the exact analysis of the difference between all the predictions here presented is beyond its scope. The analysis below, however, attempts a very preliminary comparison that makes evidence of what kind of data is available from each PMT.

5.5.1 Confined fire – temperature distribution

Figures 5-20 to **5-22** presents the predicted temperature during the confined fire in Fire Scenario 2. The differences between the three PMTs are evident just by looking at each figure. While FDS, **Figure 5-20**, yields a detailed profile of the temperature in every spot of the plane, at different times, the results from CFAST, **Figure 5-21**, are temperatures in an upper and lower layer. The results from FLUENT, **Figure 5-22**, while giving information on various points in the space, do not allow to discern variations with time. Furthermore, the fact that a steady state and complete combustion are assumed in the CFD simulations causes very high and unrealistic temperature predictions.

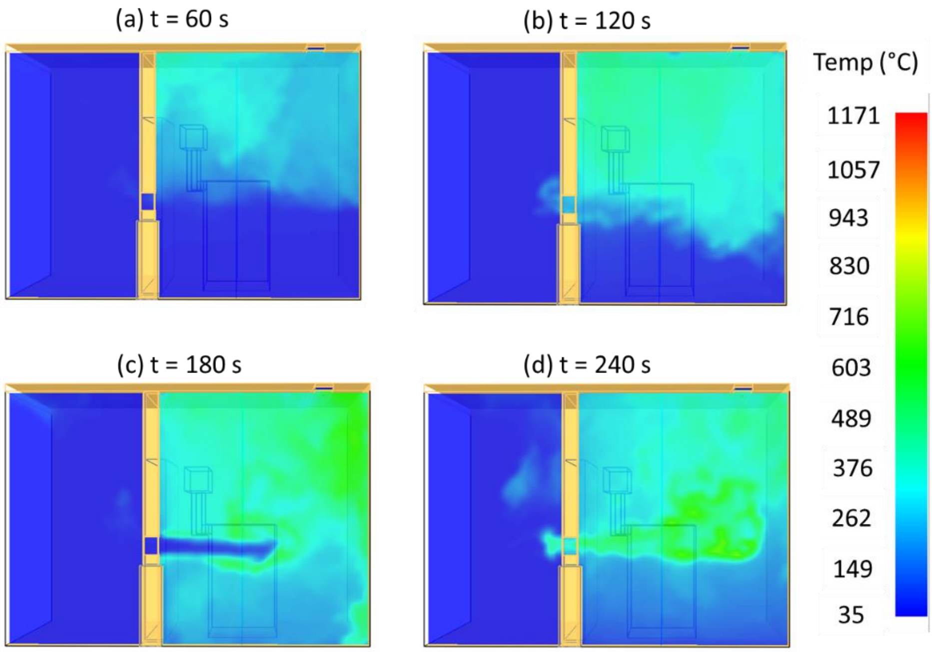


Figure 5-20: Variation of the temperature predicted by FDS for Fire scenario 2. (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 0 s

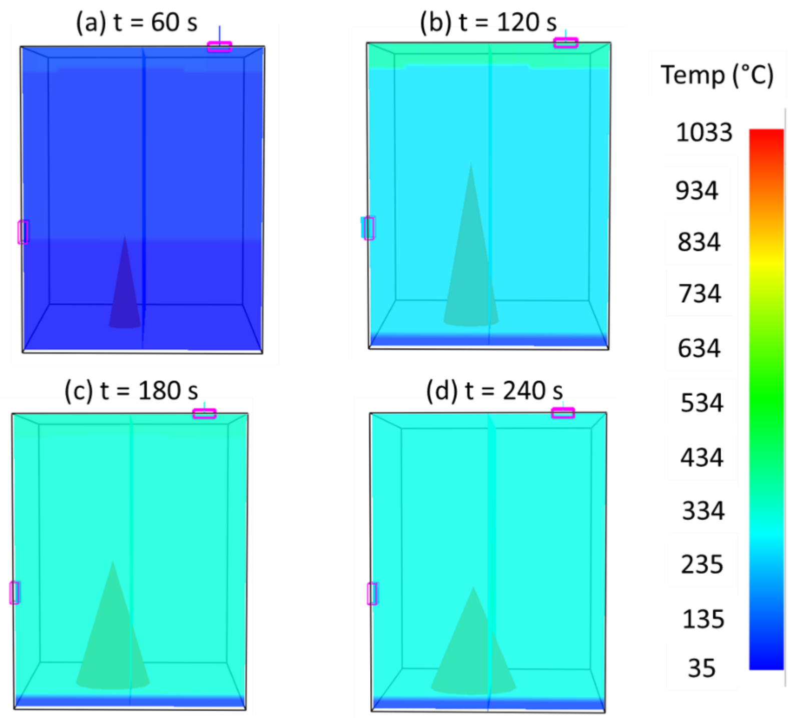


Figure 5-21: Variation of the temperature predicted by CFAST for Fire scenario 2. (a) t = 60 s, (b) t = 120 s, (c) t = 180 s, (d) t = 240 s

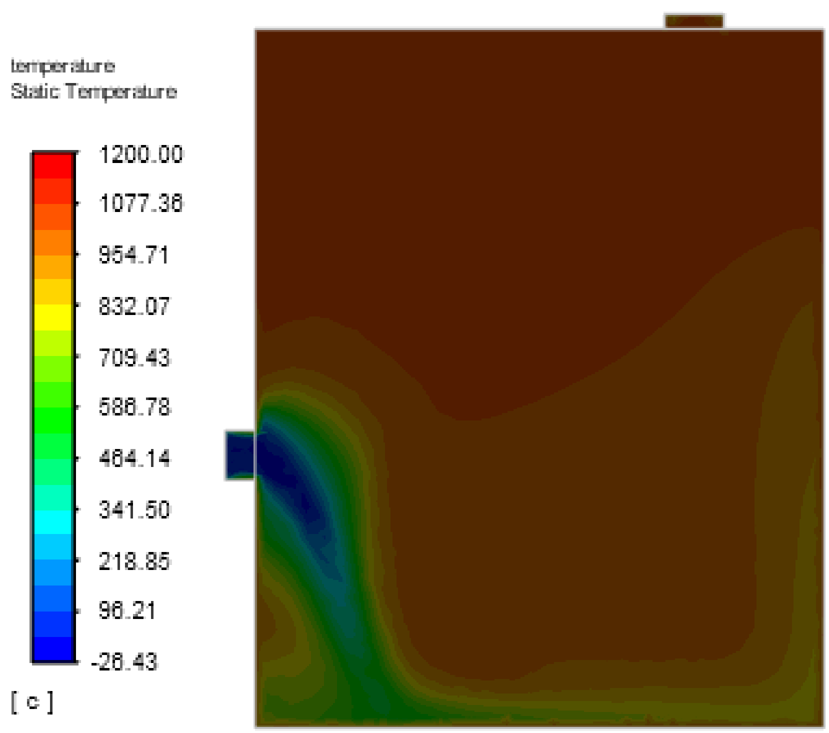


Figure 5-22: Variation of the temperature predicted by FLUENT for Fire scenario 2

5.5.2 Unconfined Fire – Temperature distribution

While in a different configuration, the difference in the predictions of the three PMTs for the unconfined fire are like those of the unconfined fire, While FDS gives a point-to-point indication on how the hot layer is disturbed by the presence of the exhaust system (**Figure 5-23**), CFAST gives only the temperature for the hot and cold layers (**Figure 5-24**), for the fire compartments used to model the hallway. Although it may be possible to infer from the predictions for CFAST that the hot layer is disrupted as its temperature constantly changes along the hallway, the results from FDS are much more evident when indicating that the exhaust system disturbs the hot layer. The FLUENT simulation (**Figure 5-25**) showed a much higher temperature, as was the case for Fire scenario 2 and does not give important information regarding the fire dynamics.

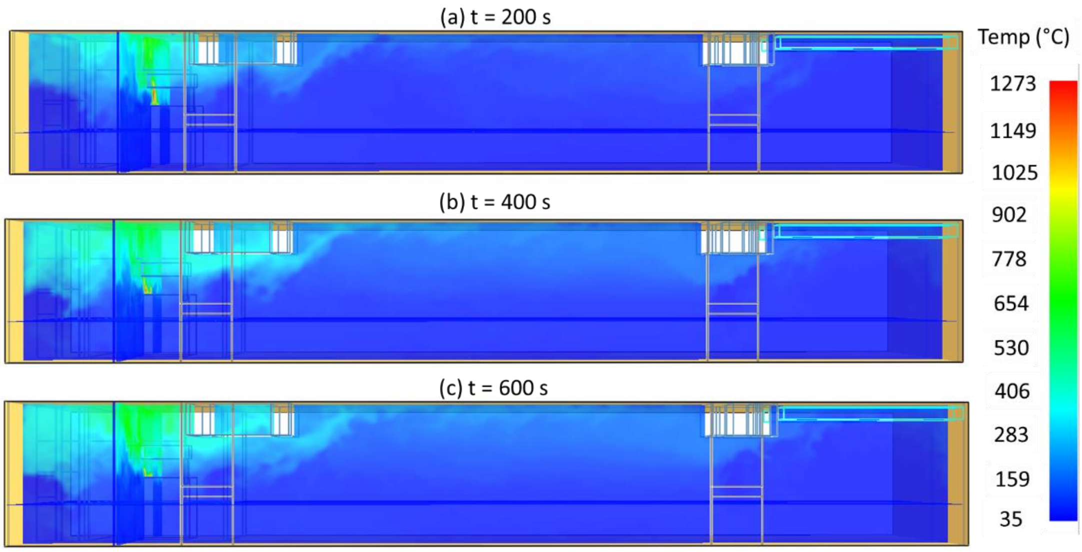


Figure 5-23: Variation of the temperature predicted by FDS for Fire scenario 5. (a) t = 200 s, (b) t = 400 s, (c) t = 600 s.

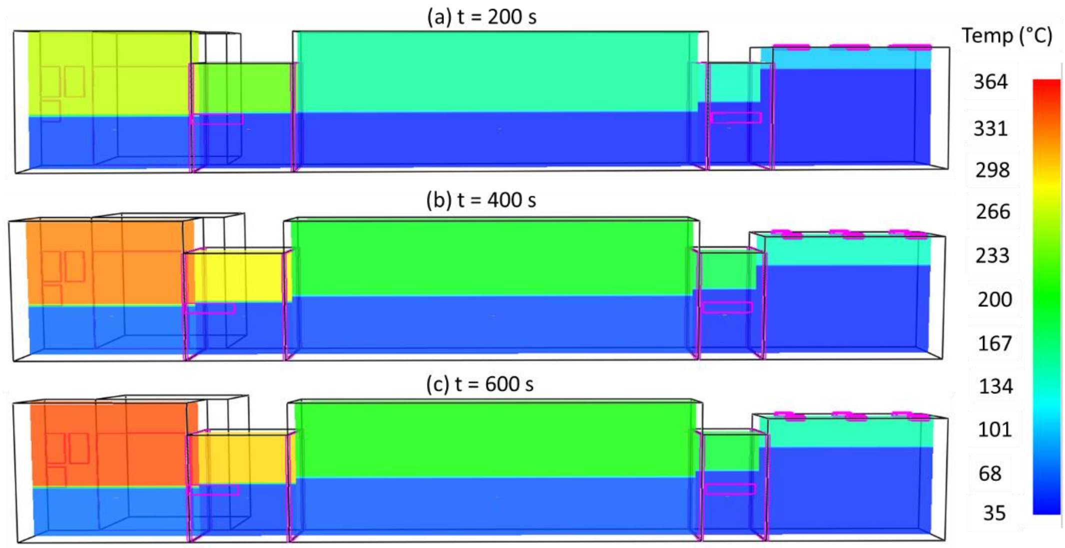


Figure 5-24: Variation of the temperature predicted by CFAST for Fire scenario 5. (a) t = 200 s, (b) t = 400 s, (c) t = 600 s.

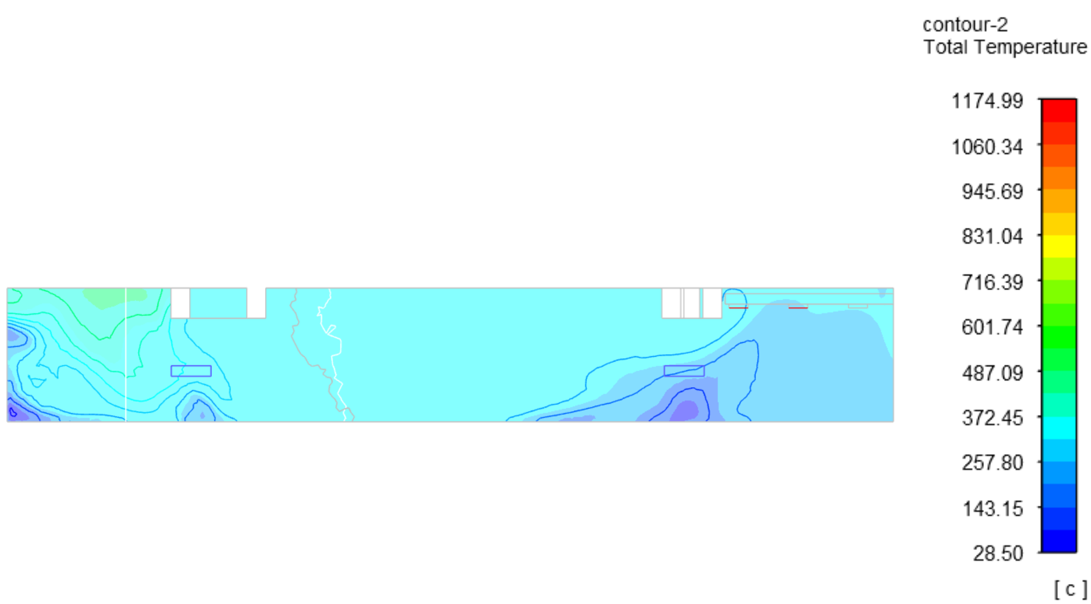


Figure 5-25: Variation of the temperature predicted by FLUENT for Fire scenario 4

5.6 Prescriptive vs Physical models

More interesting than a comparison among PMTs is the understanding that can be obtained when comparing the insight about the fire given by the prescriptive model in Chapter 4 and that obtained by the PMTs. The following sections, while not giving a thorough review, compare the prescriptive and PMTs predictions for HRR and the extinction temperature.

Although previously briefly discussed, **Figure 5-26** compares again the HRR predicted by the prescriptive method as well as those by the three PMT for Fire Scenario 2. It is important to note that, while the HRR is an input parameter for all the PMTs, FDS and CFAST calculate an “actual” HRR based on the fire conditions. In other words, prior knowledge on how the fuel burns at well controlled conditions, such as a cone calorimeter (Babrauskas & Grayson, 1990) , is used to predict an “actual” HRR based on the real conditions in the fire. The prescriptive approach would not take this into account, nor the FLUENT simulation in this study that used steady state and did not model combustion.

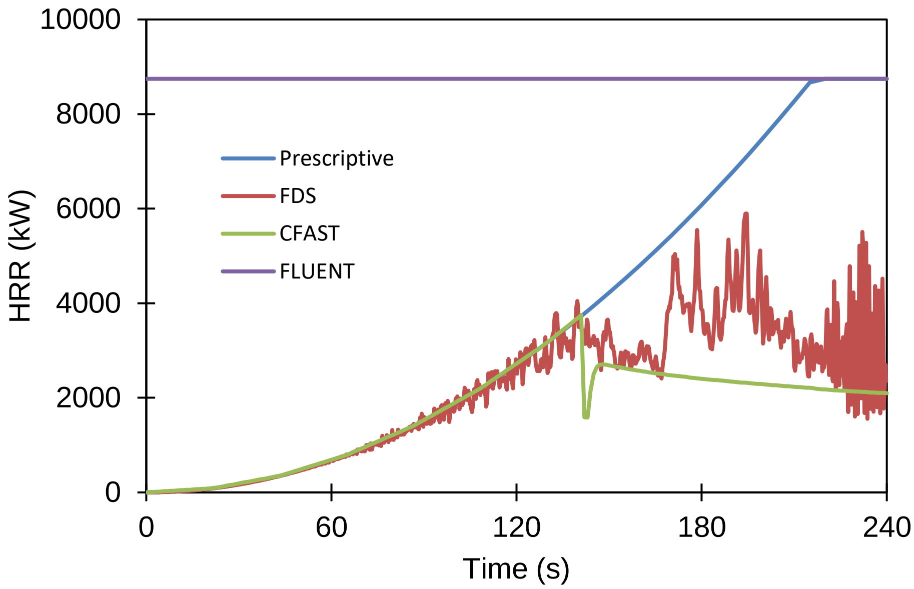


Figure 5-26: Comparison of the predicted HRR for Fire scenario 2

The prescriptive method reflects the t-squared curve that was used to characterize the HRR. As expected, the HRR increases until it finds the maximum value of HRR and from this point it becomes constant.

Both simulations, those by FDS and CFAST, recognize the low oxygen availability in the compartment and, therefore, obtain a maximum HRR that is less than half the maximum value that the prescriptive method suggests. As explained before the FDS simulation recognizes the effect of turbulence in the fire, therefore, there is a high-frequency variation in the HRR with time.

The HRR curve for the simulation carried out in FLUENT is a straight line that agrees with the maximum of the HRR of the prescriptive method. This was expected because a constant fire source, equivalent to the maximum HRR, was defined in the FLUENT simulation.

Figure 5-27 presents the results for Fire scenario 5 for the “actual” HRR either predicted or used by the PMTs. The figure shows the, already known, constant behavior for FLUENT and the t-squared curve for the prescriptive case. Given that the exhaust system in Fire scenario 5 provides oxygen to the fire, in this scenario both CFAST and FDS predict HRR curves that are very close to the input HRR. The FDS simulation presents the already explained variation because of turbulence. While CFAST and FDS provide some insight into how the environment affects the expected HRR, the prescriptive approach and the FLUENT steady state simulation fail to do this. It is possible, however, that more complex implementations to a prescriptive recommendation, e.g., correlations that make corrections because of oxygen availability, or having a dynamic FLUENT simulation that has, instead of a constant HRR, a t-squared curve as input would give more information regarding the effect of the environment on the fire. But these kinds of approaches would probably escape the fire-safety practitioners as they will require more knowledge and time than a CFAST or FDS simulation.

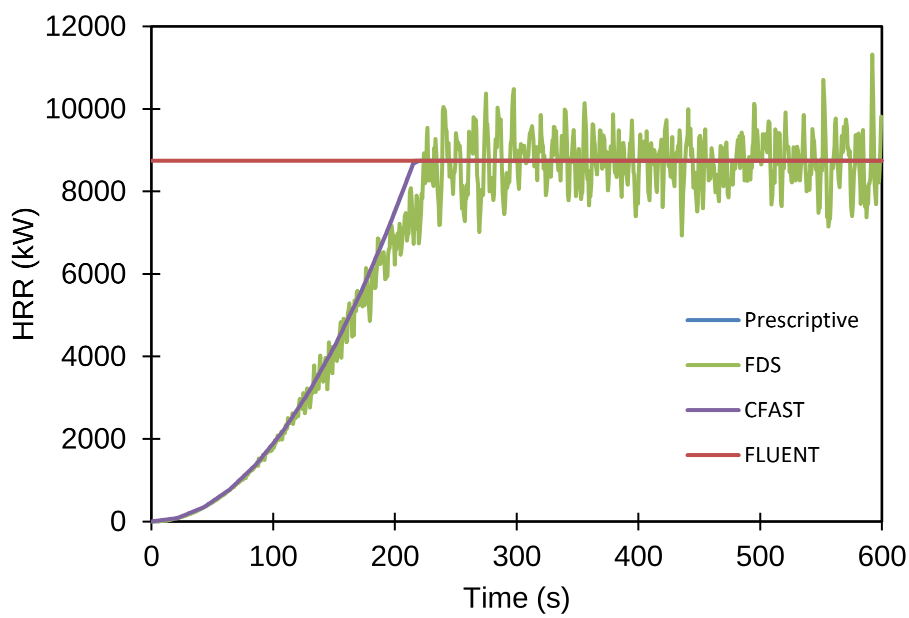


Figure 5-27: Comparison of the predicted HRR curve compare for Fire scenario 5

The predicted temperature of the smoke layer in the extraction area in **Figure 5-28** gives further insight into the information that can be obtained from the PMTs for Fire scenario 2. The steady FLUENT simulation gives a temperature much higher than that expected by the prescriptive recommendation. This could be the result of the fact that a steady-state simulation with a constant heat source was used. Clearly, this is not the best approach when modeling a fire with FLUENT.

While the predicted temperature for CFAST follows that of the prescriptive approach, at a certain point the simulations recognize the oxygen deficiency and predict a higher temperature rise at about 120 s and a lower maximum temperature. FDS also predicts a much faster temperature rise, as it probably notices that the exhaust is placed just above the fire source and a lower maximum temperature, although not as low as that predicted with CFAST. The FDS simulations presents as well the aforementioned sensitivity to turbulence, that is not captured by the other PMTs.

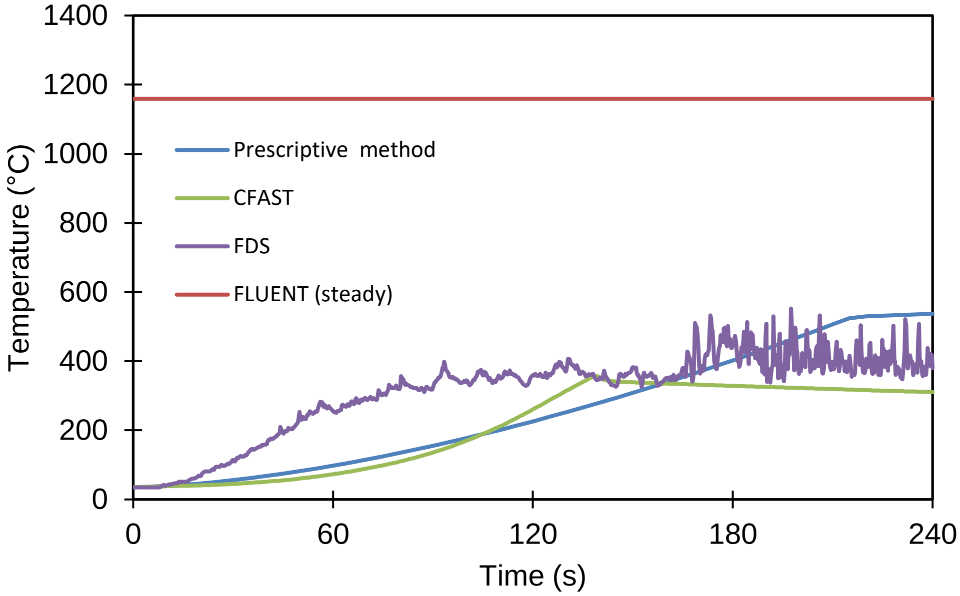


Figure 5-28: Comparison of the predicted exhaust temperature for Fire scenario 2.

Interestingly, for Fire scenario 5 some of the trends observed for Fire scenario 2 change. For instance, FLUENT now predicts the lowest temperature. This could be because the steady state simulation yields the highest mixing among the upper and lower layers and, therefore, the lowest temperature. The fact that the temperature predicted by FLUENT and that by the prescriptive recommendation are similar agrees with that conclusion.

The somewhat higher temperatures predicted by FDS and CFAST are somehow puzzling, but may be related with poor mixing for CFAST, as the zone-model approach is not the best one for hallways; and with certain degree of hot air stratification that is capture by the finer flid dynamics model in CFAST. Further study needs to be carried out to make this clearer.

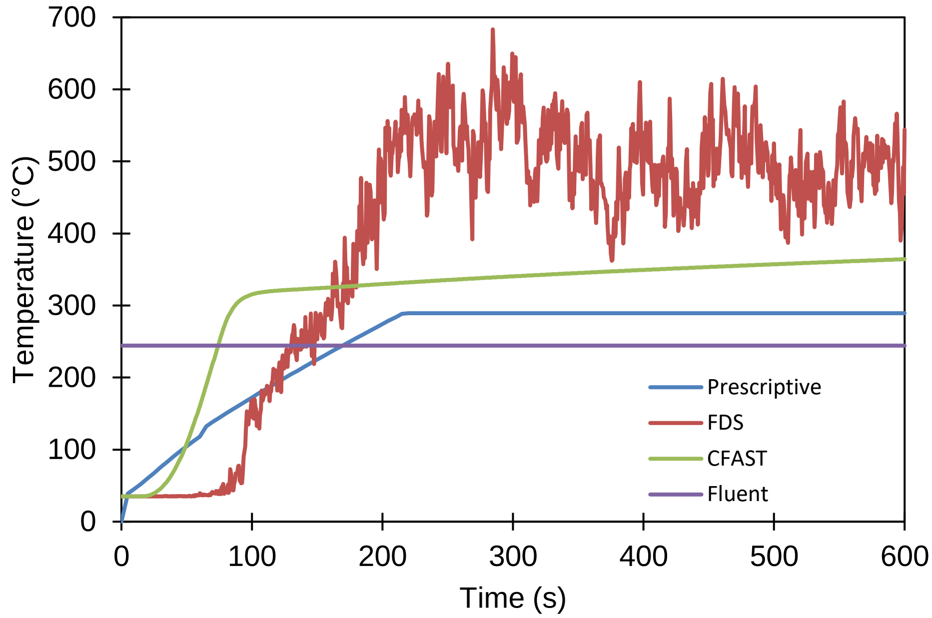


Figure 5-29: Comparison of the predicted exhaust temperature for Fire scenario 5.

5.7 ASET

This section presents the analysis of the evacuation of personnel for Fire scenario 4 and Fire scenario 5 corresponding to unconfined fire scenarios. Furthermore, as RSET and ASET are by definition of dynamic character, only the results with CFAST and FDS were analyzed. Understanding of RSET and ASET is a complex issue and some even consider that it cannot be modeled (Torero, 2011). According to what was calculated in **3.8.2**, the minimum time required for safe evacuation (RSET) is 162 s, considering the safety factor. **Table 5-2** presents the estimated the available evacuation time (ASET). APPENDIX F shows the plots that were used to infer the times in **Table 5-2**. A NO RISK entry in **Table 5-2** indicates that that condition is not obtained, i.e., that the simulation did not predict temperatures above 60°C, oxygen concentrations below 14% mol, carbon dioxide concentrations above 5% mol, carbon monoxide concentrations above 3000 ppm or a radiative heat flux higher than 2.5 kW/m^2, limits recommended in **Table 3-4**.

For the three PMTs, **Table 5-2** defines when the risk level is obtained. For instance, for FDS, with smoke extraction, a temperature higher than 60 °C is reached after 218 s. That time decreases to 184 s when there is no extraction. The predictions of ASET by CFAST, while not the same as those of FDS, follow the same trend as they recognize the importance of smoke extraction to increase ASET.

As others have argued (Torero, 2011), the ability of the PMTs to exactly capture ASET is questionable as it would be highly dependent on the inputs used in the model, particularly on the HRR. If the HRR used is the same, probably different PMT's would yield, if not the exact same solution, similar trends. This is the case in **Table 5-2** where only in one case would FDS and CFAST provide conflicting advice regarding the presence of a risk and this is in the prediction of radiative risk in the presence of a smoke detector as FDS would consider that there is no risk while CFAST indicates risk. Given the simplicity of the CFAST calculation that for radiation assumes a simple point source approximation and neglects radiative exchange between compartments and is not designed to model hallways one would prefer the FDS result.

Table 5-1: Predicted values of ASET for FDS and CFAST as based on the simulations of fire scenarios 4 (no extraction) and 5 (extraction)

Description	**Risk Level**	**FDS**		**CFAST**	
		No extraction	**Extraction**	**No extraction**	**Extraction**
Temperature	> 60 °C	184 s	218 s	**70 s**	233 s
Oxygen	< 14%	306 s	No risk	239 s	No risk
Carbon dioxide	> 5 %	357 s	No risk	349 s	No risk
Carbon Monoxide	> 3000 ppm	No Risk	No risk	No risk	No risk
Radiative heat	> 2.5 kW/m2	385 s	No risk	185 s	205 s

5.8 Comparison of the PMTs

The experience gained from the use of the three PMTs selected in this study, was used when completing **Table 5-3** that presents a comparison of some of their characteristics of FDS, CFAST and FLUENT. In 2003 Olenik and Carpenter (Olenick & Carpenter, 2003) used a simple matrix for describing the results of software available for modeling fire and smoke, survey that is still being used today (Olenick, 2023). The data in **Table 5-3** was, however, compiled to assist the fire-safety practitioner with a quick reference to these three PMTs. It firstly presents general information such as typical technical requirements (as of

2023), developer, latest version and update, webpage address, estimated license cost and technical reference. A second section describes important software characteristics, such as the mathematical method, computational cost, mesh, user interface, and how to view the results. Finally, a section describes how easy it is to get information about the software.

As mentioned several times above, a clear distinction between CFAST, the zone model, and FDS and FLUENT, the CFD (or field) PMTs, is the speed and easiness of calculations. CFAST is much faster and computationally simpler than FDS and FLUENT. FDS is, for modeling a fire, faster and simpler to use than FLUENT: CFAST and FDS are free software. FLUENT is of a commercial nature.

The theory behind each software is more complex for FLUENT and FDS and is much simpler for CFAST. However, regarding fires, the theory in FDS is more complex and available than that in FLUENT. It should be mentioned that FLUENT has the potential to construct models similar to FDS, but that would be out of reach for the typical fire practitioner.

While CFAST does not require a mesh, meshing is very simple in FDS and can get very complex in FLUENT if all the details of the geometry are to be captured. While FDS is not provided with an interface, although some commercial software, e.g., BlenderFDS (BlenderFDS, 2023) are available. CFAST does include a user-friendly interface. As commercial software, FLUENT has a very nice graphical interface, however it has many options that require some CFD knowledge to navigate to those important for a fire simulation.

Last, but not least, a fire-safety practitioner would like to have access to free information about the software's use. While all these three PMTs have good manuals, particularly FLUENT that has a detailed reference, several tutorials, and numerous videos on their applications, only FDS has a significant presence on the internet detailing how to model a fire. Probably because of its simplicity, few information is available for CFAST. FLUENT has a significant presence on the web but is rather infrequent to get examples regarding fires.

Table 5-2: Software compare.

FEATURES	FDS	CFAST	FLUENT
GENERAL INFORMATION			
Technical requirements	Operating System: 64-bit Windows 7 Disk space: 10 GB of storage space	Operating System: 32-bit Windows XP Disk space: 1 GB of storage space	Operating System: 64-bit Windows 11 or 10

FEATURES	FDS	CFAST	FLUENT
	Memory: 4GB RAM per core	Memory: 256 MB RAM	Disk space: 10.0 GB Memory: 8 GB (16GB recommended)
Developer	NIST	NIST	ANSYS
Last Version	FDS 6.7.9, SMV 6.7.21	CFAST 7.7.3, Smokeview 6.7.17	2022
Last update	June 2022	May 2022	July 2022
Webpage	https://pages.nist.gov/fds-smv/	https://pages.nist.gov/cfast/index.html	https://www.ansys.com/products/fluids/ansys-fluent
Estimated license cost	Open-source	Open-source	>50000 USD per year
Technical reference	User Manual FDS (K. McGrattan et al., 2020)	User Manual CFAST (Peacock et al., 2015a)	User Manual FLUENT (ANSYS, 2020a)
SOFTWARE			
Mathematical method	Discretization of Navier-Stokes equations - Finite volume Method (FVM)	Two-zone model that uses ODEs to describe mass and energy balance	Discretization of Navier-Stokes equations - Finite volume Method (FVM)
Turbulence model	LES	N/A	A wide variety of models
Computational Cost	Medium	Low	High

FEATURES	FDS	CFAST	FLUENT
Mesh type	Structured	N/A	Unstructured/Structured
Mesh construction	Simple	N/A	May be complex if one wants to capture all the geometry details.
Graphical user interface (GUI)	The input is on a text document where complex syntaxis rules are followed	A simple graphical interface	Friendly graphical interface with too many parameters
Results presentation	Smokeview software	Smokeview software	The simulation results are observed in the same FLUENT and can be exported to other platforms
ACCES TO INFORMATION			
Access to tutorials	Yes, YouTube and Google Groups	Did not identify	Yes, made by ANSYS
User guide/manual	Yes	Yes	Yes
Information internet	Yes	Very little information	Yes, but not over fire simulations

5.9 Recommended Procedure for Performance-based Design

The purpose of this procedure is to serve as an input so that fire safety practitioner, who make a first approach to physical simulation tools, can implement performance-based designs in a more agile way. Based in part on the experiences obtained in the development of this monograph and supported by different sources of information (Hurley, 2015; Hurley & Rosenbaum, 2015; Society of Fire Protection Engineers, 2019), the following procedure is proposed to develop the performance-based design.

1. Define Project scope

This numeral seeks to define the context in which the computer simulations will be carried out, the description of the site and its occupants, the possible sources of fire and its characteristics. Among others, it is recommended to collect and describe the following:

- Building context and characteristics

Determine site location and environmental conditions such as ambient temperature, ambient pressure, wind direction, and relative humidity. Materials and fuels must also be identified.

It is important to characterize the surroundings because they can also be affected by the fire.

- People of interest

It should be reviewed who are the stakeholders and what are their characteristics and needs. Additionally, who are the people to whom the analysis report will be directed, in such a way that the objective of the design can be clearly defined later.

- Occupant characteristics

The age, gender, state of health and training of the personnel within the facilities must be characterized.

- Building emergency response strategy, evacuation strategies and procedures.

Emergency plans should be described, as well as checking available evacuation routes and emergency lighting. Additionally, the location of the fire brigade and emergency personnel and the fire equipment tools they have must be identified.

- Fire scenarios of interest for stakeholders

In some cases, stakeholders already have defined particular risk scenarios that they are interested in analyzing, which must be added to the analysis.

- Collect fire scenarios that have occurred on the site

In the event that fire incidents have occurred in the facilities that are being analyzed, it is important to collect said information, since it can serve as an input to analyze the different strategies that are used to attend to fire events, in addition to serving as an input to compare with the results of the analysis performed.

- Make a Fire risk analysis

In the fire risk analysis, all the possible fire sources of the site are determined, and the behavior of the fire is analyzed. They are ranked from highest to lowest risk, considering the frequency probability of the events vs. the consequences of these in the facilities analyzed. In the event that the chain of events that triggered the fire cannot be easily determined, analysis strategies such as What If? can be used, and historical events can be consulted in fire databases.

Once the fire event to be analyzed has been identified, a presentation of the fire scenario or scenarios is made. It is recommended to make a plot of the general location of the fire event for each of the scenarios analyzed. This plot must identify the source of the fire, additional fuel elements, air openings and inlets, ventilation and smoke extraction systems, and evacuation routes available to personnel.

2. Identify goals

The NFPA (National Fire Protection Association, 2021a) has four primary objectives in fire protection. These objectives define the how the fire should be analyzed.

Human safety. If the objective is human safety, it is recommended to check gas concentrations, temperatures, and visibility. Designs focused on life safety focus on determining the ASET.

Property protection. For this purpose, it is important to review the temperatures in the walls and ceilings and verify these values with those reported in the literature or in the structural designs for the elements. Usually in these simulations the performance of the fire extinguishing systems is also evaluated.

Business/Mission continuity. The purpose of these analyzes is to evaluate the performance of the extinguishing systems and how they can be activated earlier to protect most of the equipment in the facilities. Additionally, it seeks to reduce the impact of the extinguishing systems on the equipment surrounding the fire scene.

Environmental protection. In this type of analysis, the smoke extraction systems, the discharge and route of the combustion gases and the route of the water from the extinguishing system to the nearby sources, after the discharge, are analyzed. The fire scenarios that seek this purpose are usually open fire scenarios, usually forest fires are investigated, and environmental management plans are analyzed.

3. Define objectives

The objective of the simulation focuses on determining why we do what we do, it is the definition of the scope of the simulation. To clearly define the objective of the simulation, some of the following questions must be asked: What do you want to achieve? Who are the stakeholders? What operation is being analyzed? What is important to analyze? Why are these simulations required? What do stakeholders want?

The process of defining the design objectives must be clear, in such a way that not only the way of presenting the results can be defined, but also the type of language used to present them. It also clarifies the scope according to the expectation of the person who will receive the information, since a report for a group of scientists will not be the same as for a group of system operators or for a business manager. It is important to bring the results closer to the stakeholders.

4. Develop performance criteria

This area defines which are the variables that are going to be measured and the process by means of which these measurements are going to be carried out in such a way that it is possible to define the minimum number of levels required to evaluate the results of the simulation, make comparisons between the different results of the simulations, and validate that the results corresponding to the real fire behavior.

The variables that are recommended to be measured are the following: temperature, speed, concentration of O_2, CO, and CO_2. In some cases, it is also required to measure visibility and other fire byproducts such as HCN.

5. Develop fire scenarios and design fire scenarios

This numeral is, perhaps, the most important in the performance-based design process. It is recommended that at this point to present a simple presentation of the physical simulation tool that will be used, in such a way that the technical characteristics of the software used when proposing the fire scenarios are considered.

- Describe the fire scenarios

The fire scenario must be related to how the sequence of events of the fire occurs and how it ignites. A general description of the site and the materials in it must also be made as well as any extinction systems implemented, or smoke extraction systems present.

In addition to the above, the area or areas in which the fire breaks out must be defined. It is important to clearly define the fire impact area, since the HRR is directly related to the fire area (see Equation (3-1))

To define the location of measurement devices and slices, it is recommended that temperature sensors be installed above the source of the fire, in the air inlet dampers and in the exhaust grilles. Additionally, Slices X, Y in the center of the fire source and in the center of the corridors and Z at a height of 2m for human safety analysis.

- Define the assumptions

All simplifications or fundamental assumptions that were made at a general level for the simulation analysis should be described. It must be considered, when defining the simplifications, that the limitations of the PMT must also be described, as well as the lack of knowledge in the phenomenon analyzed, in such a way that all possible consequences of simplifications can be identified.

- Set the simulation time

Attention must be paid to the time of the simulation because it is essential to determinate the severity of the fire (Khan et al., 2021). The time of the fire must be adjusted considering the time of the growth and decay stages.

A minimum simulation time of 60 s is recommended, since most of the HRR curves exceed this value, and from this value the time required can be increased according to the selected fire. However, if the simulation time is required to be greater than 30 minutes, it is recommended that the simulation requirements be re-evaluated to adjust it, since it is a very long computational time from a computational point of view.

If it is required to evaluate components related to human safety, it is recommended to initially perform an analytical calculation to determine the RSET and, based on this result, determine the simulation time.

- Determinate the fire design curve

The first source of consultation to determine the HRR curve are the real studies that have been carried out at an experimental level, however, in case there is no record of the real behavior of the HRR curve, it is recommended to consult documents such as the NUREG-2232 (U.S. Nuclear Regulatory Commission & Electric Power Research Institute (EPRI), 2019) of the U.S: Nuclear Regulatory Commission, in which different HRRs are found for different elements found in nuclear power plants. Additionally, a prescriptively recommended t-squared type curve can be used (Hurley, 2015; National Fire Protection Association, 2021b, 2021d).

In case there are other fuel elements, the HRR must be defined for each of these elements and the ignition temperature, in addition to the other chemical and thermal properties of these elements.

- Determine the chemical and thermal properties of the fire source

In addition to defining the maximum HRR and defining the fire curve, it is important to consult the chemical properties of the element being analyzed, in such a way that it is possible to get as close as possible to the behavior of the element in a real fire. For the above, the chemical formula must be defined, as well as the autoignition temperature (AIT), the ignition temperature, the heat of combustion, soot, and CO,yields, and the radiative fraction. It is recommended to consult the chemical properties in SFPE Handbook of Fire Protection Engineering (Hurley, 2015) and Drysdale's Fire Dynamics (Drysdale, 2011).

- Define the geometry of the control volume

Determine the geometry of the fire scenario, which is known as the domain of the model (boundary conditions). For this, it is recommended to simplify the geometry of the site in those areas in which it is not decisive to have such exact results, such as areas far from the source of the fire. In such a way, that it is possible to carry out a simpler meshing in these areas.

- Determinate the inlets and outlets to control volume (initial and boundary conditions)

The air inlets and outlets must be defined, as well as their conditions in case of re-entry into the control volume.

If there are air inlets, the control volume should be lengthened in these areas, so that the PMT being used can better calculate the air inlet and outlet.

- Extraction systems

For extraction systems, it must be verified that the phenomenon of plugholing does not occur in the extraction, therefore, the extraction dampers must be spaced in agreement with regulations (National Fire Protection Association, 2021b, 2022c).

- Define the mesh size

Regarding the meshing process, it must be considered that the size of the mesh must be adjusted according to the results to be obtained. To determine the resolution or size of the mesh by means of the equivalent fire diameter equation for the fire, it is recommended to maintain the relationship presented in the FDS User Manual (K. McGrattan et al., 2020): $5 < D^*/\delta x < 10$. The above allows a compromise between computational cost and accuracy.

However, if it is necessary to find the best results in specific sites, the mesh size must be optimized by means of a sensitivity analysis, in such a way that the mesh is refined in those areas where the most accurate results are required and guarantee mash independence.

- Sensitivity analysis of importat parameters

A sensitivity analysis of the most important should be carried out. This to understand the sensitivity of the predictions to the simulation parameters. Some important parameters are HRR, ignition temperatures, and radiative fraction. See reference (Jahn et al., 2008) for more details.

6. **Develop trial designs**

The purpose of this step is to propose the different modifications to the analyzed fire scenario, in such a way that the compliance with the objectives and goals can be verified. Possible optimization to the proposed design is reviewed, such as improving the arrangement of nozzles and sprinklers; relocating the smoke extraction grills or adding more if it is the case; and installing firewalls. The result of the proposed optimization shod improve on the minimum protection conditions required by the regulations.

7. **Evaluate trial designs**

In this numeral, it must be verified if the proposed test scenarios meet the proposed objectives and which of the proposed design options are viable, both in the performance of the systems and within the interests of the stakeholders (cost, time, and scope).

Additionally, to verify that the fire scenarios are adequately developed, the test fires that have been carried out experimentally can be verified, and the validation documents of the simulation programs can be verified (ANSYS, 2020b; K. B. McGrattan, 2006b; Mcgrattan & Hostikka, 2013). It is also recommended to run simulations of the fire scenario in other physical simulation tools to compare the results obtained, or to document it in a completely prescriptive manner, since some standards such as NFPA 850 (National Fire Protection Association, 2020) present fire scenarios that have occurred in similar facilities.

8. Select the final design

After the different alternatives have been shared with the stakeholders, the selection of the final design and its detailed engineering must be carried out.

9. Prepare fire protection design brief

A summary document should be prepared explaining the considerations that were considered in the design and describing the calculation process carried out and presenting the results. It is proposed to use the steps of this procedure as content of the design brief.

6 Conclusions and recommendations

6.1 Conclusions

- In general, it was possible to implement performance-based designs for a fire in a power transformer in an underground hydroelectric power plant, finding a clear procedure to analyze each of the proposed fire scenarios, and considering the difficulties of each of the PMT's such as: the relationship between the accuracy of the results and the computational cost, the learning of each of the programming and configuration codes, and the knowledge of the mathematical models used by each of the PMT's.

- PMTs of zone models and field models (CFD) were identified for fire simulation. Although the two-zone models, such as the CFAST, are simple in their configuration and deliver results very quickly, they give little detail in the results and their application is limited to simulate, for example, extinction systems due to deluge or open spaces. Field models, of the FDS type, are more complicated in their configuration since it requires knowing the text language to configure the simulations, but they give much more theoretical detail and versatility in the results. In addition, there are general CFD models such as FLUENT with a limited application when simulating a fire and more for fire extinguishing systems.

- In the study of the use of PMT's, it was observed that the easiest program to use is CFAST since its graphical interface and simple mathematical model facilitates the use of the tool. Since the FDS is considered the "standard" in the industry, it was possible to find technical information and interest groups that can be supported for the assembly of the different simulations, which facilitated the learning process of the tool. Regarding FLUENT, the difficulty presented in the configuration of the proposed scenarios was clear.

- Comparisons were made of the results of the HRR curve and the temperature of the smoke layer, both for the results obtained in the different PMTs and for the results obtained by the prescriptive method. It was observed that, for certain cases, the results of the prescriptive method are close to the results by means of PMT, but they do not do so adequately for fire scenarios in compartments in which the fire is exhausted due to a decrease in oxygen concentration.

- A general procedure for the implementation of performance-based designs was proposed, which is expected to be a starting point for the Fire Protection Engineering student to develop their analysis process more agilely.

6.2 Recommendations

- It is recommended that, before carrying out a simulation, a calculation of the fire scenario is carried out by prescriptive recommendations to verify that the results obtained later by means of physical modelling tools are consistent. Although a prescriptive recommendation is not exact for all cases, it facilitates the uncertainty in the approval of the results and is recommended for those cases in which a fast result with a flexible degree of accuracy is required.

- To select a physical modelling tool, one must take into account the time required to obtain the calculations, the level of accuracy required in the results, the computer equipment in which the simulations are intended to be carried out, the type of results that they need to be presented, the above, because a tool as simple and versatile as CFAST may be enough to obtain the required results.

- For cases in which there are complex geometries such as arched ceilings, long corridors and unconfined fire scenarios, use of computer tools such as the FDS is recommended, in addition to the fact that this program is the "standard" in simulation of fire events.

- Given the long simulation times in the transient state, it is recommended to use FLUENT when it is necessary to analyze scenarios in which the fire is fully developed, since these can be simulated in a steady state. Additionally, FLUENT should be used in scenarios where there is an air inlet and air outlet from the control volume.

- To perform a simulation in FLUENT in a better way, it is proposed to characterize the fire as a generation of a heat source that enters the control volume and use an UDT code to characterize the fire source and the fire curve. In this way, minimum oxygen values required for ignition can be defined.

- Additionally, it is recommended to study Non-premixed combustion models, since some of them allow replicating gas combustion and facilitate the characterization of combustion products.

- Finally, it is recommended for future studies to use the FireFoam tool (WiKi, 2021), developed by Factory Mutual (FM) to replicate the simulations carried out in this monograph. This is due to the fact that this tool was developed for simulations that relate fluid mechanics, heat transfer and combustion and uses the OpenFoam solver for the simulation of fire scenarios and is, perhaps, the second most used at the research level after FDS.

A. Appendix A: General variables and entrance values

Variable	Name	Value	Units
T,amb	Ambient temperature	35	°C
(RH)	Relative Humidity	55	%
Pressure	Atmospheric pressure	89278	Pa
Fuel	Transformer oil	$C_{14}H_{28}$	-
S,yield	Soot Yield	0.097	
CO, Yield	CO Yield	0.041	
Cp. Concrete	Specific heat concrete	1000	J / kg K
	Density concrete	2300	kg / m3
	Thermal conductivity, concrete	1.6	W/m K
	Emissivity, concrete	0.8	-
	Specific heat steel	600	J / kg K
	Density steel	7850	kg / m3

Variable	Name	Value	Units
	Thermal conductivity, steel	45	W/m K
	Emissivity, steel	0.8	-

B. Appendix B: Sensitivity analysis of heat release rate

As previously excluded during the definition of the HRR curve (see **3.4**), for an electrical transformer, the influence of the stone-fill pits located in the lower part of electric transformer has a direct incidence on the behavior of the fire. Particularly, this stone-fill pits lower the temperature and control the combustion air.

Figure B-1 shows the sensitivity analysis performed for the HRR, in which the HRR input variables were modified in the FDS tool for Fire scenario 2 (confined fire with smoke extraction). The inputs for the fire source in FDS are HRRPUA, HRR per unit of area, and TAU_Q, which corresponds to time after effective ignition, which is the time to reach the steady state, and is a parameter that prescribes the HRR ramp for a t-squared growth rate. Initially, the HRR was set at its maximum value with HRRPUA of 1534.3 kW/m^2 and TAU_Q was set in 215.9 s, both represented in **Figure B-1** as HRR-100%. In this sensitivity analysis, the entrance values were modified for HRR at 25% (HRR-25%), 50% (HRR-50%) and 75% (HRR-75%), with the intention of representing a lower power of the fire, due to the configuration of the transformer cell, and, to the loss of fuel and, the value of TAU_Q at 80% (TAU_Q-80%) and at 120% (TAU_Q-120%), representing the effect of the stones around the transformer, which can accelerate or delay the effect of fire, in this case the HRR.

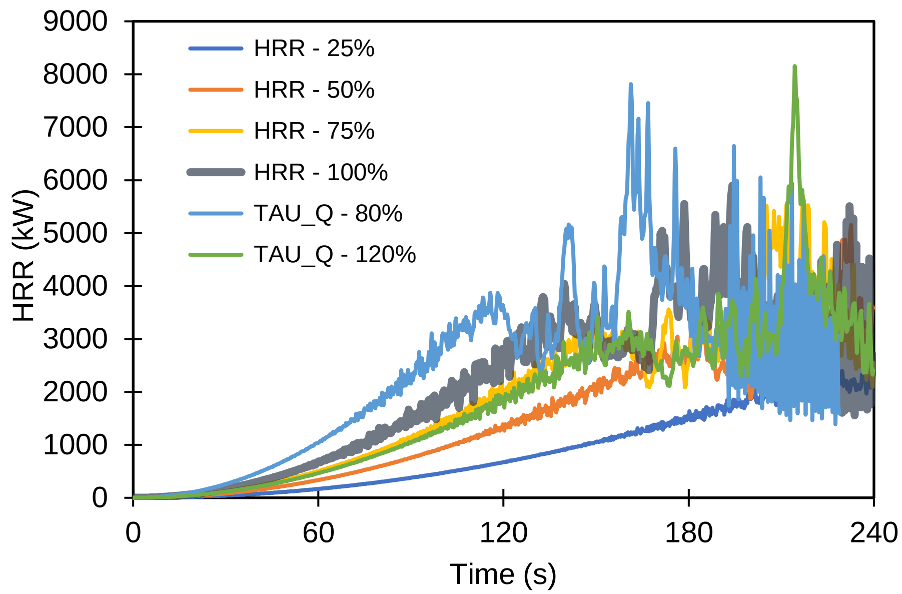


Figure B-1: Comparison of HRR for sensitivity analysis in Fire scenario 2

According to what was observed in **Figure B-1**, the HRR increases according to the prescribed curve, however, it stops increasing and take a steady state in values close to 3000 kW, much lower than the maximum value of HRR that was estimated at 8745 kW (see **Figure 3-2**). It is assumed that the increase in the HRR for this fire scenario is fundamentally controlled by the availability of oxygen in the room, as identified in **5.2.6**. Therefore, it is possible to determine that the maximum value of the HRR, for this fire scenario, is fundamentally controlled by the air inlet and outlet conditions in the transformer cell and not solely by the variations in the HRR product of stone- filled pits.

In addition to the above, in **Figure B-2** a comparison was made for the temperature measured in the smoke extraction damper (see **Figure 4-2**), which supposes the maximum temperature in the extraction ducts and that allows to properly select the equipment for the smoke extraction system . For this case, it was observed that the temperature presents a behavior like that shown for the HRR, in which there is an increase in each of the curves that depends on the configuration of the HRR, but it converges to a steady state lower than expected. (See **Figure 3-3**).

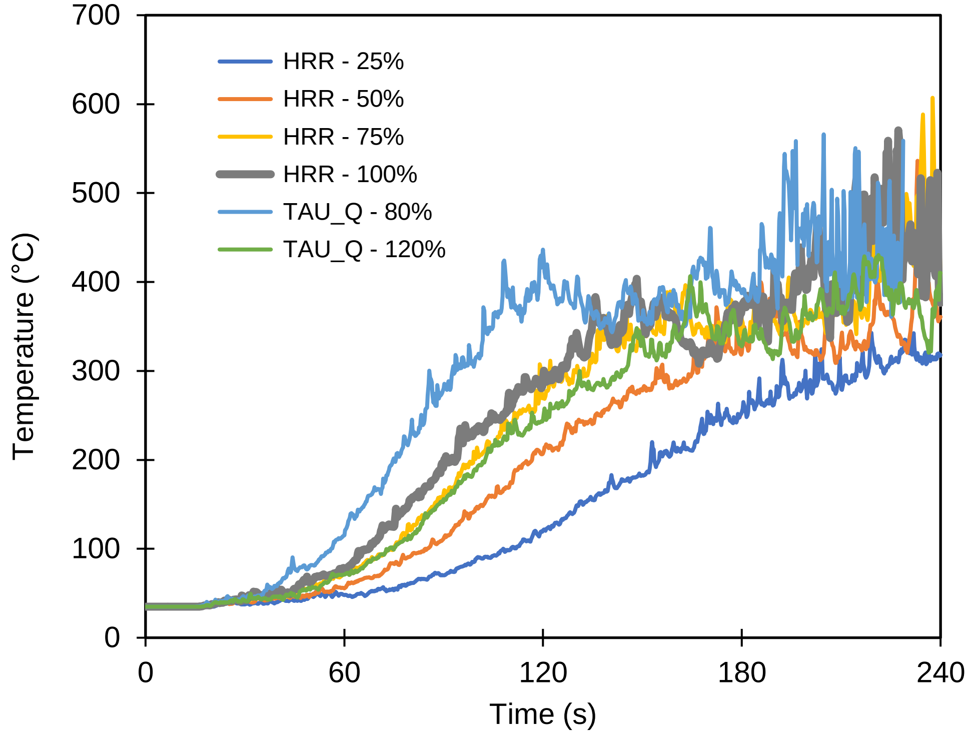


Figure B-2: Comparison of temperature at extraction point for sensitivity analysis of HRR in Fire scenario 2

C. Appendix C: FDS Simulation programming

FDS – FIRE SCENARIO 1 -

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FDS – FIRE SCENARIO 2

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&DEVC ID='CO2_3', XYZ=5.125,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_4', XYZ=5.125,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&SLCF PBY= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBX= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBY= 6.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBX= 8, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /

&DEVC ID='CO_1', XYZ=1.25,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_2', XYZ=1.25,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_3', XYZ=5.125,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_4', XYZ=5.125,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON
MONOXIDE'/
&SLCF PBY= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBX= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBY= 6.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBX= 8, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBX= 1.25, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /

&DEVC ID='RHF_1', XYZ=1.25,1,2,  QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_2', XYZ=1.25,5.85,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_3', XYZ=5.125,1,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_4', XYZ=5.125,5.85,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&BNDF QUANTITY='RADIATIVE HEAT FLUX' /

&TAIL / End of file.
```

FDS – FIRE SCENARIO 3

```
&HEAD CHID='fire_scenario_3', TITLE= 'Confined Fire – fire_scenario 3' /

#####Initial conditions#####

&MESH IJK=100,70,100,  XB=0,10,0,7,0,7.2 / mesh

&TIME T_END=240. / time
&DUMP DT_RESTART=10/
&MISC TMPA=35, RESTART=.FALSE./

###Geometry #####

&MATL ID = 'CONCRETE'
FYI = 'walls'
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 1
DENSITY = 2300. /

&MATL ID = 'STEEL'
FYI = 'doors'
CONDUCTIVITY = 45
SPECIFIC_HEAT = 0.6
DENSITY = 1440. /

&OBST XB=2.5,4.5,2,4.85,0,3.3, MATL_ID='STEEL', COLOR='PURPLE' / Transformer
&OBST XB=4.45,5.15,1.8,5,4.3,5.03, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.65,4.95,4.55,4.85,3,4.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.5,4.65,4.55,4.85,3,3.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.65,4.95,2,2.3,3,4.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.5,4.65,2,2.3,3,3.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer

&OBST XB=5.75,6.15,0,7,0,7, MATL_ID = 'CONCRETE'/ enclosure
&OBST XB=0,10,0,7,7,7.2, MATL_ID = 'CONCRETE'/ enclosure
&OBST XB=5.7,6.25,0,5.5,0,5.2, MATL_ID = 'STEEL', COLOR='GRAY' / enclosure
&OBST XB=5.7,6.25,6,7,0,2.2, MATL_ID='STEEL', COLOR='GRAY' / enclosure
&OBST XB=1,1.5,6.4,6.9,6.9,7.2, MATL_ID='STEEL', COLOR='GRAY' / enclosure

#### Fire #####

&SURF ID='fire', HRRPUA=1534.3, E_COEFFICIENT=0.064, TAU_Q=-215.94 /
&VENT XB=2.5,4.5,2,4.85,3.3,3.3, SURF_ID='fire', COLOR='RED' /

&REAC ID='REACTION_1',
FUEL = 'REAC_FUEL',
FORMULA = 'C14H28',
HEAT_OF_COMBUSTION= 46400,
CO_YIELD = 0.041,
SOOT_YIELD = 0.097,
IDEAL=.TRUE./

###### Extraction #######
&HOLE XB=1,1.5,6.4,6.9,6.9,7.1/
```

```
&SURF ID='EXHAUST', VEL=6.092, COLOR='BLUE' /
&VENT XB=1,1.5,6.4,6.9,7.1,7.1, SURF_ID='EXHAUST'/

#######Air entrance #######
&VENT MB='XMAX', SURF_ID='OPEN' /
&HOLE XB=5.7,6.25,6.25,6.75,2.5,3/

######Deluge#####
&SPEC ID='WATER VAPOR'/
&PART ID='water drops', DIAMETER=1000., SPEC_ID='WATER VAPOR' /

&PROP ID='Nozzle'
OFFSET=0.05
PART_ID='water drops'
FLOW_RATE=30.28
K_FACTOR=25.9
ORIFICE_DIAMETER=0.00635
SPRAY_ANGLE=0.0,47.5
SMOKEVIEW_ID='nozzle'

&DEVC XYZ=0.3,2,0.8, PROP_ID='Nozzle', ORIENTATION=1,0,0, QUANTITY='TIME',SETPOINT=30., ID='noz_1' /
&DEVC XYZ=0.3,2,2, PROP_ID='Nozzle', ORIENTATION=1,0,0, QUANTITY='TIME',SETPOINT=30., ID='noz_2' /
&DEVC XYZ=0.3,4,2, PROP_ID='Nozzle', ORIENTATION=1,0,0, QUANTITY='TIME',SETPOINT=30., ID='noz_3' /
&DEVC XYZ=0.3,4,0.8, PROP_ID='Nozzle', ORIENTATION=1,0,0, QUANTITY='TIME',SETPOINT=30., ID='noz_4' /
&DEVC XYZ=0.3,2,3.4, PROP_ID='Nozzle', ORIENTATION=1,0,0, QUANTITY='TIME',SETPOINT=30., ID='noz_5' /
&DEVC XYZ=0.3,4,3.4, PROP_ID='Nozzle', ORIENTATION=1,0,0, QUANTITY='TIME',SETPOINT=30., ID='noz_6' /
&DEVC XYZ=2.7,0.2,2.5, PROP_ID='Nozzle', ORIENTATION=0,1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_7' /
&DEVC XYZ=2.7,0.2,0.8, PROP_ID='Nozzle', ORIENTATION=0,1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_8' /
&DEVC XYZ=4.2,0.2,0.8, PROP_ID='Nozzle', ORIENTATION=0,1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_9' /
&DEVC XYZ=4.2,0.2,2.5, PROP_ID='Nozzle', ORIENTATION=0,1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_10' /
&DEVC XYZ=2.7,0.2,4.2, PROP_ID='Nozzle', ORIENTATION=0,1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_11' /
&DEVC XYZ=4.2,0.2,4.2, PROP_ID='Nozzle', ORIENTATION=0,1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_12' /
&DEVC XYZ=2.7,6.7,2.5, PROP_ID='Nozzle', ORIENTATION=0,-1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_13' /
&DEVC XYZ=2.7,6.7,0.8, PROP_ID='Nozzle', ORIENTATION=0,-1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_14' /
&DEVC XYZ=4.2,6.7,0.8, PROP_ID='Nozzle', ORIENTATION=0,-1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_15' /
&DEVC XYZ=4.2,6.7,2.5, PROP_ID='Nozzle', ORIENTATION=0,-1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_16' /
&DEVC XYZ=2.7,6.7,4.2, PROP_ID='Nozzle', ORIENTATION=0,-1,0, QUANTITY='TIME',SETPOINT=30., ID='noz_17' /
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&DEVC XYZ=4.2,6.7,4.2, PROP_ID='Nozzle', ORIENTATION=0,-1,0, QUANTITY='TIME',SETPOINT=30.,
ID='noz_18' /
&DEVC XYZ=5.3,2,0.8, PROP_ID='Nozzle', ORIENTATION=-1,0,0, QUANTITY='TIME',SETPOINT=30.,
ID='noz_19' /
&DEVC XYZ=5.3,2,2.5, PROP_ID='Nozzle', ORIENTATION=-1,0,0, QUANTITY='TIME',SETPOINT=30.,
ID='noz_20' /
&DEVC XYZ=5.3,4,2.5, PROP_ID='Nozzle', ORIENTATION=-1,0,0, QUANTITY='TIME',SETPOINT=30.,
ID='noz_21' /
&DEVC XYZ=5.3,4,0.8, PROP_ID='Nozzle', ORIENTATION=-1,0,0, QUANTITY='TIME',SETPOINT=30.,
ID='noz_22' /
&DEVC XYZ=5.3,2,4.2, PROP_ID='Nozzle', ORIENTATION=-1,0,0, QUANTITY='TIME',SETPOINT=30.,
ID='noz_23' /
&DEVC XYZ=5.3,4,4.2, PROP_ID='Nozzle', ORIENTATION=-1,0,0, QUANTITY='TIME',SETPOINT=30.,
ID='noz_24' /
&DEVC XYZ=5.3,2,5, PROP_ID='Nozzle', ORIENTATION=-1,0,-1, QUANTITY='TIME',SETPOINT=30.,
ID='noz_25' /
&DEVC XYZ=5.3,4,5, PROP_ID='Nozzle', ORIENTATION=-1,0,-1, QUANTITY='TIME',SETPOINT=30.,
ID='noz_26' /
&MISC ALLOW_UNDERSIDE_PARTICLES=.TRUE. /

### Fire results#####
&DUMP SMOKE3d=.TRUE./

&SLCF PBX=3.5, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBX=8, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=3.5, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=6.5, QUANTITY='VELOCITY', VECTOR=.TRUE./
&DEVC ID='T_Extrac', XYZ=1.25,6.65,6.9, QUANTITY='TEMPERATURE'/
&DEVC ID='T_Techo1', XYZ=3.5,3.5,6.9, QUANTITY='TEMPERATURE'/
&DEVC ID='T_Techo2', XYZ=3.5,6.65,6.9, QUANTITY='TEMPERATURE'/
&SLCF PBX=8, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY=6.5, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /

####Human safety#######

&DEVC ID='T_1', XYZ=1.25,1,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_2', XYZ=1.25,5.85,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_3', XYZ=5.125,1,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_4', XYZ=5.125,5.85,2, QUANTITY='TEMPERATURE'/
&SLCF PBX=3.5, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY=3.5, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBZ=2, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /

&DEVC ID='ox_1', XYZ=1.25,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_2', XYZ=1.25,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_3', XYZ=5.125,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_4', XYZ=5.125,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&SLCF PBY= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /
&SLCF PBX= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /

&DEVC ID='Vis_1', XYZ=1.25,1,2, QUANTITY='VISIBILITY'/
&DEVC ID='Vis_2', XYZ=1.25,5.85,2, QUANTITY='VISIBILITY'/
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&DEVC ID='Vis_3', XYZ=5.125,1,2, QUANTITY='VISIBILITY'/
&DEVC ID='Vis_4', XYZ=5.125,5.85,2, QUANTITY='VISIBILITY'/
&SLCF PBY=3.5, QUANTITY='VISIBILITY' /
&SLCF PBX=3.5, QUANTITY='VISIBILITY' /
&SLCF PBZ=2, QUANTITY='VISIBILITY' /

&DEVC ID='CO2_1', XYZ=1.25,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_2', XYZ=1.25,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_3', XYZ=5.125,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_4', XYZ=5.125,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&SLCF PBY= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBX= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /

&DEVC ID='CO_1', XYZ=1.25,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_2', XYZ=1.25,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_3', XYZ=5.125,1,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_4', XYZ=5.125,5.85,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON
MONOXIDE'/
&SLCF PBY= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBX= 3.5, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /

&DEVC ID='RHF_1', XYZ=1.25,1,2,  QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_2', XYZ=1.25,5.85,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_3', XYZ=5.125,1,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_4', XYZ=5.125,5.85,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&BNDF QUANTITY='RADIATIVE HEAT FLUX' /

&TAIL / End of file.
```

FDS – FIRE SCENARIO 4

```
&HEAD CHID='fire_scenario_4', TITLE= 'Non confined fire – fire scenario 4' /

&MESH IJK=110,468,70,  XB=0,11,0,46.8,0,7 / mesh

&TIME T_END=600. /
&DUMP DT_RESTART=10/
&MISC TMPA=35, RESTART=.FALSE./

###Geometry####

&MATL ID = 'CONCRETE'
FYI = 'walls'
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 1
DENSITY = 2300. /

&MATL ID = 'STEEL'
FYI = 'bus ducts'
CONDUCTIVITY = 45
SPECIFIC_HEAT = 0.6
DENSITY = 1440. /
```

```
###Site####

&OBST XB=6,6.2,0,46.8,0,7, MATL_ID = 'CONCRETE', COLOR='GRAY' / enclosure
&HOLE XB=6,6.2,2.7,7.7,0,5.2/ enclosure
&OBST XB=0,0.2,2.5,9.9,0,7,  MATL_ID = 'CONCRETE', COLOR='GRAY' / enclosure
&OBST XB=0,6.2,9.7,9.9,0,7,  MATL_ID = 'CONCRETE', COLOR='GRAY' / enclosure
&OBST XB=0,6.2,2.5,2.7,0,7,  MATL_ID = 'CONCRETE', COLOR='GRAY' / enclosure
&OBST XB=10.4,10.6,0,46.8,0,7, MATL_ID = 'CONCRETE', COLOR='GRAY' / enclosure

&OBST XB=2.5,4.5,4.7,7.55,0,3.3, MATL_ID='STEEL', COLOR='PURPLE' / Transformer
&OBST XB=4.45,5.15,4.5,7.7,4.3,5.03, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.65,4.95,7.25,7.55,3,4.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.5,4.65,7.25,7.55,3,3.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.65,4.95,4.7,5,3,4.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer
&OBST XB=4.5,4.65,4.7,5,3,3.3, MATL_ID='STEEL',COLOR='PURPLE' / Transformer

&OBST XB=6.2,9.4,8.6,9.6,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs
&OBST XB=6.2,9.4,12.6,13.6,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs
&OBST XB=9.4,10.4,8.6,13.6,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs
&OBST XB=6.2,8.4,35.4,37.7,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs
&OBST XB=8.4,9.9,36.5,37.7,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs
&OBST XB=9.9,10.4,36.5,36.7,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs
&OBST XB=8.8,10.4,35.4,36.5,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs
&OBST XB=7.1,10.4,34.4,35.4,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' / ducs

&VENT MB='XMIN', SURF_ID='OPEN' / boundary
&VENT MB='XMAX', SURF_ID='OPEN' / boundary

#### Fire#####

&SURF ID='fire', HRRPUA=1534.3, E_COEFFICIENT=0.064, TAU_Q=-215.94 /
&VENT XB=2.5,4.5,4.7,7.55,3.3,3.3, SURF_ID='fire', COLOR='RED' /

&REAC ID='REACTION_1',
FUEL = 'REAC_FUEL',
FORMULA = 'C14H28',
HEAT_OF_COMBUSTION= 46400,
CO_YIELD = 0.041,
SOOT_YIELD = 0.097,
IDEAL=.TRUE./

###### Extraction #######
&SURF ID='EXHAUST', VOLUME_FLOW=0, COLOR='BLUE' /

&OBST XB=9.2,10.4,37.9,46.8,6.2,6.8, COLOR='CYAN' /
&VENT XB=9.4,10.1,38.7,39.7,6.2,6.2, SURF_ID='EXHAUST'/
&VENT XB=9.4,10.1,41.8,42.8,6.2,6.2, SURF_ID='EXHAUST'/
&VENT XB=9.4,10.1,45,46,6.2,6.2, SURF_ID='EXHAUST'/

&OBST XB=6.2,7.4,37.9,46.8,6.2,6.8, COLOR='CYAN' /
&VENT XB=6.4,7.1,38.7,39.7,6.2,6.2, SURF_ID='EXHAUST'/
&VENT XB=6.4,7.1,41.8,42.8,6.2,6.2, SURF_ID='EXHAUST'/
```

```
&VENT XB=6.4,7.1,45,46,6.2,6.2, SURF_ID='EXHAUST'/

### Fire results#####
&DUMP SMOKE3d=.TRUE./
&SLCF PBX=3.5, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBX=6.8, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBX=9.8, QUANTITY='VELOCITY', VECTOR=.TRUE./

&SLCF PBY=0.6, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=1.7, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=5.2, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=9.7, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=35.5, QUANTITY='VELOCITY', VECTOR=.TRUE./

&DEVC ID='T_1_Ext_C1', XYZ=8.3,5.2,6.9, QUANTITY='TEMPERATURE'/
&DEVC ID='T_2_Ext_GB1', XYZ=8.3,11.1,5.3, QUANTITY='TEMPERATURE'/
&DEVC ID='T_3_Ext_GB1aGB2', XYZ=8.3,22.6,6.9, QUANTITY='TEMPERATURE'/
&DEVC ID='T_4_Ext_GB2', XYZ=8.3,36.1,5.3, QUANTITY='TEMPERATURE'/

&DEVC ID='T_5_Ext_CM', XYZ=9.5,39.2,6.1, QUANTITY='TEMPERATURE'/
&DEVC ID='T_5_Ext_CEL', XYZ=6.7,39.2,6.1, QUANTITY='TEMPERATURE'/

####Huma safety#######

&DEVC ID='T_1', XYZ=8.3,0.6,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_2', XYZ=8.3,9.7,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_3', XYZ=8.3,22.6,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_4', XYZ=8.3,35.5,2, QUANTITY='TEMPERATURE'/
&SLCF PBX=8.3, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY=5.2, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /

&DEVC ID='ox_1', XYZ=8.3,0.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_2', XYZ=8.3,9.7,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_3', XYZ=8.3,22.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_4', XYZ=8.3,35.5,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&SLCF PBX= 8.3, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /
&SLCF PBY= 5.2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /

&DEVC ID='Vis_1', XYZ=8.3,0.6,2,  QUANTITY='VISIBILITY'/
&DEVC ID='Vis_2', XYZ=8.3,9.7,2, QUANTITY='VISIBILITY'/
&DEVC ID='Vis_3', XYZ=8.3,22.6,2, QUANTITY='VISIBILITY'/
&DEVC ID='Vis_4', XYZ=8.3,35.5,2, QUANTITY='VISIBILITY'/
&SLCF PBX=8.3, QUANTITY='VISIBILITY' /
&SLCF PBY=5.2, QUANTITY='VISIBILITY' /

&DEVC ID='CO2_1', XYZ=8.3,0.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_2', XYZ=8.3,9.7,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_3', XYZ=8.3,22.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_4', XYZ=8.3,35.5,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&SLCF PBX= 8.3, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBY= 5.2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /

&DEVC ID='CO_1', XYZ=8.3,0.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_2', XYZ=8.3,9.7,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
```

```
&DEVC ID='CO_3', XYZ=8.3,22.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_4', XYZ=8.3,35.5,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&SLCF PBX= 8.3, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBY= 5.2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /

&DEVC ID='RHF_1', XYZ=8.3,0.6,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_2', XYZ=8.3,9.7,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_3', XYZ=8.3,22.6,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_4', XYZ=8.3,35.5,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&BNDF QUANTITY='RADIATIVE HEAT FLUX' /

&TAIL / End of file.
```

FDS – FIRE SCENARIO 5

```
&HEAD CHID='fire_scenario_5', TITLE= 'Non confined fire – fire scenario 5' /

&MESH IJK=110,468,70,  XB=0,11,0,46.8,0,7 /

&TIME T_END=600. /
&DUMP DT_RESTART=10/
&MISC TMPA=35, RESTART=.FALSE./

###Geomety prop####

&MATL ID = 'CONCRETE'
FYI = 'Muros y losas'
CONDUCTIVITY = 1.2
SPECIFIC_HEAT = 1
DENSITY = 2400. /

&MATL ID = 'STEEL'
FYI = 'Cerramientos'
CONDUCTIVITY = 45
SPECIFIC_HEAT = 0.6
DENSITY = 1440. /

###geometry####
&OBST XB=6,6.2,0,46.8,0,7, MATL_ID = 'CONCRETE', COLOR='GRAY' /
&HOLE XB=6,6.2,0,1,2.3,3.4/
&HOLE XB=6,6.2,0,1,3.6,5.2/
&HOLE XB=6,6.2,1.25,2.15,3.6,5.2/
&HOLE XB=6,6.2,2.7,7.7,0,5.2/

&OBST XB=0,0.2,2.5,9.9,0,7,  MATL_ID = 'CONCRETE', COLOR='GRAY' /
&OBST XB=0,6.2,9.7,9.9,0,7,  MATL_ID = 'CONCRETE', COLOR='GRAY' /
&OBST XB=0,6.2,2.5,2.7,0,7,  MATL_ID = 'CONCRETE', COLOR='GRAY' /

&OBST XB=10.4,10.6,0,46.8,0,7, MATL_ID = 'CONCRETE', COLOR='GRAY' /
&HOLE XB=10.4,10.6,8.4,10.9,2.4,2.9/
&HOLE XB=10.4,10.6,34.3,36.8,2.4,2.9/
```

```
&OBST XB=2.5,4.5,4.7,7.55,0,3.3, MATL_ID='STEEL', COLOR='PURPLE' /
&OBST XB=4.45,5.15,4.5,7.7,4.3,5.03, MATL_ID='STEEL',COLOR='PURPLE' /
&OBST XB=4.65,4.95,7.25,7.55,3,4.3, MATL_ID='STEEL',COLOR='PURPLE' /
&OBST XB=4.5,4.65,7.25,7.55,3,3.3, MATL_ID='STEEL',COLOR='PURPLE' /
&OBST XB=4.65,4.95,4.7,5,3,4.3, MATL_ID='STEEL',COLOR='PURPLE' /
&OBST XB=4.5,4.65,4.7,5,3,3.3, MATL_ID='STEEL',COLOR='PURPLE' /

&OBST XB=6.2,9.4,8.6,9.6,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /
&OBST XB=6.2,9.4,12.6,13.6,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /
&OBST XB=9.4,10.4,8.6,13.6,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /
&OBST XB=6.2,8.4,35.4,37.7,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /
&OBST XB=8.4,9.9,36.5,37.7,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /
&OBST XB=9.9,10.4,36.5,36.7,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /
&OBST XB=8.8,10.4,35.4,36.5,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /
&OBST XB=7.1,10.4,34.4,35.4,5.4,7,MATL_ID='STEEL', COLOR='STEEL BLUE' /

&VENT MB='XMIN', SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /

#### Fire#####
&SURF ID='fire', HRRPUA=1534.3, E_COEFFICIENT=0.064, TAU_Q=-215.94 /
&VENT XB=2.5,4.5,4.7,7.55,3.3,3.3, SURF_ID='fire', COLOR='RED' /

&REAC ID='REACTION_1',
FUEL = 'REAC_FUEL',
FORMULA = 'C14H28',
HEAT_OF_COMBUSTION= 46400,
CO_YIELD = 0.041,
SOOT_YIELD = 0.097,
IDEAL=.TRUE./

###### Extraction #######
&SURF ID='EXHAUST', VOLUME_FLOW=3.63, COLOR='BLUE' /

&OBST XB=9.2,10.4,37.9,46.8,6.2,6.8, COLOR='CYAN' /
&VENT XB=9.4,10.1,38.7,39.7,6.2,6.2, SURF_ID='EXHAUST'/
&VENT XB=9.4,10.1,41.8,42.8,6.2,6.2, SURF_ID='EXHAUST'/
&VENT XB=9.4,10.1,45,46,6.2,6.2, SURF_ID='EXHAUST'/

&OBST XB=6.2,7.4,37.9,46.8,6.2,6.8, COLOR='CYAN' /
&VENT XB=6.4,7.1,38.7,39.7,6.2,6.2, SURF_ID='EXHAUST'/
&VENT XB=6.4,7.1,41.8,42.8,6.2,6.2, SURF_ID='EXHAUST'/
&VENT XB=6.4,7.1,45,46,6.2,6.2, SURF_ID='EXHAUST'/

### Fire results#####
&DUMP SMOKE3d=.TRUE./

&SLCF PBX=3.5, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBX=6.8, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBX=9.8, QUANTITY='VELOCITY', VECTOR=.TRUE./

&SLCF PBY=0.6, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=1.7, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=5.2, QUANTITY='VELOCITY', VECTOR=.TRUE./
```

```
&SLCF PBY=9.7, QUANTITY='VELOCITY', VECTOR=.TRUE./
&SLCF PBY=35.5, QUANTITY='VELOCITY', VECTOR=.TRUE./

&DEVC ID='T_1_Ext_C1', XYZ=8.3,5.2,6.9, QUANTITY='TEMPERATURE'/
&DEVC ID='T_2_Ext_GB1', XYZ=8.3,11.1,5.3, QUANTITY='TEMPERATURE'/
&DEVC ID='T_3_Ext_GB1aGB2', XYZ=8.3,22.6,6.9, QUANTITY='TEMPERATURE'/
&DEVC ID='T_4_Ext_GB2', XYZ=8.3,36.1,5.3, QUANTITY='TEMPERATURE'/

&DEVC ID='T_5_Ext_CM', XYZ=9.5,39.2,6.1, QUANTITY='TEMPERATURE'/
&DEVC ID='T_5_Ext_CEL', XYZ=6.7,39.2,6.1, QUANTITY='TEMPERATURE'/

&DEVC ID='RHF_1_Ext_C1', XYZ=8.3,5.2,0.1, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_2_Ext_GB1', XYZ=8.3,11.1,0.1, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_3_Ext_GB1aGB2', XYZ=8.3,22.6,0.1, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_4_Ext_GB2', XYZ=8.3,22.6,0.1, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_5_Ext_CM', XYZ=9.5,39.2,0.1, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_5_Ext_CEL', XYZ=6.7,39.2,0.1, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/

####Human safety#######
&DEVC ID='T_1', XYZ=8.3,0.6,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_2', XYZ=8.3,9.7,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_3', XYZ=8.3,22.6,2, QUANTITY='TEMPERATURE'/
&DEVC ID='T_4', XYZ=8.3,35.5,2, QUANTITY='TEMPERATURE'/
&SLCF PBX=8.3, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY=5.2, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBZ=2, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /

&DEVC ID='ox_1', XYZ=8.3,0.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_2', XYZ=8.3,9.7,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_3', XYZ=8.3,22.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&DEVC ID='ox_4', XYZ=8.3,35.5,2, QUANTITY='VOLUME FRACTION', SPEC_ID='OXYGEN'/
&SLCF PBX= 8.3, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /
&SLCF PBY= 5.2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'OXYGEN' /

&DEVC ID='Vis_1', XYZ=8.3,0.6,2,  QUANTITY='VISIBILITY'/
&DEVC ID='Vis_2', XYZ=8.3,9.7,2, QUANTITY='VISIBILITY'/
&DEVC ID='Vis_3', XYZ=8.3,22.6,2, QUANTITY='VISIBILITY'/
&DEVC ID='Vis_4', XYZ=8.3,35.5,2, QUANTITY='VISIBILITY'/
&SLCF PBX=8.3, QUANTITY='VISIBILITY' /
&SLCF PBY=5.2, QUANTITY='VISIBILITY' /
&SLCF PBZ=2, QUANTITY='VISIBILITY' /

&DEVC ID='CO2_1', XYZ=8.3,0.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_2', XYZ=8.3,9.7,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_3', XYZ=8.3,22.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
&DEVC ID='CO2_4', XYZ=8.3,35.5,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON DIOXIDE'/
```

```
&SLCF PBX= 8.3, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBY= 5.2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON DIOXIDE' /

&DEVC ID='CO_1', XYZ=8.3,0.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_2', XYZ=8.3,9.7,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_3', XYZ=8.3,22.6,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&DEVC ID='CO_4', XYZ=8.3,35.5,2, QUANTITY='VOLUME FRACTION', SPEC_ID='CARBON MONOXIDE'/
&SLCF PBX= 8.3, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBY= 5.2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /
&SLCF PBZ= 2, QUANTITY='VOLUME FRACTION', SPEC_ID= 'CARBON MONOXIDE' /

&DEVC ID='RHF_1', XYZ=8.3,0.6,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_2', XYZ=8.3,9.7,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_3', XYZ=8.3,22.6,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&DEVC ID='RHF_4', XYZ=8.3,35.5,2, QUANTITY='RADIATIVE HEAT FLUX GAS', ORIENTATION=0,0,1/
&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&TAIL / End of file.
```

D. Appendix D: CFAST Simulation programming

CFAST – FIRE SCENARIO 1

```
&HEAD VERSION = 7700, TITLE = 'CFAST Simulation' /
&MHDR NUMBER_OF_CASES = 3 /
!! Scenario Configuration
&TIME SIMULATION = 240 PRINT = 60 SMOKEVIEW = 1 SPREADSHEET = 1 /
&INIT PRESSURE = 89278 RELATIVE_HUMIDITY = 55 INTERIOR_TEMPERATURE = 35
EXTERIOR_TEMPERATURE = 35 /
!! Material Properties
&MATL ID = 'concrete1' MATERIAL = 'concrete',
CONDUCTIVITY = 1.2 DENSITY = 2400 SPECIFIC_HEAT = 1, THICKNESS = 0.3 EMISSIVITY = 0.9 /
!! Compartments
&COMP ID = 'Comp 1'
DEPTH = 5.5 HEIGHT = 7 WIDTH = 7
CEILING_MATL_ID = 'concrete1' CEILING_THICKNESS = 0.15 WALL_MATL_ID = 'concrete1'
WALL_THICKNESS = 0.15 FLOOR_MATL_ID =
'concrete1' FLOOR_THICKNESS = 0.3
ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /
!! Fires
&FIRE ID = 'fire' COMP_ID = 'Comp 1', FIRE_ID = 'transformer' LOCATION = 3.425, 2.25 /
&CHEM ID = 'transformer' CARBON = 14 CHLORINE = 0 HYDROGEN = 28 NITROGEN = 0 OXYGEN = 0
HEAT_OF_COMBUSTION = 46400
RADIATIVE_FRACTION = 0.35 /
&TABL ID = 'transformer' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' ,
'HCN_YIELD' , 'HCL_YIELD' ,
'TRACE_YIELD' /
&TABL ID = 'transformer', DATA = 0, 0, 0, 0.001, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 21.594, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 43.188, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 64.782, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 86.376, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 107.97, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 129.564, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 151.158, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 172.752, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 194.346, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 215.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 515.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 523.44, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 530.94, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
```

```
&TABL ID = 'transformer', DATA = 538.44, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 545.94, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 553.44, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 560.94, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 568.44, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 575.94, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 583.44, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 590.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 600.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
!! Visualizations
&ISOF VALUE = 60 /
&SLCF DOMAIN = '2-D' POSITION = 6.65, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 3.425, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 2.25, PLANE = 'Y' /
&SLCF DOMAIN = '3-D' /
!! Monte Carlo Random Distributions
&MRND ID = 'Vent Width Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 0.25 MAXIMUM = 2 /
&MRND ID = 'Vent Height Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 1.5 MAXIMUM = 2.5 /
&MRND ID = 'Peak HRR' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 500 MAXIMUM = 3000 /
&MRND ID = 'End of Fire HRR' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 0 /
&MRND ID = 'Peak HRR Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 900 /
&MRND ID = 'Fire Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 10 /
!! Monte-Carlo Field Definitions
&MFLD ID = 'Wall Vent Width' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Width Generator' FIELD = 'Wall Vent',
'WIDTH'
ADD_TO_PARAMETERS = .FALSE. /
&MFLD ID = 'Wall Vent Height' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Height Generator' FIELD = 'Wall
Vent', 'TOP'
ADD_TO_PARAMETERS = .FALSE. /
!! Monte Carlo Fire Specifications
&MFIR ID = 'Fire_generator' FIRE_ID = 'Fire'
FIRE_TIME_GENERATOR_IDS = 'Fire Time Interval', 'Peak HRR Time Interval', 'Fire Time Interval'
FIRE_HRR_GENERATOR_IDS = 'Peak HRR', 'Peak HRR', 'End of Fire HRR' /
!! User-specified Outputs
&OUTP ID = 'Time to Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Actual HRR at Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Fire', 'HRR Actual' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Time to Layer Height 1.5 m'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_LESSER' CRITERION = 1.5
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Upper Layer Temp'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Minimum Layer Height'
FILE = 'COMPARTMENTS' TYPE = 'MINIMUM'
FIRST_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Actual HRR'
```

FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Fire', 'HRR Actual' /
!! Monte-Carlo Statistics Outputs
&MSTT ID ='Correlation Tree on Temp' ANALYSIS_TYPE = 'DECISION_TREE' COLUMN_LABEL = 'Maximum Upper Layer Temp'
&TAIL /

CFAST – FIRE SCENARIO 2

&HEAD VERSION = 7700, TITLE = 'CFAST Simulation' /
&MHDR NUMBER_OF_CASES = 3 /
!! Scenario Configuration
&TIME SIMULATION = 240 PRINT = 60 SMOKEVIEW = 1 SPREADSHEET = 1 /
&INIT PRESSURE = 89278 RELATIVE_HUMIDITY = 55 INTERIOR_TEMPERATURE = 35 EXTERIOR_TEMPERATURE = 35 /
!! Material Properties
&MATL ID = 'concrete1' MATERIAL = 'concrete',
CONDUCTIVITY = 1.2 DENSITY = 2400 SPECIFIC_HEAT = 1, THICKNESS = 0.3 EMISSIVITY = 0.9 /
!! Compartments
&COMP ID = 'Comp 1'
DEPTH = 5.5 HEIGHT = 7 WIDTH = 7
CEILING_MATL_ID = 'concrete1' CEILING_THICKNESS = 0.15 WALL_MATL_ID = 'concrete1' WALL_THICKNESS = 0.15 FLOOR_MATL_ID =
'concrete1' FLOOR_THICKNESS = 0.3
ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /
!! Wall Vents
&VENT TYPE = 'WALL' ID = 'Wall Vent' COMP_IDS = 'Comp 1' 'OUTSIDE' , BOTTOM = 2.5 HEIGHT = 0.5, WIDTH = 0.5
FACE = 'FRONT' OFFSET = 6.25 /
!! Mechanical Vents
&VENT TYPE = 'MECHANICAL' ID = 'extrac' COMP_IDS = 'Comp 1', 'OUTSIDE'
AREAS = 0.25, 0.25 HEIGHTS = 7, 7 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 1.53 OFFSETS = 6.65, 4.5 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
!! Fires
&FIRE ID = 'fire' COMP_ID = 'Comp 1', FIRE_ID = 'transformer' LOCATION = 3.425, 2.25 /
&CHEM ID = 'transformer' CARBON = 14 CHLORINE = 0 HYDROGEN = 28 NITROGEN = 0 OXYGEN = 0 HEAT_OF_COMBUSTION = 46400
RADIATIVE_FRACTION = 0.35 /
&TABL ID = 'transformer' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' ,
'TRACE_YIELD' /
&TABL ID = 'transformer', DATA = 0, 0, 0, 0.001, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 21.594, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 43.188, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 64.782, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 86.376, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 107.97, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 129.564, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 151.158, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 172.752, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 194.346, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 215.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 515.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /

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&TABL ID = 'transformer', DATA = 523.44, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 530.94, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 538.44, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 545.94, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 553.44, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 560.94, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 568.44, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 575.94, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 583.44, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 590.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 600.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
!! Visualizations
&ISOF VALUE = 60 /
&SLCF DOMAIN = '2-D' POSITION = 6.65, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 3.425, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 2.25, PLANE = 'Y' /
&SLCF DOMAIN = '3-D' /
!! Monte Carlo Random Distributions
&MRND ID = 'Vent Width Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 0.25 MAXIMUM = 2 /
&MRND ID = 'Vent Height Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 1.5 MAXIMUM = 2.5 /
&MRND ID = 'Peak HRR' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 500 MAXIMUM = 3000 /
&MRND ID = 'End of Fire HRR' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 0 /
&MRND ID = 'Peak HRR Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 900 /
&MRND ID = 'Fire Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 10 /
!! Monte-Carlo Field Definitions
&MFLD ID = 'Wall Vent Width' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Width Generator' FIELD = 'Wall Vent',
'WIDTH'
ADD_TO_PARAMETERS = .FALSE. /
&MFLD ID = 'Wall Vent Height' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Height Generator' FIELD = 'Wall
Vent', 'TOP'
ADD_TO_PARAMETERS = .FALSE. /
!! Monte Carlo Fire Specifications
&MFIR ID = 'Fire_generator' FIRE_ID = 'Fire'
FIRE_TIME_GENERATOR_IDS = 'Fire Time Interval', 'Peak HRR Time Interval', 'Fire Time Interval'
FIRE_HRR_GENERATOR_IDS = 'Peak HRR', 'Peak HRR', 'End of Fire HRR' /
!! User-specified Outputs
&OUTP ID = 'Time to Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Actual HRR at Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Fire', 'HRR Actual' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Time to Layer Height 1.5 m'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_LESSER' CRITERION = 1.5
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Upper Layer Temp'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Minimum Layer Height'
FILE = 'COMPARTMENTS' TYPE = 'MINIMUM'
```

FIRST_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Actual HRR'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Fire', 'HRR Actual' /
!! Monte-Carlo Statistics Outputs
&MSTT ID ='Correlation Tree on Temp' ANALYSIS_TYPE = 'DECISION_TREE' COLUMN_LABEL = 'Maximum Upper Layer Temp'
&TAIL /

CFAST – FIRE SCENARIO 3

&HEAD VERSION = 7700, TITLE = 'CFAST Simulation' /
&MHDR NUMBER_OF_CASES = 3 /
!! Scenario Configuration
&TIME SIMULATION = 240 PRINT = 60 SMOKEVIEW = 1 SPREADSHEET = 1 /
&INIT PRESSURE = 89278 RELATIVE_HUMIDITY = 55 INTERIOR_TEMPERATURE = 35 EXTERIOR_TEMPERATURE = 35 /
!! Material Properties
&MATL ID = 'concrete1' MATERIAL = 'concrete',
CONDUCTIVITY = 1.2 DENSITY = 2400 SPECIFIC_HEAT = 1, THICKNESS = 0.3 EMISSIVITY = 0.9 /
!! Compartments
&COMP ID = 'Comp 1'
DEPTH = 5.5 HEIGHT = 7 WIDTH = 7
CEILING_MATL_ID = 'concrete1' CEILING_THICKNESS = 0.15 WALL_MATL_ID = 'concrete1' WALL_THICKNESS = 0.15 FLOOR_MATL_ID =
'concrete1' FLOOR_THICKNESS = 0.3
ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /
!! Wall Vents
&VENT TYPE = 'WALL' ID = 'Wall Vent' COMP_IDS = 'Comp 1' 'OUTSIDE' , BOTTOM = 2.5 HEIGHT = 0.5, WIDTH = 0.5
FACE = 'FRONT' OFFSET = 6.25 /
!! Mechanical Vents
&VENT TYPE = 'MECHANICAL' ID = 'extrac' COMP_IDS = 'Comp 1', 'OUTSIDE'
AREAS = 0.25, 0.25 HEIGHTS = 7, 7 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 1.53 OFFSETS = 6.65, 4.5 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
!! Fires
&FIRE ID = 'Fire_Trans_spk' COMP_ID = 'Comp 1', FIRE_ID = 'Transformer_SPK' LOCATION = 3.425, 2.25 /
&CHEM ID = 'Transformer_SPK' CARBON = 14 CHLORINE = 0 HYDROGEN = 28 NITROGEN = 0 OXYGEN = 0 HEAT_OF_COMBUSTION = 46400
RADIATIVE_FRACTION = 0.35 /
&TABL ID = 'Transformer_SPK' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' ,
'TRACE_YIELD' /
&TABL ID = 'Transformer_SPK', DATA = 0, 0, 0, 0.001, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 3.72, 2.0916, 0, 0.00515843715269441, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 7.44, 8.3664, 0, 0.0156374572992833, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 11.16, 18.8244, 0, 0.0299165942504933, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 14.88, 33.4656, 0, 0.0474039061732453, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 18.6, 52.29, 0, 0.0677438930441063, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 22.32, 75.2976, 0, 0.0906901550380848, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 26.04, 102.4884, 0, 0.116057980104473, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 29.76, 133.8624, 0, 0.143701771808185, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 33.48, 169.4196, 0, 0.173502668551687, 0.041, 0.097, 0, 0, 0 /

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&TABL ID = 'Transformer_SPK', DATA = 37.2, 209.16, 0, 0.205361081933721, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 38.2, 209.16, 0, 0.205361081933721, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 45.7, 169.4196, 0, 0.173502668551687, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 53.2, 133.8624, 0, 0.143701771808185, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 60.7, 102.4884, 0, 0.116057980104473, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 68.2, 75.2976, 0, 0.0906901550380848, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 75.7, 52.29, 0, 0.0677438930441063, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 83.2, 33.4656, 0, 0.0474039061732452, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 90.7, 18.8244, 0, 0.0299165942504933, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 98.2, 8.3664, 0, 0.0156374572992833, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 105.7, 2.0916, 0, 0.00515843715269441, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 113.2, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'Transformer_SPK', DATA = 123.2, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
!! Visualizations
&ISOF VALUE = 60 /
&SLCF DOMAIN = '2-D' POSITION = 6.65, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 3.425, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 2.25, PLANE = 'Y' /
&SLCF DOMAIN = '3-D' /
!! Monte Carlo Random Distributions
&MRND ID = 'Vent Width Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 0.25 MAXIMUM = 2 /
&MRND ID = 'Vent Height Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 1.5 MAXIMUM = 2.5 /
&MRND ID = 'Peak HRR' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 500 MAXIMUM = 3000 /
&MRND ID = 'End of Fire HRR' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 0 /
&MRND ID = 'Peak HRR Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 900 /
&MRND ID = 'Fire Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 10 /
!! Monte-Carlo Field Definitions
&MFLD ID = 'Wall Vent Width' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Width Generator' FIELD = 'Wall Vent',
'WIDTH'
ADD_TO_PARAMETERS = .FALSE. /
&MFLD ID = 'Wall Vent Height' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Height Generator' FIELD = 'Wall
Vent', 'TOP'
ADD_TO_PARAMETERS = .FALSE. /
!! Monte Carlo Fire Specifications
&MFIR ID = 'Fire_generator' FIRE_ID = 'Fire'
FIRE_TIME_GENERATOR_IDS = 'Fire Time Interval', 'Peak HRR Time Interval', 'Fire Time Interval'
FIRE_HRR_GENERATOR_IDS = 'Peak HRR', 'Peak HRR', 'End of Fire HRR' /
!! User-specified Outputs
&OUTP ID = 'Time to Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Actual HRR at Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Fire', 'HRR Actual' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Time to Layer Height 1.5 m'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_LESSER' CRITERION = 1.5
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Upper Layer Temp'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Comp 1', 'Upper Layer Temperature' /
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&OUTP ID = 'Minimum Layer Height'
FILE = 'COMPARTMENTS' TYPE = 'MINIMUM'
FIRST_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Actual HRR'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Fire', 'HRR Actual' /
!! Monte-Carlo Statistics Outputs
&MSTT ID ='Correlation Tree on Temp' ANALYSIS_TYPE = 'DECISION_TREE' COLUMN_LABEL = 'Maximum Upper Layer Temp'
&TAIL /

CFAST – FIRE SCENARIO 4

&HEAD VERSION = 7700, TITLE = 'CFAST Simulation' /
&MHDR NUMBER_OF_CASES = 3 /
!! Scenario Configuration
&TIME SIMULATION = 600 PRINT = 1 SMOKEVIEW = 1 SPREADSHEET = 1 /
&INIT PRESSURE = 89278 RELATIVE_HUMIDITY = 60 INTERIOR_TEMPERATURE = 35 EXTERIOR_TEMPERATURE = 35 /
!! Material Properties
&MATL ID = 'CONCRETE' MATERIAL = 'concreto',
CONDUCTIVITY = 1.2 DENSITY = 2400 SPECIFIC_HEAT = 1, THICKNESS = 0.3 EMISSIVITY = 0.94 /
!! Compartments
&COMP ID = 'Comp 1'
DEPTH = 7 HEIGHT = 7 WIDTH = 5.75
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 0, 2.7, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 2'
DEPTH = 8.6 HEIGHT = 7 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 0, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 3'
DEPTH = 5 HEIGHT = 5.4 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 8.6, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 4'
DEPTH = 20.8 HEIGHT = 7 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 13.6, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 5'
DEPTH = 3.3 HEIGHT = 5.4 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 34.4, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 6'
DEPTH = 9.1 HEIGHT = 6.2 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3

ORIGIN = 5.75, 37.7, 0 GRID = 50, 50, 50 /
!! Wall Vents
&VENT TYPE = 'WALL' ID = '1 a 2' COMP_IDS = 'Comp 1', 'Comp 2', BOTTOM = 0 HEIGHT = 5.2, WIDTH = 5
FACE = 'RIGHT' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = '2a3' COMP_IDS = 'Comp 2', 'Comp 3', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = '3a4' COMP_IDS = 'Comp 3', 'Comp 4', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = '4a5' COMP_IDS = 'Comp 4', 'Comp 5', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = '5a6' COMP_IDS = 'Comp 5', 'Comp 6', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
!! Fires
&FIRE ID = 'New Fire 2' COMP_ID = 'Comp 1', FIRE_ID = 'transformer' LOCATION = 3, 3.425 /
&CHEM ID = 'transformer' CARBON = 14 CHLORINE = 0 HYDROGEN = 28 NITROGEN = 0 OXYGEN = 0 HEAT_OF_COMBUSTION = 46400
RADIATIVE_FRACTION = 0.35 /
&TABL ID = 'transformer' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' ,
'TRACE_YIELD' /
&TABL ID = 'transformer', DATA = 0, 0, 0, 0.001, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 21.594, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 43.188, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 64.782, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 86.376, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 107.97, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 129.564, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 151.158, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 172.752, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 194.346, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 215.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1015.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1023.44, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1030.94, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1038.44, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1045.94, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1053.44, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1060.94, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1068.44, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1075.94, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1083.44, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1090.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 1100.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
!! Devices
&DEVC ID = 'Targ 1' COMP_ID = 'Comp 2' LOCATION = 2.325, 4.3, 2 TYPE = 'PLATE' MATL_ID = 'CONCRETE' SURFACE_ORIENTATION = 'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /

&DEVC ID = 'Targ 2' COMP_ID = 'Comp 3' LOCATION = 2.325, 2.5, 2 TYPE = 'PLATE' MATL_ID = 'CONCRETE' SURFACE_ORIENTATION = 'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /
&DEVC ID = 'Targ 3' COMP_ID = 'Comp 4' LOCATION = 2.325, 10.4, 2 TYPE = 'PLATE' MATL_ID = 'CONCRETE' SURFACE_ORIENTATION =
'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /
&DEVC ID = 'Targ 4' COMP_ID = 'Comp 5' LOCATION = 2.325, 1.65, 2 TYPE = 'PLATE' MATL_ID = 'CONCRETE' SURFACE_ORIENTATION =
'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /
!! Visualizations
&SLCF DOMAIN = '3-D' /
&SLCF DOMAIN = '2-D' POSITION = 3.425, PLANE = 'Y' /
&SLCF DOMAIN = '2-D' POSITION = 3, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 2, PLANE = 'Z' /
&SLCF DOMAIN = '2-D' POSITION = 8, PLANE = 'X' /
!! Monte Carlo Random Distributions
&MRND ID = 'Vent Width Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 0.25 MAXIMUM = 2 /
&MRND ID = 'Vent Height Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 1.5 MAXIMUM = 2.5 /
&MRND ID = 'Peak HRR' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 500 MAXIMUM = 3000 /
&MRND ID = 'End of Fire HRR' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 0 /
&MRND ID = 'Peak HRR Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 900 /
&MRND ID = 'Fire Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 10 /
!! Monte-Carlo Field Definitions
&MFLD ID = 'Wall Vent Width' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Width Generator' FIELD = 'Wall Vent', 'WIDTH'
ADD_TO_PARAMETERS = .FALSE. /
&MFLD ID = 'Wall Vent Height' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Height Generator' FIELD = 'Wall Vent', 'TOP'
ADD_TO_PARAMETERS = .FALSE. /
!! Monte Carlo Fire Specifications
&MFIR ID = 'Fire_generator' FIRE_ID = 'Fire'
FIRE_TIME_GENERATOR_IDS = 'Fire Time Interval', 'Peak HRR Time Interval', 'Fire Time Interval'
FIRE_HRR_GENERATOR_IDS = 'Peak HRR', 'Peak HRR', 'End of Fire HRR' /
!! User-specified Outputs
&OUTP ID = 'Time to Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Actual HRR at Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Fire', 'HRR Actual' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Time to Layer Height 1.5 m'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_LESSER' CRITERION = 1.5
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Upper Layer Temp'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Minimum Layer Height'
FILE = 'COMPARTMENTS' TYPE = 'MINIMUM'
FIRST_FIELD = 'Comp 1', 'Layer Height' /

&OUTP ID = 'Maximum Actual HRR'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Fire', 'HRR Actual' /
!! Monte-Carlo Statistics Outputs
&MSTT ID ='Correlation Tree on Temp' ANALYSIS_TYPE = 'DECISION_TREE' COLUMN_LABEL = 'Maximum Upper Layer Temp'
&TAIL /

CFAST – FIRE SCENARIO 5

&HEAD VERSION = 7700, TITLE = 'CFAST Simulation' /
&MHDR NUMBER_OF_CASES = 3 /
!! Scenario Configuration
&TIME SIMULATION = 600 PRINT = 1 SMOKEVIEW = 1 SPREADSHEET = 1 /
&INIT PRESSURE = 89278 RELATIVE_HUMIDITY = 60 INTERIOR_TEMPERATURE = 35 EXTERIOR_TEMPERATURE = 35 /
!! Material Properties
&MATL ID = 'CONCRETE' MATERIAL = 'concreto',
CONDUCTIVITY = 1.2 DENSITY = 2400 SPECIFIC_HEAT = 1, THICKNESS = 0.3 EMISSIVITY = 0.94 /
!! Compartments
&COMP ID = 'Comp 1'
DEPTH = 7 HEIGHT = 7 WIDTH = 5.75
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 0, 2.7, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 2'
DEPTH = 8.6 HEIGHT = 7 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 0, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 3'
DEPTH = 5 HEIGHT = 5.4 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 8.6, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 4'
DEPTH = 20.8 HEIGHT = 7 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 13.6, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 5'
DEPTH = 3.3 HEIGHT = 5.4 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 34.4, 0 GRID = 50, 50, 50 /
&COMP ID = 'Comp 6'
DEPTH = 9.1 HEIGHT = 6.2 WIDTH = 4.65
CEILING_MATL_ID = 'CONCRETE' CEILING_THICKNESS = 0.3 WALL_MATL_ID = 'CONCRETE' WALL_THICKNESS = 0.3
ORIGIN = 5.75, 37.7, 0 GRID = 50, 50, 50 /
!! Wall Vents
&VENT TYPE = 'WALL' ID = '1 a 2' COMP_IDS = 'Comp 1', 'Comp 2', BOTTOM = 0 HEIGHT = 5.2, WIDTH = 5
FACE = 'RIGHT' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = '2a3' COMP_IDS = 'Comp 2', 'Comp 3', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = '3a4' COMP_IDS = 'Comp 3', 'Comp 4', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = '4a5' COMP_IDS = 'Comp 4', 'Comp 5', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = '5a6' COMP_IDS = 'Comp 5', 'Comp 6', BOTTOM = 0 HEIGHT = 5.4, WIDTH = 4.65
FACE = 'REAR' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'damper1' COMP_IDS = 'Comp 2' 'OUTSIDE' , BOTTOM = 3.6 HEIGHT = 1.6, WIDTH = 1
FACE = 'LEFT' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'damper2' COMP_IDS = 'Comp 2' 'OUTSIDE' , BOTTOM = 3.6 HEIGHT = 1.6, WIDTH = 1
FACE = 'LEFT' OFFSET = 1.25 /
&VENT TYPE = 'WALL' ID = 'damper3' COMP_IDS = 'Comp 2' 'OUTSIDE' , BOTTOM = 2.3 HEIGHT = 1.1, WIDTH = 1
FACE = 'LEFT' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'damper4' COMP_IDS = 'Comp 3' 'OUTSIDE' , BOTTOM = 2.4 HEIGHT = 0.5, WIDTH = 2.5
FACE = 'RIGHT' OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'damper5' COMP_IDS = 'Comp 5' 'OUTSIDE' , BOTTOM = 2.4 HEIGHT = 0.5, WIDTH = 2.5
FACE = 'RIGHT' OFFSET = 0.2 /
!! Mechanical Vents
&VENT TYPE = 'MECHANICAL' ID = 'Extractor1' COMP_IDS = 'Comp 6', 'OUTSIDE'
AREAS = 0.7, 0.7 HEIGHTS = 6.2, 6.2 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 3.63
OFFSETS = 1, 1.5 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
&VENT TYPE = 'MECHANICAL' ID = 'Extractor2' COMP_IDS = 'Comp 6', 'OUTSIDE'
AREAS = 0.7, 0.7 HEIGHTS = 6.2, 6.2 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 3.63
OFFSETS = 4, 1.5 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
&VENT TYPE = 'MECHANICAL' ID = 'Extractor3' COMP_IDS = 'Comp 6', 'OUTSIDE'
AREAS = 0.7, 0.7 HEIGHTS = 6.2, 6.2 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 3.63
OFFSETS = 1, 4.6 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
&VENT TYPE = 'MECHANICAL' ID = 'Extractor4' COMP_IDS = 'Comp 6', 'OUTSIDE'
AREAS = 0.7, 0.7 HEIGHTS = 6.2, 6.2 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 3.63
OFFSETS = 4, 4.6 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
&VENT TYPE = 'MECHANICAL' ID = 'Extractor5' COMP_IDS = 'Comp 6', 'OUTSIDE'
AREAS = 0.7, 0.7 HEIGHTS = 6.2, 6.2 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 3.63
OFFSETS = 1, 7.8 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
&VENT TYPE = 'MECHANICAL' ID = 'Extractor6' COMP_IDS = 'Comp 6', 'OUTSIDE'
AREAS = 0.7, 0.7 HEIGHTS = 6.2, 6.2 ORIENTATIONS = 'HORIZONTAL', 'HORIZONTAL' FLOW = 3.63
OFFSETS = 4, 7.8 FILTER_TIME = 0
FILTER_EFFICIENCY = 0 /
!! Fires
&FIRE ID = 'New Fire 2' COMP_ID = 'Comp 1', FIRE_ID = 'transformer' LOCATION = 3, 3.425 /

```
&CHEM ID = 'transformer' CARBON = 14 CHLORINE = 0 HYDROGEN = 28 NITROGEN = 0 OXYGEN = 0
HEAT_OF_COMBUSTION = 46400
RADIATIVE_FRACTION = 0.35 /
&TABL ID = 'transformer' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' ,
'HCN_YIELD' , 'HCL_YIELD' ,
'TRACE_YIELD' /
&TABL ID = 'transformer', DATA = 0, 0, 0, 0.001, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 21.594, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 43.188, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 64.782, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 86.376, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 107.97, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 129.564, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 151.158, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 172.752, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 194.346, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 215.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 715.94, 8745.51, 0, 4.06970893606864, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 723.44, 7083.8631, 0, 3.43836015075363, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 730.94, 5597.1264, 0, 2.84778585771872, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 738.44, 4285.2999, 0, 2.29995963346984, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 745.94, 3148.3836, 0, 1.7972369978605, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 753.44, 2186.3775, 0, 1.34250328392143, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 760.94, 1399.2816, 0, 0.939418991861756, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 768.44, 787.0959, 0, 0.592867109052663, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 775.94, 349.8204, 0, 0.309892697822971, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 783.44, 87.4551, 0, 0.102226466567041, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 790.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
&TABL ID = 'transformer', DATA = 800.94, 0, 0, 0.09, 0.041, 0.097, 0, 0, 0 /
!! Devices
&DEVC ID = 'Targ 1' COMP_ID = 'Comp 2' LOCATION = 2.325, 4.3, 2 TYPE = 'PLATE' MATL_ID =
'CONCRETE' SURFACE_ORIENTATION = 'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /
&DEVC ID = 'Targ 2' COMP_ID = 'Comp 3' LOCATION = 2.325, 2.5, 2 TYPE = 'PLATE' MATL_ID =
'CONCRETE' SURFACE_ORIENTATION = 'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /
&DEVC ID = 'Targ 3' COMP_ID = 'Comp 4' LOCATION = 2.325, 10.4, 2 TYPE = 'PLATE' MATL_ID =
'CONCRETE' SURFACE_ORIENTATION =
'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /
&DEVC ID = 'Targ 4' COMP_ID = 'Comp 5' LOCATION = 2.325, 1.65, 2 TYPE = 'PLATE' MATL_ID =
'CONCRETE' SURFACE_ORIENTATION =
'CEILING'
TEMPERATURE_DEPTH = 0.5 DEPTH_UNITS = 'M' /
!! Visualizations
&SLCF DOMAIN = '3-D' /
&SLCF DOMAIN = '2-D' POSITION = 3.425, PLANE = 'Y' /
&SLCF DOMAIN = '2-D' POSITION = 3, PLANE = 'X' /
&SLCF DOMAIN = '2-D' POSITION = 2, PLANE = 'Z' /
&SLCF DOMAIN = '2-D' POSITION = 8, PLANE = 'X' /
!! Monte Carlo Random Distributions
&MRND ID = 'Vent Width Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 0.25 MAXIMUM = 2 /
```

```
&MRND ID = 'Vent Height Generator' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 1.5 MAXIMUM = 2.5 /
&MRND ID = 'Peak HRR' DISTRIBUTION_TYPE = 'UNIFORM'
MINIMUM = 500 MAXIMUM = 3000 /
&MRND ID = 'End of Fire HRR' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 0 /
&MRND ID = 'Peak HRR Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 900 /
&MRND ID = 'Fire Time Interval' DISTRIBUTION_TYPE = 'CONSTANT' CONSTANT = 10 /
!! Monte-Carlo Field Definitions
&MFLD ID = 'Wall Vent Width' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Width Generator' FIELD = 'Wall Vent', 'WIDTH'
ADD_TO_PARAMETERS = .FALSE. /
&MFLD ID = 'Wall Vent Height' FIELD_TYPE = 'VALUE' RAND_ID = 'Vent Height Generator' FIELD = 'Wall Vent', 'TOP'
ADD_TO_PARAMETERS = .FALSE. /
!! Monte Carlo Fire Specifications
&MFIR ID = 'Fire_generator' FIRE_ID = 'Fire'
FIRE_TIME_GENERATOR_IDS = 'Fire Time Interval', 'Peak HRR Time Interval', 'Fire Time Interval'
FIRE_HRR_GENERATOR_IDS = 'Peak HRR', 'Peak HRR', 'End of Fire HRR' /
!! User-specified Outputs
&OUTP ID = 'Time to Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Actual HRR at Upper Layer 600 C'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_GREATER' CRITERION = 600
FIRST_FIELD = 'Fire', 'HRR Actual' SECOND_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Time to Layer Height 1.5 m'
FILE = 'COMPARTMENTS' TYPE = 'TRIGGER_LESSER' CRITERION = 1.5
FIRST_FIELD = 'Time', 'Simulation Time' SECOND_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Upper Layer Temp'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Comp 1', 'Upper Layer Temperature' /
&OUTP ID = 'Minimum Layer Height'
FILE = 'COMPARTMENTS' TYPE = 'MINIMUM'
FIRST_FIELD = 'Comp 1', 'Layer Height' /
&OUTP ID = 'Maximum Actual HRR'
FILE = 'COMPARTMENTS' TYPE = 'MAXIMUM'
FIRST_FIELD = 'Fire', 'HRR Actual' /
!! Monte-Carlo Statistics Outputs
&MSTT ID ='Correlation Tree on Temp' ANALYSIS_TYPE = 'DECISION_TREE' COLUMN_LABEL = 'Maximum Upper Layer Temp'
&TAIL /
```

E. Appendix E: FLUENT simulation programming

FLUENT – FIRE SCENARIO 2

FLUENT FIRE SCENARIO 2 - SETUP			
GENERAL	Solver	Type	Pressure-based
		Velocity Formulation	Absolute
	Time	Steady	
	Gravity acceleration	X (m/s2)	0
		Y (m/s2)	-9,8
		Z (m/s2)	0
MODELS			
Energy	Energy Equation	On	
Viscous	Model	K-epsilon (2 eqn)	
	K-epsilon Model	Realizable	
	Near-wall treatment	Enhanced Wall treatment	
Radiation	Discrete Ordinates (DO)	On	
	Energy iterations per radiation iteration	50	
Species	Species transport	On	
MATERIALS			
Fluid	Material Name	Air	
	Density (kg/m-s)	1,225	Constant
	Cp (J/Kg*K)	1.006,43	Constant
	Thermal Conductivity (W/m*K)	0,0242	Constant
	Viscosity (kg/m*s)	1,79E-05	Constant
	Molecular Weight (kg/kmol)	28,966	Constant
	Absorption coefficient (m-1)	0	Constant
	Scattering coefficient (m-1)	0	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant

	Material Name	Carbon Dioxide	CO2
	Density (kg/m-s)	1,7878	Constant
	Cp (J/Kg*K)	N/A	Piecewise-polynomial
	Thermal Conductivity (W/m*K)	0,0145	Constant
	Viscosity (kg/m*s)	1,37E-05	Constant
	Molecular Weight (kg/kmol)	44,000995	Constant
	Absorption coefficient (m-1)	0,43	Constant
	Scattering coefficient (m-1)	0	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant
	Material Name	Carbon Monoxide	CO
	Density (kg/m-s)	1,1233	Constant
	Cp (J/Kg*K)	N/A	Piecewise-polynomial
	Thermal Conductivity (W/m*K)	0,025	Constant
	Viscosity (kg/m*s)	1,75E-05	Constant
	Molecular Weight (kg/kmol)	28,01055	Constant
	Absorption coefficient (m-1)	0,17	Constant
	Scattering coefficient (m-1)	0	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant
Solid	Material Name	Concrete	
	Density (kg/m-s)	2400	Constant
	Cp (J/Kg-K)	1000	Constant
	Thermal Conductivity (W/m-K)	1,2	Constant
	Absorption coefficient (m-1)	0,1	Constant
	Scattering coefficient	0,1	Constant
	Scattering phase function	N/A	Isotropic
	Refractive Index	1	Constant
Mixture	Name	Combustion_Gases	
	Mixture species	O2, CO2, CO, H2O, N2	
	Density (kg/m-s)	incompressible-ideal-gas	
	Cp (J/Kg-K)	mixing-law	
	Thermal Conductivity (W/m-K)	mass-weighted-mixing-law	

	Viscosity (kg/m-s)	mass-weighted-mixing-law	
	Mass diffusivity (m2/s)	2,88E-05	
	Absorption coefficient (m-1)	N/A	wsggm-domain-based
	Scattering coefficient (m-1)	0,012	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant
CELL ZONE CONDITIONS			
Solid	Material name	Combustion:gases	
	Rotation-axis direction	X	0
		Y	0
		Z	1
BOUNDARY CONDITIONS			
Inlet	Zone Name	Inlet_Fire_source	
	Type	Mass flow inlet	
	Momentum	Reference frame	absolute
		Mass flow specification method	Mass flow rate
		Mass flow rate (kg/seg)	0,1885
		Supersonic/initial Gauge pressure (Pa)	0
		Direction specification method	Normal to boundary
	Turbulence	Specification method	Intensity and viscosity ratio
		Turbulent Intensity (%)	10
		Turbulent viscosity ratio	100
	Thermal	Total temperature (°C)	1.200
	Radiation	External black body temperature Method	Boundary temperature
		Internal emissivity	1
	Species	H2O	0,082
		O2	0
		CO2	0,197
		CO	0,003
	Zone Name	Inlet_damper1	
	Type	Pressure Inlet	
	Momentum	Reference frame	Absolute
		Gauge total pressure (Pa)	0
		Supersonic/initial Gauge pressure (Pa)	0
		Direction specification method	Normal to boundary
	Turbulence	Specification method	Intensity and viscosity ratio

		Turbulent Intensity (%)	5
		Turbulent viscosity ratio	10
	Thermal	Total temperature (°C)	35
	Radiation	External black body temperature Method	Boundary temperature
		Internal emissivity	1
	Species	H2O	0
		O2	0,23
		CO2	0
		CO	0
Oulet	Zone Name	Outlet_extract1	
	Type	Exhaust Fan	
	Momentum	Backflow Reference frame	Absolute
		Gauge total pressure (Pa)	-25,556
		Pressure profile multiplier	1
		Backflow direction specification method	Normal to boundary
		Backflow pressure specification	Total pressure
		Pressure Jump (Pa)	Polinomial
	Turbulence	Specification method	Intensity and viscosity ratio
		Turbulent Intensity (%)	5
		Turbulent viscosity ratio	5
	Thermal	Backflow Total temperature (°C)	35
	Radiation	External black body temperature Method	Boundary temperature
		Internal emissivity	1
	Species	H2O	0
		O2	0,23
		CO2	0
		CO	0
Wall	Zone Name	Wall-solid	
	Momentum	Wall motion	Stationary wall
		Shear condition	No slip
	Thermal	Thermal conditions	Heat Flux
		Heat Flux (W/m2)	0
		Internal emissivity	1
		Wall thickness (m)	0,3
		Heat generation rate (W/m3)	0

	Species boundary condition	H2O	Zero Diffusive flux
		O2	Zero Diffusive flux
		CO2	Zero Diffusive flux
		CO	Zero Diffusive flux
SOLUTION			
Operating conditions	Pressure	Operating pressure (Pa)	89278
	Gravity	Gravity	On
	Gravitational acceleration	X (m/s2)	0
		Y (m/s2)	-9,8
		Z (m/s2)	0
	Boussinesq parameters	Operating temperature (°C)	35
Methods	Pressure-velocity coupling	Scheme	coupled
		Flux Type	Rhie-Chow: distance based
	Spatial discretization	Gradient	Least square cell-based
	Pressure	Pressure	Second order
	Momentum	Momentum	Second order Upwind
	Turbulent Kinetic Energy	Turbulent Kinetic Energy	Second order Upwind
		Turbulent Dissipation Rate	Second order Upwind
		H2O	Second order Upwind
		O2	Second order Upwind
		CO2	Second order Upwind
		CO	Second order Upwind
		Energy	Second order Upwind
		Transient formulation	First order implicit
Controls	Solution controls	Flow Courant Number	200
	Explicit relaxation factors	Pressure	0,5
		Momentum	0,5
	Under relaxation factors	Density	1
		Body forces	1
		Turbulent Kinetic Energy	0,8
		Turbulent Dissipation Rate	0,8
		Turbulent viscosity	1
		H2O	1
		O2	1
		CO2	1
		CO	1
		Energy	1
		Discretes Ordinates	1

Initialization	Initialization method	Standard initialization	
	Reference frame	Relative to cell zone	
	Initial Values	Gauge pressure (Pa)	89278
		X velocity (m/s)	0
		Y velocity (m/s)	0
		Z velocity (m/s)	0
		Turbulent Kinetic Energy (m2/s2)	1
		Turbulent Dissipation Rate (m2/s2)	1
		H2O	0
		O2	0,23
		CO2	0
		CO	0
		Temperature	35
Run calculation	Parameters	Number of iterations	2000
		Report interval	1
		Profile update interval	1

FLUENT – FIRE SCENARIO 5

FLUENT FIRE SCENARIO 5 - SETUP			
GENERAL	Solver	Type	Pressure-based
		Velocity Formulation	Absolute
	Time	Steady	
	Gravity acceleration	X (m/s2)	0
		Y (m/s2)	-9,8
		Z (m/s2)	0
MODELS			
Energy	Energy Equation	On	
Viscous	Model	K-epsilon (2 eqn)	
	K-epsilon Model	Realizable	
	Near-wall treatment	Enhanced Wall treatment	
Radiation	Discrete Ordinates (DO)	On	
	Energy iterations per radiation iteration	50	
Species	Species transport	On	
MATERIALS			
Fluid	Material Name	Air	

	Density (kg/m-s)	1,225	Constant
	Cp (J/Kg*K)	1.006,43	Constant
	Thermal Conductivity (W/m*K)	0,0242	Constant
	Viscosity (kg/m*s)	1,79E-05	Constant
	Molecular Weight (kg/kmol)	28,966	Constant
	Absorption coefficient (m-1)	0	Constant
	Scattering coefficient (m-1)	0	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant
	Material Name	Carbon Dioxide	CO2
	Density (kg/m-s)	1,7878	Constant
	Cp (J/Kg*K)	N/A	Piecewise-polynomial
	Thermal Conductivity (W/m*K)	0,0145	Constant
	Viscosity (kg/m*s)	1,37E-05	Constant
	Molecular Weight (kg/kmol)	44,000995	Constant
	Absorption coefficient (m-1)	0,43	Constant
	Scattering coefficient (m-1)	0	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant
	Material Name	Carbon Monoxide	CO
	Density (kg/m-s)	1,1233	Constant
	Cp (J/Kg*K)	N/A	Piecewise-polynomial
	Thermal Conductivity (W/m*K)	0,025	Constant
	Viscosity (kg/m*s)	1,75E-05	Constant
	Molecular Weight (kg/kmol)	28,01055	Constant
	Absorption coefficient (m-1)	0,17	Constant
	Scattering coefficient (m-1)	0	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant
Solid	Material Name	Concrete	
	Density (kg/m-s)	2400	Constant
	Cp (J/Kg-K)	1000	Constant
	Thermal Conductivity (W/m-K)	1,2	Constant

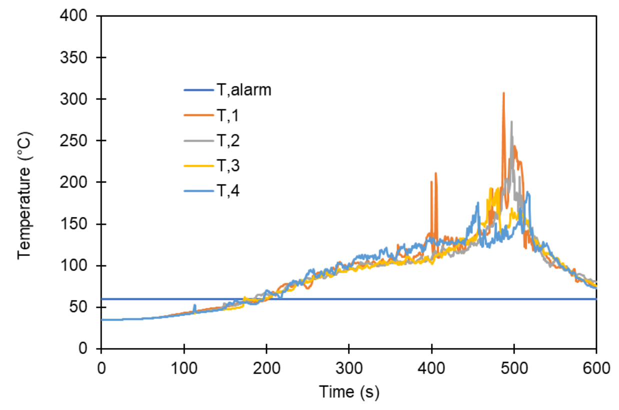
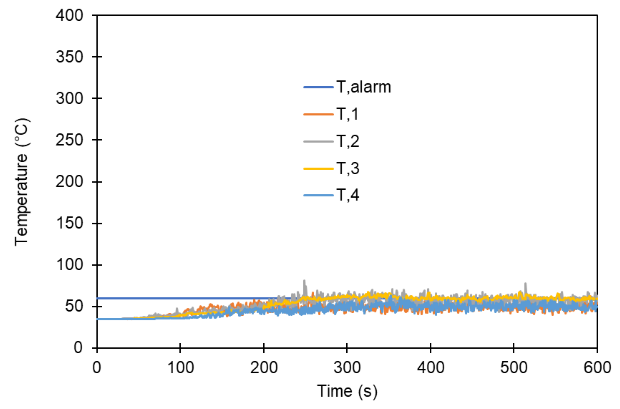
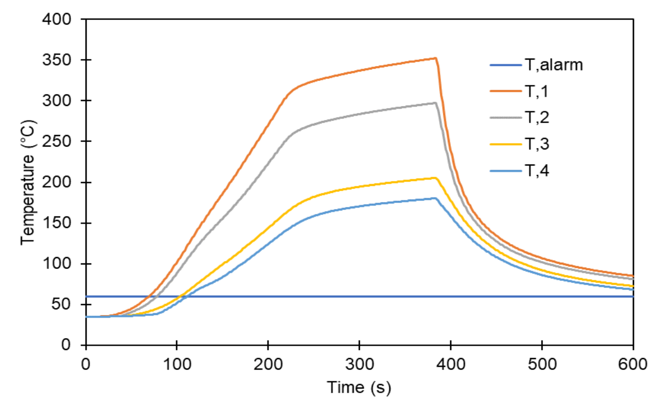
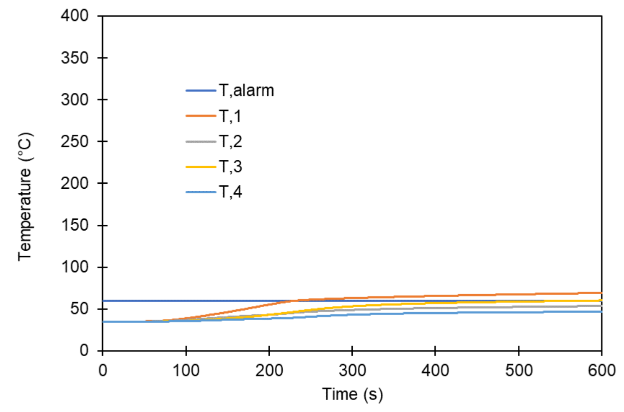
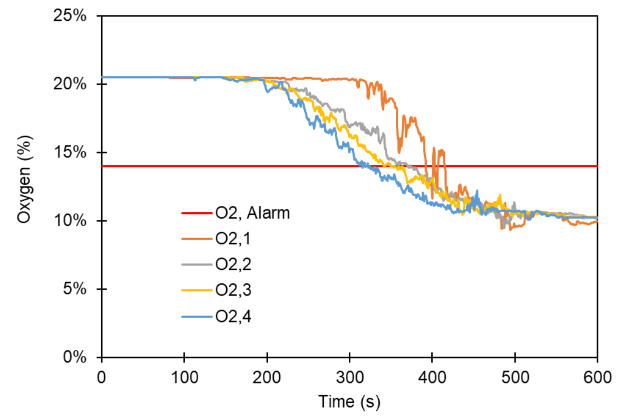
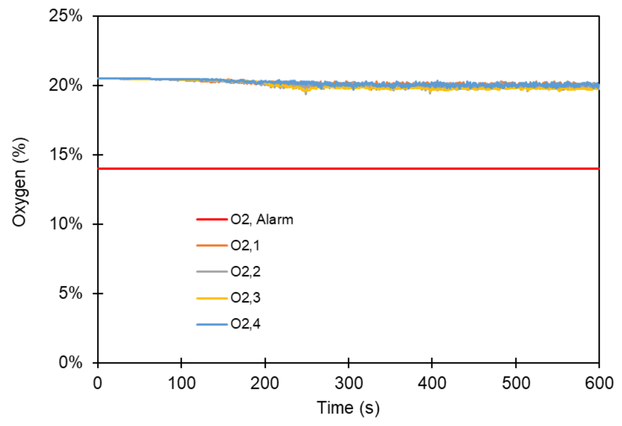
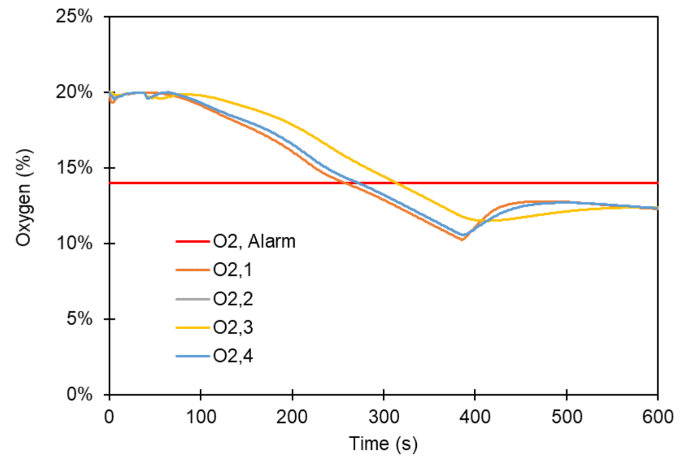
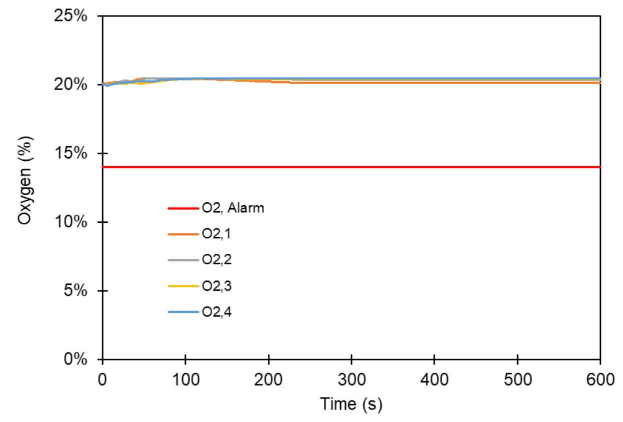
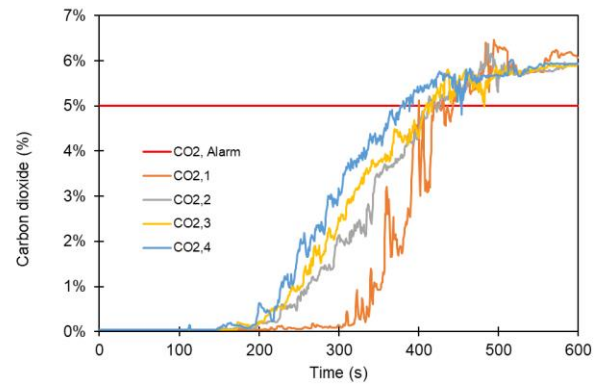
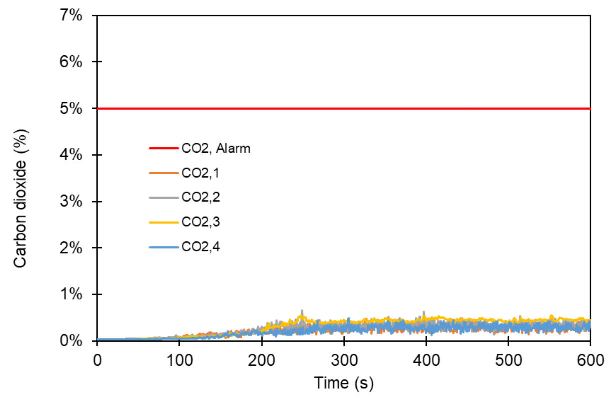
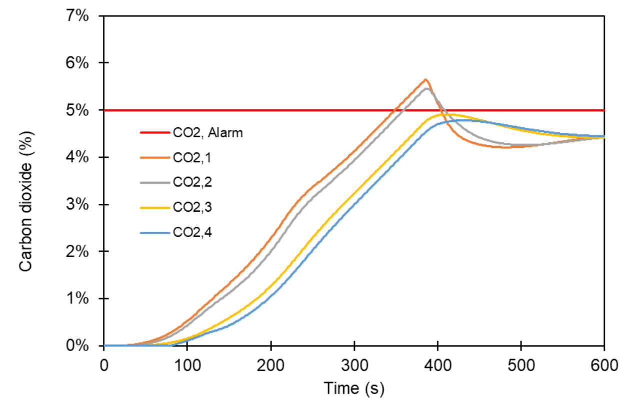
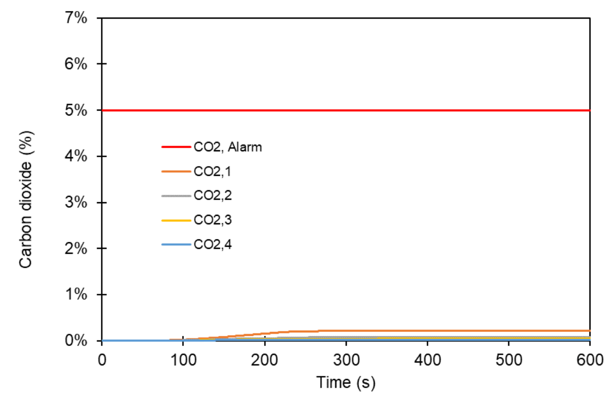
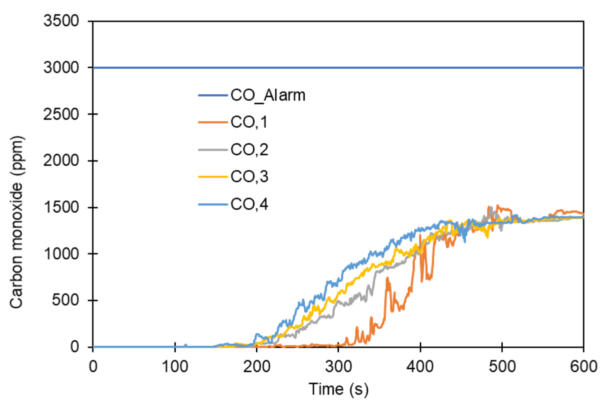
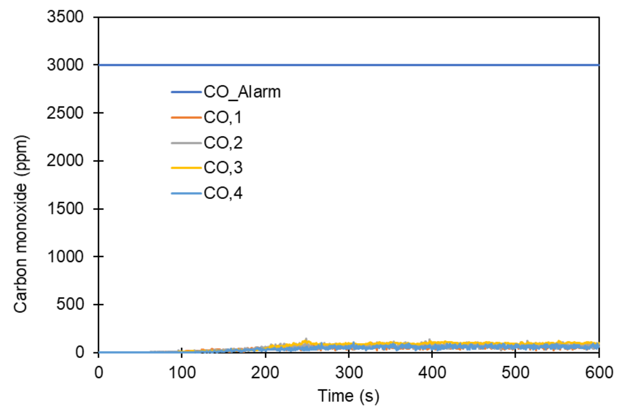
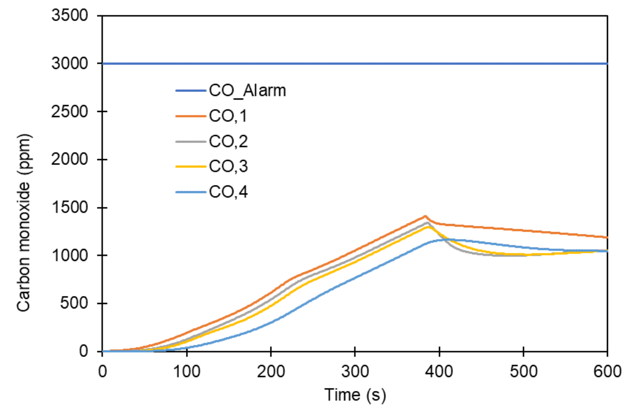
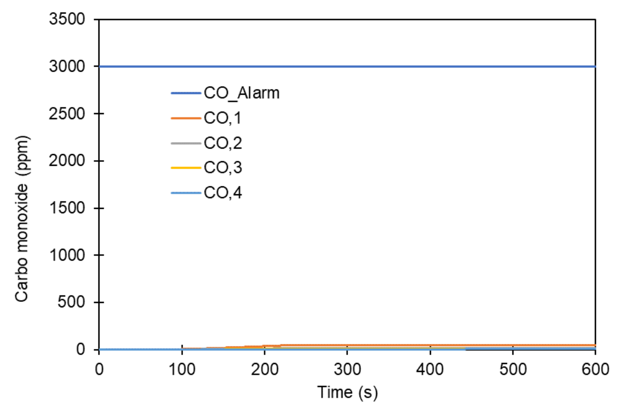
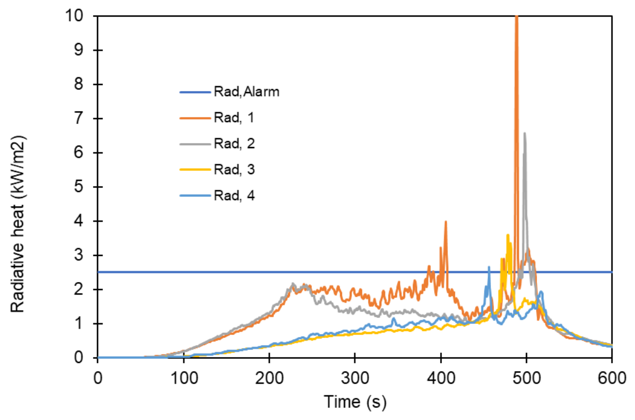
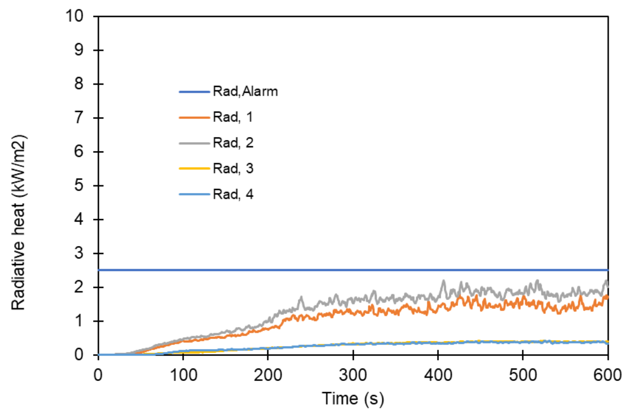
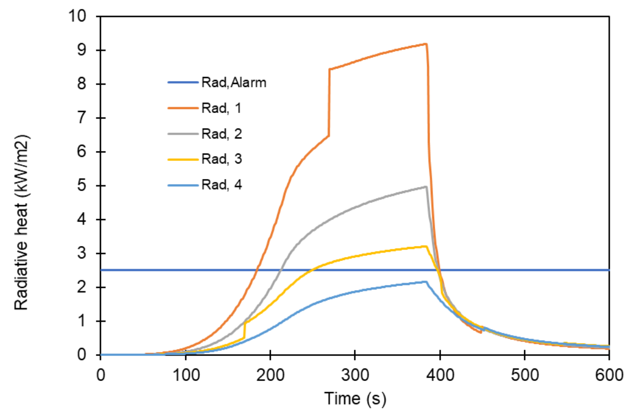
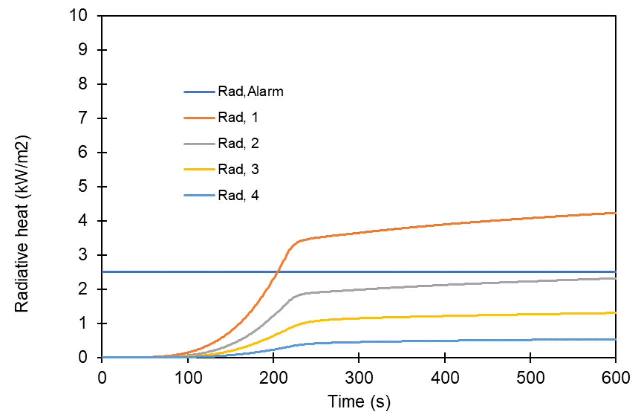
	Absorption coefficient (m-1)	0,1	Constant
	Scattering coefficient	0,1	Constant
	Scattering phase function	N/A	Isotropic
	Refractive Index	1	Constant
Mixture	Name	Combustion_Gases	
	Mixture species	O2, CO2, CO, H2O, N2	
	Density (kg/m-s)	incompressible-ideal-gas	
	Cp (J/Kg-K)	mixing-law	
	Thermal Conductivity (W/m-K)	mass-weighted-mixing-law	
	Viscosity (kg/m-s)	mass-weighted-mixing-law	
	Mass diffusivity (m2/s)	2,88E-05	
	Absorption coefficient (m-1)	N/A	wsggm-domain-based
	Scattering coefficient (m-1)	0,012	Constant
	Scaterring phase function	N/A	Isotropic
	Reflective Index	1	Constant
CELL ZONE CONDITIONS			
Solid	Material name	Combustion:gases	
	Rotation-axis direction	X	0
		Y	0
		Z	1
BOUNDARY CONDITIONS			
Inlet	Zone Name	Inlet_Fire_source	
	Type	Mass flow inlet	
	Momentum	Reference frame	absolute
		Mass flow specification method	Mass flow rate
		Mass flow rate (kg/seg)	0,1885
		Supersonic/initial Gauge pressure (Pa)	0
		Direction specification method	Normal to boundary
	Turbulence	Specification method	Intensity and viscosity ratio
		Turbulent Intensity (%)	10
		Turbulent viscosity ratio	100
	Thermal	Total temperature (°C)	1.200
	Radiation	External black body temperature Method	Boundary temperature
		Internal emissivity	1
	Species	H2O	0,082
		O2	0

		CO2	0,197
		CO	0,003
	Zone Name	Inlet_damper1	
		Inlet_damper2	
		Inlet_damper3	
		Inlet_damper4	
		Inlet_damper5	
	Type	Pressure Inlet	
	Momentum	Reference frame	Absolute
		Gauge total pressure (Pa)	0
		Supersonic/initial Gauge pressure (Pa)	0
		Direction specification method	Normal to boundary
	Turbulence	Specification method	Intensity and viscosity ratio
		Turbulent Intensity (%)	5
		Turbulent viscosity ratio	10
	Thermal	Total temperature (°C)	35
	Radiation	External black body temperature Method	Boundary temperature
		Internal emissivity	1
	Species	H2O	0
		O2	0,23
		CO2	0
		CO	0
Oulet	Zone Name	Outlet_extract1	
		Outlet_extract2	
		Outlet_extract3	
		Outlet_extract4	
		Outlet_extract5	
		Outlet_extract6	
	Type	Exhaust Fan	
	Momentum	Backflow Reference frame	Absolute
		Gauge total pressure (Pa)	-18,6359
		Pressure profile multiplier	1
		Backflow direction specification method	Normal to boundary
		Backflow pressure specification	Total pressure
		Pressure Jump (Pa)	Polinomial

	Turbulence	Specification method	Intensity and viscosity ratio
		Turbulent Intensity (%)	5
		Turbulent viscosity ratio	5
	Thermal	Backflow Total temperature (°C)	35
	Radiation	External black body temperature Method	Boundary temperature
		Internal emissivity	1
	Species	H2O	0
		O2	0,23
		CO2	0
		CO	0
Wall	Zone Name	Wall-solid	
	Momentum	Wall motion	Stationary wall
		Shear confdition	No slip
	Thermal	Thermal conditions	Heat Flux
		Heat Flux (W/m2)	0
		Internal emissivity	1
		Wall thickness (m)	0,3
		Heat generation rate (W/m3)	0
	Species boundary condition	H2O	Zero Diffusive flux
		O2	Zero Diffusive flux
		CO2	Zero Diffusive flux
		CO	Zero Diffusive flux
SOLUTION			
Operating conditions	Pressure	Operating pressure (Pa)	89278
	Gravity	Gravity	On
	Gravitational acceleration	X (m/s2)	0
		Y (m/s2)	-9,8
		Z (m/s2)	0
	Boussinesq parameters	Operating temperature (°C)	35
Methods	Pressure-velocity coupling	Scheme	coupled
		Flux Type	Rhie-Chow: distance based
	Spatial discretization	Gradient	Least square cell-based
	Pressure	Pressure	Second order
	Momentum	Momentum	Second order Upwind
	Turbulent Kinetic Energy	Turbulent Kinetic Energy	Second order Upwind
		Turbulent Dissipation Rate	Second order Upwind
		H2O	Second order Upwind

		O2	Second order Upwind
		CO2	Second order Upwind
		CO	Second order Upwind
		Energy	Second order Upwind
		Transient formulation	First order implicit
Controls	Solution controls	Flow Courant Number	200
	Explicit relaxation factors	Pressure	0,5
		Momentum	0,5
	Under relaxation factors	Density	1
		Body forces	1
		Turbulent Kinetic Energy	0,8
		Turbulent Dissipation Rate	0,8
		Turbulent viscosity	1
		H2O	1
		O2	1
		CO2	1
		CO	1
		Energy	1
		Discretes Ordinates	1
Initialization	Initialization method	Standard initialization	
	Reference frame	Relative to cell zone	
	Initial Values	Gauge pressure (Pa)	89278
		X velocity (m/s)	0
		Y velocity (m/s)	0
		Z velocity (m/s)	0
		Turbulent Kinetic Energy (m2/s2)	1
		Turbulent Dissipation Rate (m2/s2)	1
		H2O	0
		O2	0,23
		CO2	0
		CO	0
		Temperature	35
Run calculation	Parameters	Number of iterations	2000
		Report interval	1
		Profile update interval	1

F. Appendix F: RSET graphic results

Description	FDS		CFAST	
	No extraction	Extraction	No extraction	Extraction
Temperature				
Oxygen				
Carbon dioxide				
Carbon Monoxide				
Radiative heat				

References

3dcadportal.com. (2014, April 8). *STAR-CD* . https://www.3dcadportal.com/star-cd.html

ANSYS. (2020a). *ANSYS 2020 R1 Fluent User's Guide*. http://www.ansys.com

ANSYS. (2020b). *ANSYS Fluid Dynamics Verification Manual*. http://www.ansys.com

Arias, F. (2016, February 16). *Doce horas duró incendio en la central hidroeléctrica de Guatapé*. El Colombiano. https://www.elcolombiano.com/antioquia/emergencia-en-central-hidroelectrica-de-guatape-MM3608439

Asociación Colombiana de Ingeniería Sísmica. (2010). *NSR 10 - Reglamento colombiano de construcción sismoresistente*.

Babrauskas, V., & Grayson, S. J. (1990). *Heat Release in Fires*. Taylor & Francis.

Berg, H.-P., & Fritze, N. (2012). Risk and consequences of transformer explosions and fires in nuclear power plants. *Journal of KONBiN*, *3*(23), 2012. https://doi.org/10.2478/jok-2013-0034

Betancur, J. (2021, August 10). *Incendio afectó central térmica de EPM en Puerto Nare*. El Colombiano. https://www.elcolombiano.com/antioquia/incendio-en-central-termica-de-empresas-publicas-de-medellin-en-puerto-nare-antioquia-GA15377634

Binbin, W. (2011). Comparative Research on FLUENT and FDS's Numerical Simulation of Smoke Spread in Subway Platform Fire . *Procedia Engineering*, *26*, 1065–1075. https://doi.org/10.1016/j.proeng.2011.11.2275

Bishop, J., & Rodriguez, A. (2011). Electrical Transformer Fire and Explosion Protection. *KA Factor Group*.

BlenderFDS. (2023, January 27). *BlenderFDS*. https://blenderfds.org/

BRANZ. (2023, January 15). *B-RISK: Design fire tool*. https://www.branz.co.nz/fire-safety-design/b-risk/

BRE-Group. (2019). *Fire modelling with Computational Fluid Dynamics*. BRE Group | Building a Better World Together. https://bregroup.com/a-z/fire-modelling/

Cadena, J., & Muñoz, F. (2014). *Uncertainty analysis of fire simulations through FDS*. http://hdl.handle.net/1992/11981

Cao, B., Dong, J. W., & Chi, M. H. (2021). Electrical breakdown mechanism of transformer oil with water impurity: Molecular dynamics simulations and first-principles calculations. *Crystals*, *11*(2). https://doi.org/10.3390/cryst11020123

Cárdenas, S. (2017, June 23). *Bomberos atendieron incendio en la Central Playas de EPM*. El Colombiano. https://www.elcolombiano.com/antioquia/incendio-en-la-central-playas-de-epm-KG6778826

Cherbański, R., Rudniak, L., Machniewski, P., Molga, E., Tępiński, J., Klapsa, W., & Lesiak, P. (2022). Ethanol pool fire on a one-meter test tray - validation of CFD results. *Chemical and Process Engineering - Inzynieria Chemiczna i Procesowa*, *43*(1), 23–44. https://doi.org/10.24425/cpe.2022.140809

Chi, J. H., Wu, S. H., & Shu, C. M. (2011). Using Fire Dynamics Simulator to Reconstruct a Hydroelectric Power Plant Fire Accident. *Journal of Forensic Sciences*, *56*(6), 1639–1644. https://doi.org/10.1111/j.1556-4029.2011.01887.x

Darnaculleta, B. (2019). *Validation of CFD codes for risk analysis of accidental hydrocarbon fires* [Ph. D. Thesis]. Univertitat Politécnica de Catalunya - Barcelonatech.

Drysdale, D. (2011). An Introduction to Fire Dynamics: Third Edition. *An Introduction to Fire Dynamics: Third Edition*, 1–551. https://doi.org/10.1002/9781119975465

Duarte, D. (2004). A performance overview about fire risk management in the Brazilian hydroelectric generating plants and transmission network. *Journal of Loss Prevention in the Process Industries*, *17*(1), 65–75. https://doi.org/10.1016/j.jlp.2003.09.007

Duarte, D. (2012). Aspects of Transformer Fires in Brazil. *Open Journal of Safety Science and Technology*, *2*, 63–74. https://doi.org/10.4236/ojsst.2012.23009

Edin, E., & Ström, M. (2019). *Comparing a full scale test with FDS, FireFOAM, McCaffrey & Eurocode*. Luleå University of Technology.

El-Harbawi, M., & Al-Mubaddel, F. (2020). Risk of Fire and Explosion in Electrical Substations Due to the Formation of Flammable Mixtures. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-63354-4

FM Global. (2012). *FM Global: Data Sheet 7-101 Fire Protection for Steam Turbines and Electric Generators*.

FM Global. (2020). *FM Global: Data Sheet 5-3 Hydroelectric Power Plants*.

Forney, G. P. (2022). *Smokeview, A Tool for Visualizing Fire Dynamics Simulation Data Volume I: User's Guide*.

GAPS. (2015a). *GAPS Guidelines GAP 5.9.4 Transformers surroundings*.

GAPS. (2015b). *GAPS Guidelines GAP 17.12.1 Fire protection for electric generating plants and high voltage direct current conventer stations*.

Guo, X., Zhang, H., Pan, X., Zhang, L., Hua, M., Zhang, C., Zhou, J., Yan, C., & Jiang, J. (2022). Experimental and numerical simulation research on fire suppression efficiency of dry powder mediums containing molybdenum flame retardant additive. *Process Safety and Environmental Protection*, *159*, 294–308. https://doi.org/10.1016/j.psep.2021.12.009

Hadjisophocleous, G. v., & Benichou, N. (1999). Performance criteria used in fire safety design. *Automation in Construction*, *8*(4), 489–501. https://doi.org/10.1016/S0926-5805(98)00096-X

Hamins, A., & Mcgrattan, K. (2003). Reduced-Scale Experiments on the Water Suppression of a Rack-Storage Commodity Fire for Calibration of a CFD Fire Model. *Fire Safety Science*, *7*, 457–468.

Hietaniemi, J., & Mikkola, E. (2010). Design fires for safety engineering. *VTT Working Papers*, *139*. URL: http://www.vtt.fi/publications/index.jsp

Hoole, P., Anak Rufus, S., Izzati bt Hashim, N., Hafiez Izzwan Saad, M., Satari Abdullah, A., Hj Othman, A.-K., Piralaharan, K., & Hoole, S. (2017). Power Transformer Fire and Explosion: Causes and Control. *International Journal of Control Theory and Applications*, *10*. http://www.slideshare.net/marimuthusudalaimuth/mhi-transformer

Huang, L., Ma, J., Li, A., & Wu, Y. (2019). Scale modeling experiments of fire-induced smoke and extraction via mechanical ventilation in an underground hydropower plant. *Sustainable Cities and Society*, *44*, 536–549. https://doi.org/10.1016/j.scs.2018.09.021

Hui Zhong, C., & Tunku Abdul Rahman, U. (2013). *Fire dynamics simulation (FDS) study of fire in structures with curved geometry* [Bachelor of Engineering Mechanical Engineering]. Universiti Tunku Abdul Rahman.

Hurley, M. J. (2015). *SFPE Handbook of Fire Protection Engineering, 5th Edition*.

Hurley, M. J., & Rosenbaum, E. R. (2015). *SFPE Performance-Based Fire Safety Design*. http://www.copyright.com/

ICONTEC. (1982). *NORMA TÉCNICA COLOMBIANA NTC 1700: Higiene y seguridad. Medidas de seguridad en edificaciones. Medios de evacuación*.

ICONTEC. (2009a). *NORMA TÉCNICA COLOMBIANA NTC 1669: Instalación de conexiones de mangueras contra incendio*.

ICONTEC. (2009b). *NORMA TÉCNICA COLOMBIANA NTC 2885: Extintores portátiles contra incendios*.

ICONTEC. (2011). *NORMA TÉCNICA COLOMBIANA NTC 2301: Norma para la instalación de sistemas de rociadores*.

IEEE. (2005). *IEEE Std 1147, IEEE Guide for the Rehabilitation of Hydroelectric Power Plants*.

IEEE. (2012). *IEEE Std 979, IEEE Guide for Substation Fire Protection Sponsored by the Substations*.

Jahn, W., Rein, G., & Torero, J. (2008). The effect of model parameters on the simulation of fire dynamics. *Fire Safety Science, 9,* 1341–1352.

Johansson, N. (2021). Evaluation of a zone model for fire safety engineering in large spaces. *Fire Safety Journal*, *120*, 103122. https://doi.org/10.1016/j.firesaf.2020.103122

Kaplan, I. R., Rasco, J., & Lu, S.-T. (2010). Environmental Forensics Chemical Characterization of Transformer Mineral-Insulating Oils. *Chemical Characterization of Transformer Mineral-Insulating Oils, Environmental Forensics*, *11*, 1–2. https://doi.org/10.1080/15275920903558760

Khan, A. A., Usmani, A., & Torero, J. L. (2021). Evolution of fire models for estimating structural fire-resistance. *Fire Safety Journal*, *124*. https://doi.org/10.1016/j.firesaf.2021.103367

Khoat, H. T., Kim, J. T., Dang Quoc, T., Kwark, J. H., & Ryou, H. S. (2020). A Numerical Analysis of the Fire Characteristics after Sprinkler Activation in the Compartment Fire. *Energies*, *13*(12). https://doi.org/10.3390/en13123099

Klote, J., Milke, J., Turnbull, P., Kashef, A., & Ferreira, M. (2012). *Handbook of Smoke Control Engineering*.

Leonita, F., Sakti, H., & Nugroho, Y. S. (2017). Study of the Occupant Characteristics During Evacuation in Medium- and High-Rise Buildings in Indonesia. *Fire Science and Technology 2015*, 123–132. https://doi.org/10.1007/978-981-10-0376-9_12

Liu, C., Tian, X., Zhong, M., Lin, P., Gong, Y., Yin, B., & Wang, H. (2020). Full-scale experimental study on fire-induced smoke propagation in large underground plant of hydropower station. *Tunnelling and Underground Space Technology*, *103*. https://doi.org/10.1016/j.tust.2020.103447

Lucas, M. (2009). *Simulación de incendios en centrales de generación eléctrica mediante código FDS* [Proyecto final de carrera Ingeniería Industrial]. Universidad Carlos III de Madrid.

Maluk, C., Woodrow, M., & Torero, J. L. (2017). The potential of integrating fire safety in modern building design. *Fire Safety Journal*, *88*, 104–112. https://doi.org/10.1016/j.firesaf.2016.12.006

Mariño, O. A., & Muñoz, F. (2016). Implementación de modelos de producción hollín para simulaciones de incendio en FDS [Tesis de Maestría]. In *Chemical Engineering Department, UniAndes*. UniAndes.

McGrattan, K. B. (2006a). *FDS Technical Reference Guide*. https://doi.org/10.6028/NIST.SP.1018

McGrattan, K. B. (2006b). *FDS Verification Guide*. https://doi.org/10.6028/NIST.SP.1018

McGrattan, K. B. (2006c). *Fire dynamics simulator (FDS) technical reference guide volume 3: Validation*. https://doi.org/10.6028/NIST.SP.1018

Mcgrattan, K., & Hostikka, S. (2013). Verification and Validation Process of a Fire Model. *National Institute of Standards and Technology*.

McGrattan, K., McDermott, R., Vanella, M., Hostikka, S., & Floyd, J. (2020). *Fire dynamics simulator User´s Guide*. https://doi.org/10.6028/NIST.SP.1019

National Fire Protection Association. (2019). *NFPA 14: Standard for the installation of standpipe and hose systems*.

National Fire Protection Association. (2020). *NFPA 850: Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations*. www.nfpa.org.

National Fire Protection Association. (2021a). *NFPA 1: Fire Code*. The Association.

National Fire Protection Association. (2021b). *NFPA 92: Standard for Smoke Control Systems*. www.nfpa.org/docinfo.

National Fire Protection Association. (2021c). *NFPA 101: Life Safety Code ® Handbook 14th Edition* (G. Harrington & K. Bigda, Eds.; 14th ed.). NFPA.

National Fire Protection Association. (2021d). *NFPA 204: Standard for Smoke and Heat Venting, 2007 Edition*. www.nfpa.org.

National Fire Protection Association. (2022a). *NFPA 10: Standard for portable fire extinguishers*. National Fire Protection Association.

National Fire Protection Association. (2022b). *NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection*. www.nfpa.org/freeaccess.

National Fire Protection Association. (2022c). *NFPA 72: National fire alarm and signaling code*.

Olenick, S. M. (2023, January 26). *International Survey of Computer Models for Fire and Smoke*. https://www.firemodelsurvey.com/

Olenick, S. M., & Carpenter, D. J. (2003). An Updated International Survey of Computer Models for Fire and Smoke. *Journal of Fire Protection Engineering*, *13*(2), 87–110. https://doi.org/10.1177/104239103033367

Peacock, R. D., Reneke, P. A., & Forney, G. P. (2015a). *CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 7) Volume 2: User's Guide*. https://doi.org/10.6028/NIST.TN.1889v2

Peacock, R. D., Reneke, P. A., & Forney, G. P. (2015b). *CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 7) Volume 3: Software Development and Model Evaluation Guide*. https://doi.org/10.6028/NIST.TN.1889v3

Polužanski, V., Kartalović, N., & Nikolić, B. (2021). Impact of power transformer oil-temperature on the measurement uncertainty of all-acoustic non-iterative partial discharge location. *Materials*, *14*(6), 1–18. https://doi.org/10.3390/ma14061385

Roberson, J., & Stambaugh, H. (2002). Fire at Watts Bar Hydroelectric Plant. *U.S. Fire Administration / Technical Report Series*, *USFA-TR-147*. www.usfa.dhs.gov/

Ronchi, E., Arias, S., Mendola, L., & Johansson, N. (2019). A fire safety assessment approach for evacuation analysis in underground physics research facilities. *Fire Safety Journal*. https://doi.org/10.1016/j.firesaf.2019.102839

Roushan, A. (2020, August 11). *Telangana: 9 dead in Srisailam power plant fire mishap*. https://timesofindia.indiatimes.com/city/hyderabad/telangana-9-dead-in-srisailam-power-plant-fire-mishap/articleshow/77675557.cms

Society of Fire Protection Engineers. (2019). *SFPE Guide to Human Behavior in Fire*. Springer International Publishing. https://doi.org/10.1007/978-3-319-94697-9

Tavares, R. M. (2009). An analysis of the fire safety codes in Brazil: Is the performance-based approach the best practice? *Fire Safety Journal*, *44*(5), 749–755. https://doi.org/10.1016/j.firesaf.2009.03.005

Torero, J. L. (2011). Fire-induced structural failure: The World Trade Center, New York. *Proceedings of the Institution of Civil Engineers: Forensic Engineering*, *164*(2), 69–77. https://doi.org/10.1680/feng.2011.164.2.69

U.S. Nuclear Regulatory Commission, & Electric Power Research Institute (EPRI). (2019). *NUREG-2232 and EPRI3002015997, Heat Release Rate and Fire Characteristics of*

Fuels Representative of Typical Transient Fire Events in Nuclear Power Plants. www.nrc.gov/reading-rm.html.

Vallejo, L. (2023). Educational program for the prevention of fires and explosions through emerging technologies (A.Molina (Ed)). In *Maestría en ingeniería - Ingeniería química*. Universidad Nacional de Colombia - Sede Medellín.

WiKi. (2021, April). *FireFoam - OpenFOAM Wiki. Transient Solver for Fires and Turbulent Diffusion Flames with Reacting Particle Clouds, Surface Film and Pyrolysis Modelling*. https://openfoamwiki.net/index.php/FireFoam

Working Group A2.33. (2013). *537 Guide for Transformer Fire Safety Practices*.

XM. (2022). *Informe plantas de generación eléctrica en Colombia*. XM Web Page. https://www.xm.com.co/generaci%C3%B3n/plantas

Yasuda, M., & Watanabe, S. (2017). How to avoid severe incidents at hydropower plants. *International Journal of Fluid Machinery and Systems*, *10*(3), 296–306. https://doi.org/10.5293/IJFMS.2017.10.3.296

Yu, H.-Z., Lee, J. L., & Kung, H.-C. (1994). Suppression of Rack-Storage Fires by Water. *Fire Safety Science*, *4*, 901–912.

Zhang, B., Zhang, J., Huang, Y., Wang, Q., Yu, Z., & Fan, M. (2019). Burning process and fire characteristics of transformer oil A study focusing on the effects of oil type. *Journal of Thermal Analysis and Calorimetry*, *139*, 1839–1848. https://doi.org/10.1007/s10973-019-08599-6

Zhu, P., Wang, X., Wang, Z., Cong, H., & Ni, X. (2017). Experimental Study on Transformer Oil Pool Fire Suppression by Water Mist. *Fire Science and Technology 2015*, 895–901. https://doi.org/10.1007/978-981-10-0376-9_92