



INDUSTRIAL ENGINEERING MASTER'S DEGREE

FINAL MASTER'S DEGREE PROJECT
INTERACTION BETWEEN ESFR AND SMOKE
VENTS IN INDUSTRIAL WAREHOUSES

Author: Gustavo Adolfo Terrer Fos

Director: Borja Rengel Darnaculleta

Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título
Interaction Between Esfr And Smoke Vents In Industrial Warehouses
en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el
curso académico 2022/2023 es de mi autoría, original e inédito y
no ha sido presentado con anterioridad a otros efectos.

El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido
tomada de otros documentos está debidamente referenciada.

Fdo.: Gustavo Adolfo Terror Fos

Fecha: 31 / 08 / 2023

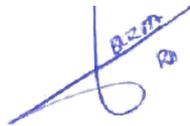


Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Borja Rengel Darnacullea

Fecha: 31 / 08 / 2023





INDUSTRIAL ENGINEERING MASTER'S DEGREE

FINAL MASTER'S DEGREE PROJECT
INTERACTION BETWEEN ESFR AND SMOKE
VENTS IN INDUSTRIAL WAREHOUSES

Author: Gustavo Adolfo Terrer Fos

Director: Borja Rengel Darnaculleta

Madrid

INTERACCIÓN ENTRE ESFR Y SALIDAS DE HUMO EN ALMACENES INDUSTRIALES.

Autor: Terror Fos, Gustavo Adolfo

Director: Rengel Darnaculleta, Borja

Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

Este proyecto se centra en el análisis de la interacción entre sistemas ESFR y sistemas de ventilación en almacenes logísticos industriales, a través de simulaciones CFD utilizando el software FDS. Se evaluarán aspectos relacionados con las normativas tanto estadounidenses como españolas que impactan en estos escenarios.

Palabras clave: ESFR, SCTEH, FDS, Almacén, Fuego, Humo, Rociador, Exutorio y Cortinas de humo.

1. Introducción

Las instalaciones logísticas industriales presentan un riesgo intrínseco elevado de incendio. Por esta razón, es imperativo que se adhieran rigurosamente a las regulaciones de protección contra incendios. Al mismo tiempo, estas directrices deben ser tanto precisas como fiables.

Los sistemas de rociado de supresión temprana y respuesta rápida (ESFR) junto con las salidas de humo constituyen sistemas de protección contra incendios activos que se instalan comúnmente en espacios de gran volumen, como los almacenes industriales. Los sistemas ESFR están diseñados para suprimir los incendios en sus etapas iniciales, mientras que los sistemas de ventilación de humo están concebidos para permitir la intervención de los bomberos una vez que el desarrollo del fuego esté bajo control.

Conforme a las normativas nacionales e internacionales, las salidas de humo deben activarse manualmente para asegurar un alto rendimiento en el patrón de activación de los rociadores. Sin embargo, surge un creciente debate acerca de la activación automática de las salidas de humo en presencia de sistemas ESFR. Dado el número limitado de pruebas experimentales que involucran la interacción entre ESFR y las salidas de humo, este estudio tiene como objetivo evaluar dicha interacción. Para lograrlo, se empleará el software CFD Fire Dynamics Simulator (FDS) para llevar a cabo múltiples simulaciones de incendios en almacenes industriales bajo diversas condiciones.

2. Definición del proyecto

Este proyecto, de naturaleza industrial mecánica, busca realizar una comparación entre distintas normativas nacionales e internacionales. Además, mediante simulaciones y el análisis de los resultados, trata de poner a prueba algunas de las pautas que estas proponen en especial de la interacción entre los sistemas ESFR y los sistemas de control de temperatura y evacuación de humos.

La principal motivación detrás de este proyecto radica en la falta de conocimiento actual y, en particular, la escasez de pruebas para optimizar la efectividad de las medidas de seguridad contra incendios en entornos industriales.

El objetivo fundamental es simular diversos escenarios de acuerdo con las medidas y requisitos establecidos por las normativas más reconocidas en el ámbito de la protección contra incendios. A través de modificaciones entre los escenarios, se busca evaluar el funcionamiento y la eficacia de estas medidas, permitiendo su comparación.

3. Características generales

Este estudio considerará las principales regulaciones de seguridad contra incendios tanto a nivel nacional como internacional, incluyendo el Reglamento de Seguridad Contra Incendios en Establecimientos Industriales y la NFPA 1. Además, abordará las normas relacionadas con sistemas de control de humo y calor, como la UNE 23585, la NFPA 92 y la NFPA 204. También se tomarán en cuenta las regulaciones pertinentes a sistemas de rociado, como la UNE 12845 y la NFPA 13.

Los criterios para diseñar las simulaciones se basarán en las normativas mencionadas. Se desarrollará el diseño de un almacén logístico (Figure 1) en el cual se llevarán a cabo ocho simulaciones de incendio en diversos escenarios. Las variaciones planificadas incluyen la presencia o ausencia de cortinas de humo, la activación manual o automática de los sistemas de evacuación de humos, el método de detección utilizado para la señal de apertura de la ventilación y la velocidad de crecimiento del incendio (media o ultrarrápida).

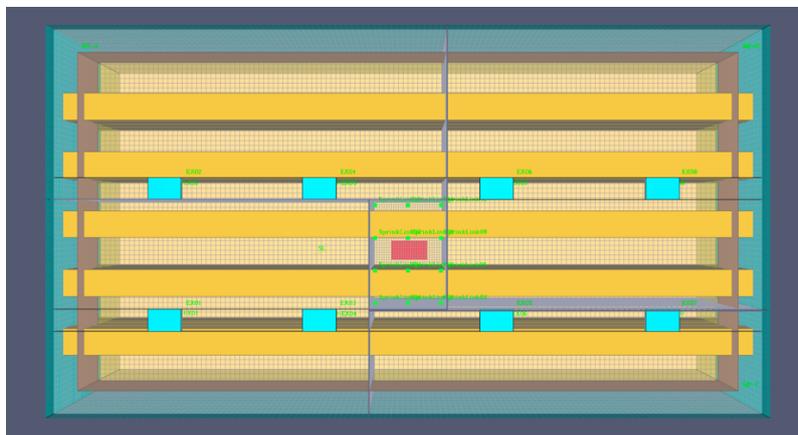


Figure 1. Vista en planta del diseño de uno de los escenarios de incendio en nave logística a simular.

4. Resultados

Tras las simulaciones, se procede a analizar los resultados obtenidos. Inicialmente, se realiza una visualización gráfica de las simulaciones mediante el software Smokeview (Figure 2), lo que permite identificar posibles errores y observar el resultado físico del escenario simulado.

A continuación, se extraen valores significativos y relevantes para estudiar el desarrollo y el impacto de las condiciones propuestas. En primer lugar, se analizan las gráficas de la relación de liberación de calor, que proporcionan una representación visual del crecimiento del incendio. En segundo lugar, se evalúa el tiempo de activación de los rociadores y la cantidad de estos que se activan en cada escenario. Finalmente, se mide el tiempo requerido para el llenado de los depósitos de humo, en aquellos casos en los que esto ocurra, con el propósito de verificar su utilidad y efectividad.

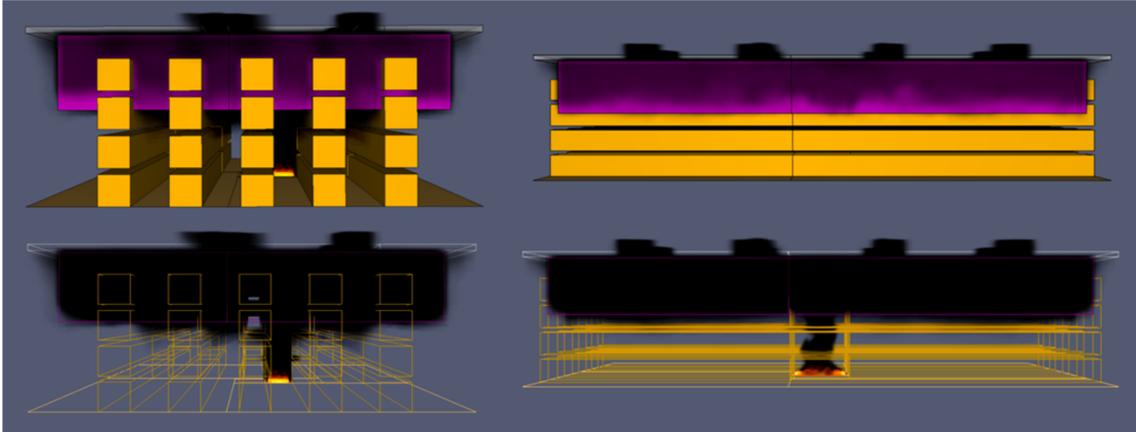


Figure 2. Perfil izquierdo y alzado de una instantánea del resultado de una de las simulaciones.

5. Metodología y desarrollo

Para llevar a cabo este proyecto, se ha seguido un proceso organizado en diferentes etapas. La fase inicial ha implicado recopilar información acerca del contexto en el que se desarrolla esta investigación. Esto incluye comprender el impacto de los incendios en edificios industriales, explorar el estado actual de la tecnología orientada a reducir los daños causados por incendios y familiarizarse con los métodos comúnmente empleados en la actualidad.

En una segunda etapa, se llevó a cabo un estudio y comparación exhaustivos de las diversas perspectivas presentes en las normativas y en la opinión de los expertos reconocidos tanto a nivel internacional como nacional.

Posteriormente, utilizando esta información, se realizaron simulaciones con el objetivo de abordar algunas de las incertidumbres que rodean la efectividad de ciertas pautas reconocidas en la actualidad.

Finalmente, los resultados obtenidos son analizados en detalle. Se examinan las conclusiones que pueden extraerse de los hallazgos y se identifican posibles mejoras o modificaciones que puedan ser implementadas desde esta perspectiva.

INTERACTION BETWEEN ESFR AND SMOKE VENTS IN INDUSTRIAL WAREHOUSES

Author: Terror Fos, Gustavo Adolfo

Supervisor: Rengel Darnaculleta, Borja

Collaborating Entity: ICAI – Universidad Pontificia Comillas

ABSTRACT

This project focuses on the analysis of the interaction between ESFR systems and ventilation systems in industrial logistic warehouses, through CFD simulations using the FDS software. Aspects related to regulations from both the United States and Spain that impact these scenarios will be evaluated.

Keywords: ESFR, SCTEH, FDS, WAREHOUSE, Fire, Smoke, Sprinkler, Vent and Fire Curtain.

1. Introduction

Industrial logistic facilities inherently carry a high risk of fire. As a result, it is imperative that they rigorously adhere to fire protection regulations. Simultaneously, these guidelines must be both precise and reliable.

Early Suppression Fast Response (ESFR) systems, in conjunction with smoke vents, constitute active fire protection systems commonly installed in large-volume spaces, such as industrial warehouses. ESFR systems are designed to suppress fires in their early stages, while smoke ventilation systems are conceived to enable firefighter intervention once fire development is under control.

In accordance with national and international regulations, smoke vents must be manually activated to ensure high performance in sprinkler activation patterns. However, an increasing debate arises regarding the automatic activation of smoke vents in the presence of ESFR systems. Given the limited number of experimental tests involving the interaction between ESFR and smoke vents, this study aims to evaluate this interaction. To achieve this goal, the CFD software Fire Dynamics Simulator (FDS) will be employed to conduct multiple fire simulations in industrial warehouses under various conditions.

2. Project definition

This project, of an industrial mechanical nature, aims to conduct a comparison among different national and international regulations. Additionally, through simulations and result analysis, it seeks to test some of the guidelines proposed by these regulations, particularly focusing on the interaction between ESFR systems and temperature and smoke control systems.

The primary motivation behind this project lies in the current lack of knowledge and, specifically, the scarcity of tests to optimize the effectiveness of fire safety measures in industrial settings.

The core objective is to simulate various scenarios in accordance with the measures and requirements outlined by the most recognized fire protection regulations. By introducing modifications across scenarios, the aim is to evaluate the functionality and efficacy of these measures, enabling a comprehensive comparison.

3. General Characteristics

This study will consider the primary fire safety regulations both at the national and international levels, including the “Reglamento de Seguridad Contra Incendios en Establecimientos Industriales” and NFPA 1. Additionally, it will address standards related to smoke and heat control systems, such as UNE 23585, NFPA 92, and NFPA 204. And, finally, relevant regulations pertaining to sprinkler systems, such as UNE 12845 and NFPA 13, will also be taken into account.

The criteria for designing the simulations will be based on the aforementioned regulations. The design of a logistic warehouse (Figure 4) will be developed, wherein eight fire simulations will be conducted across various scenarios. Planned variations encompass the presence or absence of smoke curtains, manual or automatic activation of smoke evacuation systems, the detection method used for ventilation opening signals, and the fire growth rate (average or ultra-rapid).

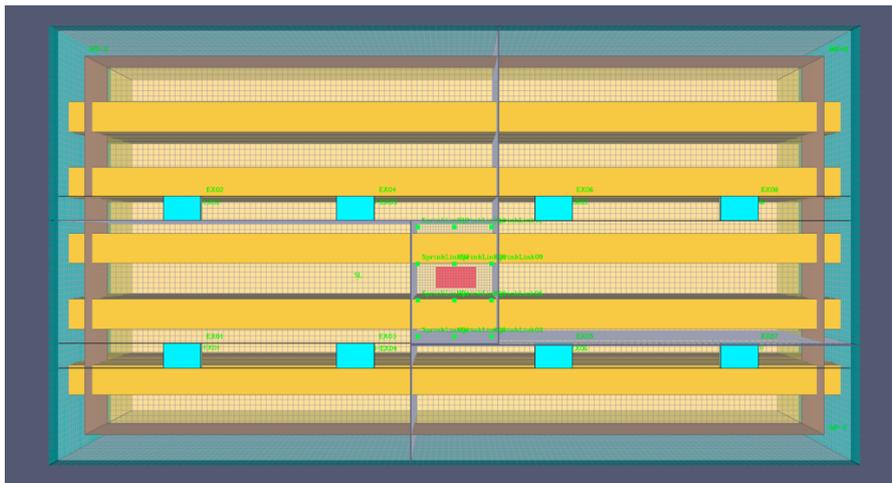


Figure 3. Floor plan of the design for one of the fire scenarios in a simulated logistics warehouse.

4. Results

After the simulations, the obtained results are subjected to analysis. Initially, a graphical visualization of the simulations is performed using the Smokeview software (Figure 4) allowing for the identification of potential errors and the observation of the physical outcome of the simulated scenario.

Subsequently, significant and relevant values are extracted for the purpose of studying the development and impact of the proposed conditions. Firstly, the heat release rate graphs are analyzed, offering a visual representation of the fire's growth. Secondly, the activation time of the sprinklers and the quantity of activated sprinklers in each scenario

are evaluated. Lastly, the time required for the smoke reservoirs to fill, in cases where this occurs, is measured to verify their utility and effectiveness.

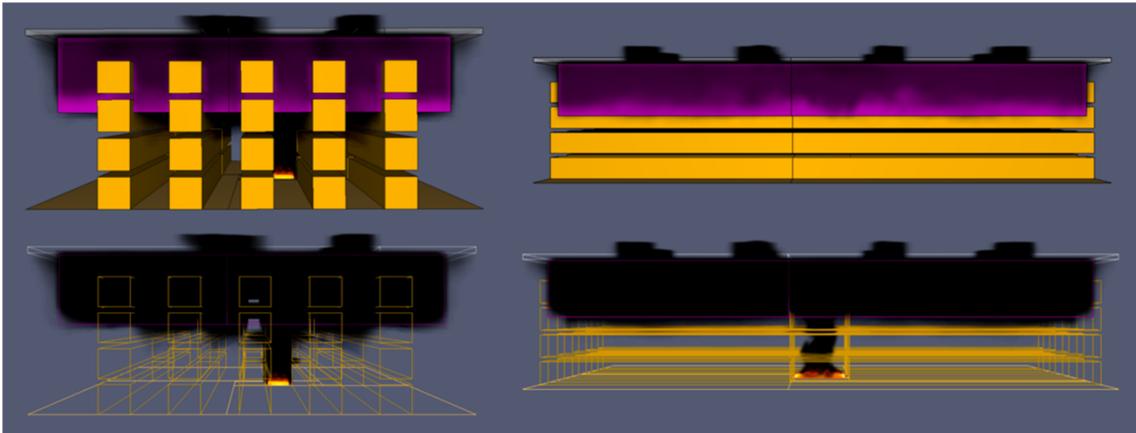


Figure 4. Left profile and elevation of a snapshot from one of the simulations' results.

5. Methodology and development

To carry out this project, a well-organized process has been followed in various stages. The initial phase involved collecting information about the context in which this research takes place. This includes understanding the impact of fires in industrial buildings, exploring the current state of technology aimed at reducing fire damages, and becoming familiar with the methods commonly used today.

In a second stage, a comprehensive study and comparison of various perspectives present in regulations and the opinions of recognized experts at both the international and national levels were conducted.

Subsequently, using this information, simulations were performed to address some of the uncertainties surrounding the effectiveness of certain recognized guidelines today.

Finally, the obtained results are analyzed in detail. The conclusions that can be drawn from the findings are examined, and potential improvements or modifications that can be implemented from this perspective are identified.

Table of contents

1. Literature review	7
1.1. Statistical analysis of fire accidents in warehouses	7
1.2. Prescriptive fire protection measures in warehouses.....	10
1.2.1. Reglamento de Seguridad Contra Incendios en Establecimientos Industriales (BOE, 2014)	10
1.2.1.1. Introduction	10
1.2.1.2. Definitions.....	11
1.2.1.3. Basics	12
1.2.1.4. Inherent Risk Level	12
1.2.1.5. Construction Requirements for Industrial Establishments	14
1.2.1.5.1. Fire detection and alarm systems	17
1.2.1.5.2. Fire water supply systems	17
1.2.1.5.3. Fire extinguishers.....	18
1.2.1.5.4. Equipped Fire Hydrant Systems.....	18
1.2.1.5.5. Dry Standpipe Systems	18
1.2.1.5.6. Fixed Automatic Fire Suppression Systems.....	18
1.2.1.5.6.1. Fixed water spray fire suppression systems	19
1.2.1.5.6.2. Fixed physical foam fire suppression systems	19
1.2.1.5.6.3. Fixed powder fire suppression systems.....	20
1.2.1.5.6.4. Fixed gas extinguishing agent fire suppression systems	20
1.2.1.5.7. Smoke and heat control systems	20
1.2.1.5.8. Emergency lighting	21
1.2.1.5.9. Signaling of protective means	21
1.2.2. NFPA 1 (NFPA, 2021)	22
1.2.2.1. General Safety Requirements	22
1.2.2.1.1. Fundamental Requirements.....	22
1.2.2.1.2. Building Evacuation.....	23
1.2.2.1.3. Fire Drills.....	23
1.2.2.1.4. Reporting of Fires and Other Emergencies	23
1.2.2.1.5. Tampering with Fire Safety Equipment	24
1.2.2.1.6. Emergency Action Plans	24
1.2.2.2. Smoke Partitions	24
1.2.2.3. Smoke Barriers	25
1.2.2.4. Automatic Sprinklers.....	25
1.2.2.5. General Fire Protection	27
1.2.2.6. Components of egress means	27
1.3. Types of fires in warehouses	32
1.3.1. Type of combustible	32
1.3.2. According to the origin or cause	33
1.3.3. According to the growing rate	35
2 Smoke control systems in warehouses	39
2.1 General description.....	39
2.1.1. Purposes of smoke control systems	39
2.1.2. Components	39

2.1.3	Working steps	40
2.1.3.1	Early stages of a fire	40
2.1.3.2	Smoke characteristics	40
2.1.3.3	Smoke logged.....	40
2.1.4	Basic design principle	40
2.1.5	Components	41
2.1.5.1	Natural smoke vents	41
2.1.5.1.1	Types of natural smoke vents (cottes, 2020)	41
2.1.5.2	Mechanical smoke vents	43
2.1.5.3	Inlet	44
2.1.6	Special considerations.....	44
2.1.6.1	High bay storage areas	44
2.1.6.2	Interaction of sprinklers & vents	44
2.2	Spanish perspective.....	45
2.2.1	UNE 23585 (Normalización Española, 2017)	45
2.2.1.1	Application of the Smoke Control and Fire Safety Management.....	46
2.2.1.2	Design fire model for high-rise storage building.....	47
2.2.1.3	Smoke reservoirs and fire curtains	47
2.2.1.4	Air inlet	48
2.2.1.5	Interactions between different zones or smoke compartments	49
2.2.1.6	Performance with a sprinkler suppression system.....	50
2.3	US perspective	52
2.3.1	NFPA 92 (NFPA, 2021)	52
2.3.1.1	Key Design Aspects and Approaches for Smoke Control.....	52
2.3.1.2	Manual and automatic activation.....	53
2.3.1.3	Equipment	54
2.3.2	NFPA 204 (NFPA, 2021)	54
2.3.2.1	Fundamentals	54
2.3.2.1.1	Design.....	55
2.3.2.1.2	Basics	55
2.3.2.2	Vents design and classification	55
2.3.2.2.1	Methods of Operation.....	56
2.3.2.2.2	Dimensions and Spacing of Vents	56
2.3.2.3	Air Inlets	56
2.3.2.3.1	Construction and location.....	56
2.3.2.3.2	Methods of Operation.....	57
2.3.2.4	Draft Curtains.....	57
2.3.2.4.1	Construction and location.....	57
2.3.2.5	Mechanical Smoke Exhaust Systems	57
2.3.2.5.1	Design.....	57
2.3.2.6	Venting in Sprinklered Buildings.....	58
2.4	Comparison between both perspectives.....	58
2.4.1	Activation type: manual or automatic	58
2.4.2	Fire curtain.....	60
3	<i>Sprinklers systems in warehouses.....</i>	63
3.1	Basics of sprinkler systems	63
3.1.1	Components and Operation.....	63
3.1.2	Types	64
3.1.2.1	Early Suppression Fast Response sprinklers	65
3.1.2.1.1	Benefits of ESFR sprinklers	68

3.2	Spanish perspective.....	68
3.2.1	UNE 12845 (Normalización Española, 2021)	68
3.2.1.1	Introduction	68
3.2.1.2	Classification of Activities and Fire Risks	69
3.2.1.3	Storage classification.....	69
3.2.1.4	Water Supply.....	71
3.2.1.5	Spacing and Placement of Sprinklers	71
3.2.1.6	Sprinkler Flow Rate and Temperature.....	72
3.2.1.7	Interaction with other measures.....	73
3.2.1.8	High-Rise Systems	73
3.2.1.9	ESFR Sprinklers.....	73
3.3	US perspective	75
3.3.1	NFPA 13 (NFPA, 2022)	75
3.3.1.1	Scope and Purpose	75
3.3.1.2	Classification of Activities and Fire Risks	75
3.3.1.3	Sprinkler classification and identification	76
3.3.1.4	Sprinkler Location Requirements.....	76
3.3.1.5	Installation Requirements for ESFR.....	77
3.3.1.6	General Requirements for Storage	78
3.3.1.7	ESFR Requirements for Storage Applications	79
3.4	Comparison between both perspectives.....	80
4	<i>Assessment of the interaction between ESFR and smoke vents</i>	83
4.1	Fire Dynamics Simulator (FDS)	83
4.2	Validation exercises FDS	83
4.2.1	Initial Assumptions.....	84
4.3	Perform FDS simulations.....	89
4.3.1	Heat Release Rate graphs	89
4.3.2	Sprinklers activation and time	94
4.3.2.1	Summary of the results	103
4.3.3	Smoke reservoirs filling time.....	104
4.3.4	Mass of smoke evacuated through the exhaust vents.....	106
5	<i>Conclusions</i>	109
5.1	Simulation results	109
5.1.1	Fire curtains	109
5.1.2	Sprinklers.....	110
5.2	Final insights.....	110
	<i>ANEX A. Alignment with the SDG.....</i>	111
	<i>ANEX B. Characterization of the products released in the combustion reaction.....</i>	113
	<i>ANEX C. FM Datasheet 2-0</i>	115
	<i>Bibliografía</i>	117

Index of figures

Figure 1. Vista en planta del diseño de uno de los escenarios de incendio en nave logística a simular.....	8
Figure 2. Perfil izquierdo y alzado de una instantánea del resultado de una de las simulaciones.....	9
Figure 3. Floor plan of the design for one of the fire scenarios in a simulated logistics warehouse.....	11
Figure 4. Left profile and elevation of a snapshot from one of the simulations' results.....	12
Figure 5. US Structure Fires in Warehouses: 1990–2020.....	8
Figure 6. Inflation-Adjusted US Direct Propriety Damage in Warehouses Structure Fires: 1980-2020.....	8
Figure 7. Estimated distribution of insured fire costs.....	9
Figure 8. Average severity of fires by type of insurance.....	10
Figure 9. Fire stages and growing rates (Normalización Española, 2017).....	36
Figure 10. Lamella exhaust vent (cottes, 2020).....	42
Figure 11. Compartmental exhaust vent (cottes, 2020).....	42
Figure 12. Architectural Solution Vents (cottes, 2020).....	43
Figure 13. Smoke Control and Temperature Evacuation System.....	46
Figure 14. Smoke curtain (cottes, 2020).....	50
Figure 16. Sprinkler parts (firewize).....	63
Figure 15. Sprinklers glass bulb color grading (Day-Impex Ltd).....	63
Figure 17. K-Factor comparison for automatic sprinklers. [5].....	65
Figure 18. Heat release rate vs Time. Fire supression and fire control (NFPA, 2022) ..	66
Figure 19. Fast-response and a standard-response sprinkler (ESFR Sprinklers: A Strong Line of Defense in Storage Applications, 2022).....	67
Figure 20. Axonometric view warehouse scenario 1 and 2.....	87
Figure 21. Left profile edge view warehouse scenario 1 and 2.....	87
Figure 22. Axonometric view warehouse scenario 3, 4, 5, 6, 7 and 8.....	88
Figure 23. Left profile edge view warehouse scenario 3, 4, 5, 6, 7 and 8.....	88
Figure 24. Snapshot in second 200 of ultra-rapid fire growth rate scenario.....	89
Figure 25. Snapshot in second 200 of medium fire growth rate scenario.....	89
Figure 26. HRR Case 1.....	90
Figure 27. HRR Case 2.....	90
Figure 28. HRR Case 3.....	91
Figure 29. HRR Case 4.....	91
Figure 30. HRR Case 5.....	92
Figure 31. HRR Case 6.....	92
Figure 32. HRR Case 7.....	93
Figure 33. HRR Case 8.....	93
Figure 34. Top-down view of the sprinkler distribution in relation to the simulated fire area (moderate growth rate).....	94
Figure 35. Top-down view of the sprinkler distribution in relation to the simulated fire area (ultra-fast growth rate).....	95
Figure 36. Sprinklers temperature vs time in Case 1.....	96

Figure 37. Sprinklers temperature vs time in Case 2.....	97
Figure 38. Sprinklers temperature vs time in Case 3.....	98
Figure 39. Sprinklers temperature vs time in Case 4.....	99
Figure 40. Sprinklers temperature vs time in Case 5.....	100
Figure 41. Sprinklers temperature vs time in Case 6.....	101
Figure 42. Sprinklers temperature vs time in Case 7.....	102
Figure 43. Sprinklers temperature vs time in Case 8.....	103
Figure 44. Smoke distribution with no curtains. Scenarios 1 and 2.....	105
Figure 45. Smoke spillage over curtains. Scenarios 3, 4, 7 and 8.....	106
Figure 46. No smoke spillage over curtains and smoke evacuation through vents. Scenarios 5 and 6.....	106
Figure 47. SDG 3.....	111
Figure 48. SDG 9.....	111
Figure 49. SDG 11.....	112
Figure 50. SDG 13.....	112
Figure 51. Flowchart for potential recommendations when vents or smoke vents must be installed (FM Global, 2021)	115

Index of tables

Table 1. Intrinsic risk level based on weighted and adjusted fire load density (Q_s)	13
Table 2. Maximum allowable constructed area for each fire sector.....	15
Table 3. Fire resistance of construction elements delimiting fire sectors	16
Table 4. Adaptation for single-story above-grade buildings with lightweight roofing, equipped with a fixed automatic fire suppression system and smoke and heat control system.	16
Table 5. Sprinklers temperature ratings and color coding from NFPA 1	26
Table 6. Growing rates fire classification.....	37
Table 7. Natural and mechanical smoke ventilation.....	43
Table 8. High-rise storage building equations and definitions.....	47
Table 9. Unexpanded plastic in cardboard boxes in ST2, ST3, and ST4 storage configurations UNE 12845 (Normalización Española, 2021).....	70
Table 10. Sprinklers temperature ratings and color coding from UNE 12845.....	72
Table 11. Coverage area of ESFR sprinkler in UNE 12845.....	74
Table 12. Sprinklers temperature ratings and color coding from NFPA 13.....	76
Table 13. Coverage area of ESFR sprinkler in NFPA 13.....	78
Table 14. Unexpanded plastic in cardboard boxes in ST2, ST3, and ST4 storage configurations NFPA 13 (NFPA, 2022)	80
Table 15. Comparison of sprinklers classification by the color of the glass bulb	81
Table 16. Fire scenarios simulated.	86
Table 17. Sprinklers activation and temperatures in medium ultra-fast growth rate	103
Table 18. Sprinklers activation and temperatures in medium growth rate	104
Table 19. Filling Time of Smoke Reservoirs	105
Table 20. Total smoke mass evacuated in each scenario	106
Table 21. Physicochemical data of the polyurethane foam.	113

1. Literature review

1.1. Statistical analysis of fire accidents in warehouses

Warehouses are buildings or storage facilities where goods are stored, and the accumulation of these goods and the materials used in storage can create conditions that increase the likelihood of a fire. Factors such as poor ventilation, inadequate fire suppression systems, and the presence of flammable materials can all contribute to making a warehouse a fire hazard. Among this problem it is added the exponential growth of logistical warehouses, both in number and sizes, making this issue in need of even more attention.

Fire hazards are definitely one of the main dangers that these stores, boosted by the actual high density stock trend, can front. This risk is not only an economical and business disaster but can led into an environmental and natural catastrophe with oversized fires hard to control, and goes without saying, the huge risk that implies for the workers and firemen.

All these factors make a perfect scenario to develop and search for the best systems to avoid, as much as possible, this risk, and when not possible mitigate it in the shortest period of time possible and reduce their impact and damage.

The following data displays some of the most representative information pertaining to this issue in various localities and points of interest:

In Madrid, during the year 2020 alone, there were 1.473 fires inside buildings, and 1.677 in the year 2021. These incidents not only caused significant damage to the properties involved, but also posed a risk to human lives and the environment. Among these fires, up to 25, in the year 2020, and 28, in the year 2021, took place in industries and warehouses. These types of fires are particularly concerning as they often involve large quantities of potentially flammable materials and chemicals, which can lead to extensive damage and costly repairs. Despite being a relatively small portion of the overall number of fires, those that occur in industries and warehouses are particularly costly and can have severe consequences. (Dirección General de Emergencias y Protección civil, 2021; Dirección General de Emergencias y Protección civil, 202)

Up until 2016, the United States saw an average of 1,210 warehouse fires per year, resulting in an average annual cost of \$155 million related to property damage, 19 civilian injuries, and 3 civilian deaths. Electrical distribution and lighting equipment was one of the main causes of these fires, accounting for 18% of total warehouse fires. Additionally, 18% of warehouse fires were caused by intentional acts of arson, which tend to be more destructive and cause 32% of the most severe property damage. (HRRSS, 2021)

The number of total structure fires in warehouses in the US has been reduced by 74 percent since 1980, falling from 4,700 fires per year in 1980 to 1,200 in 2013, mostly thanks to the development of better technology for fire detection and fire suppression systems, combined with upgraded building standards, adoption of better safety practices and greater awareness and knowledge of fire risks and prevention measures. (Figure 5)

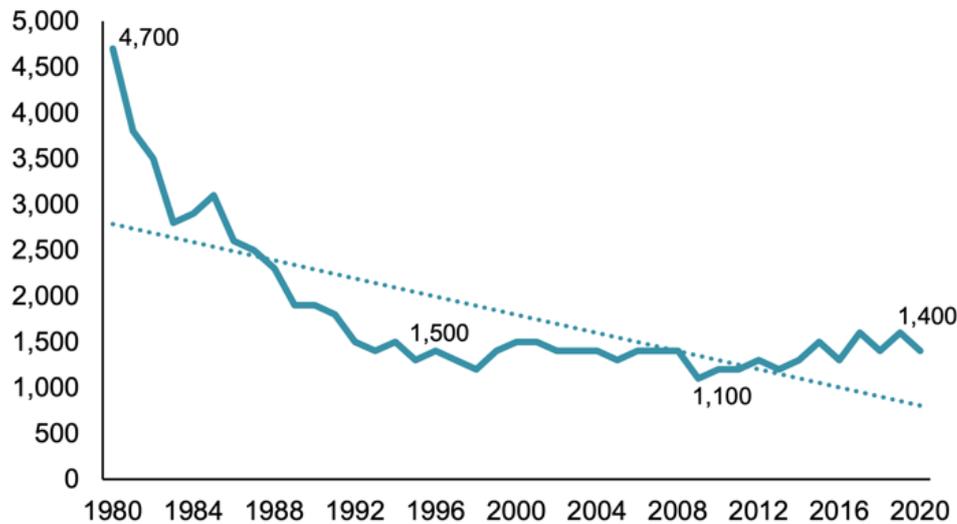


Figure 5. US Structure Fires in Warehouses: 1990–2020

Even though these results are very encouraging, besides the increase in the last years due to the exponential build of these structures, the decrease in the number of this incidents do not correspond with direct property damage due to this same cause. Contrarily it shows a moderate increase over these years in losses. (Figure 6)

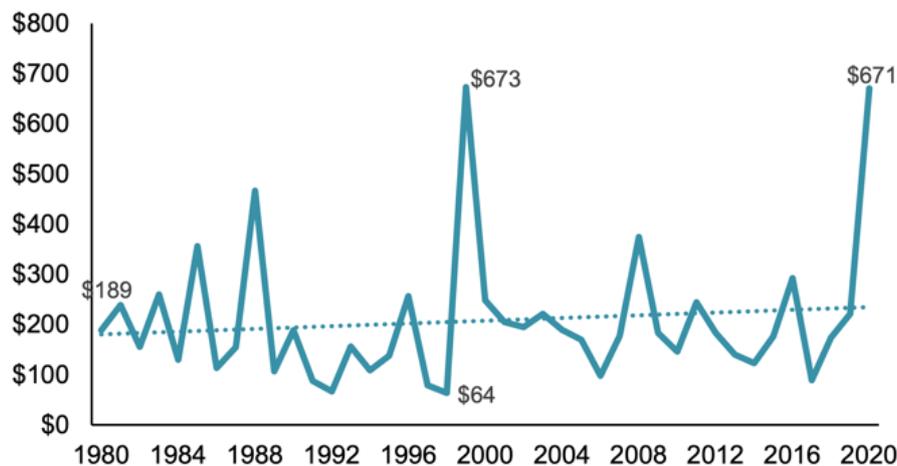


Figure 6. Inflation-Adjusted US Direct Propriety Damage in Warehouses Structure Fires: 1980-2020

The explicit and implicit reasons of a high frequency of fires in logistic infrastructures may be dependent on the characteristics of the logistics industry as it is shown in the following paragraphs.

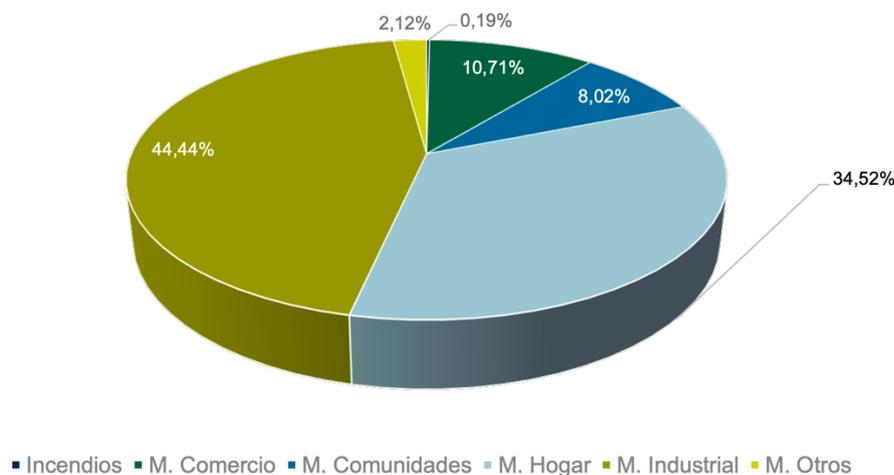
- **Characteristics of Logistics Industry.** Modern logistics encompasses various components such as storage, transfer, sorting, processing, and distribution. In order to fulfill the ever-increasing need for express deliveries, logistics warehouses have evolved to become larger, taller, and more advanced than traditional ones. They are designed to accommodate heavier loads, offer multifunctionality, and operate with

high levels of automation, all in line with the demands of "light-speed delivery" and "zero storage".

- **Hazards of Logistics Warehouse Fires.** The presence of fire characteristics serves as indications of fire hazards. Incidents involving fires in logistics warehouses typically result in extensive destruction of space, the release of harmful gases, rapid spreading, and ultimately, the collapse of the warehouses.

As shown, fire is indeed a risk with a relatively low probability, but with potentially high effects. Its capability extends to reducing the affected object to ashes, which means complete destruction and disappearance.

(Unespa, 2020-2021) According to data from 30 insurance companies, estimated to represent an 82.4% market share, the total costs of fires in Spain between July 2020 and June 2021 are estimated to be around 500 million euros, a magnitude similar to the previous year. The two main components of the cost are fires in industries and homes. (Figure 7)

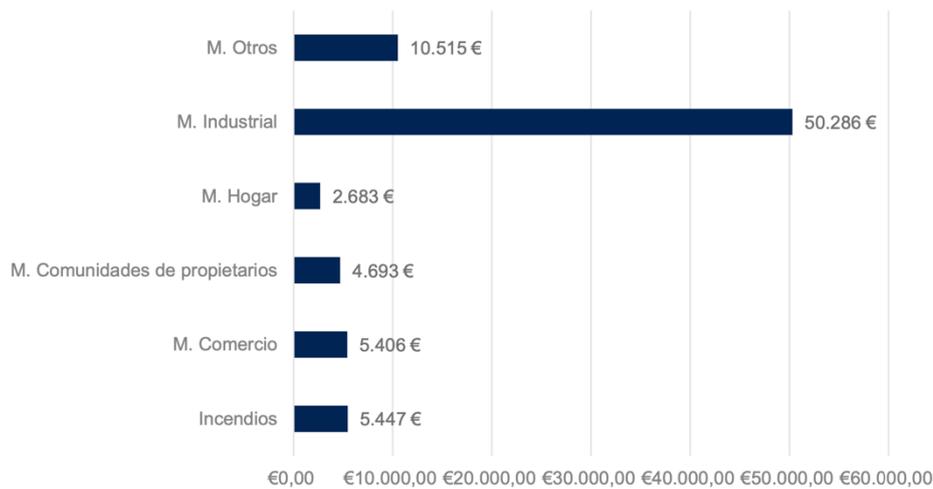


Fuente: Elaboración de Estamos Seguros.

Figure 7. Estimated distribution of insured fire costs.

The severity of fires is derived from their cost. In other words, the study assumes that the higher the amount paid by the insurance company, the more severe the fire is considered to be.

Based on the data collected in this year's database, the average cost of incidents is around 5,600 euros (Figure 8). However, there are significant differences depending on the types, indicating that fires in homes tend to be less severe, while industrial fires, logically, are of greater severity.



Fuente: Elaboración de Estamos Seguros.

Figure 8. Average severity of fires by type of insurance

1.2. Prescriptive fire protection measures in warehouses

1.2.1. Reglamento de Seguridad Contra Incendios en Establecimientos Industriales (BOE, 2014)

1.2.1.1. Introduction

The “*Reglamento de Seguridad Contra Incendios en Establecimientos Industriales*”, from now on RSCIEI, is the Regulation of Fire Safety in Industrial Establishments. (BOE, 2014) It is the Spanish regulation which has the objective of establishing the necessary safety measures to prevent and protect against fires in industrial establishments and ensure the safety of people, property, and the environment.

The RSCIEI establishes the technical requirements that industrial establishments must meet in terms of fire prevention and protection, as well as the emergency procedures to be followed. Fire prevention activities aim to limit the presence of fire risk and the circumstances that can trigger a fire. Fire response activities aim to control or fight the fire, extinguish it, and minimize the damage or losses it can cause. The safety measures established include passive and active fire protection, evacuation of people, signage, training of workers and emergency drills.

RSCIEI compliance is mandatory for all industrial establishments in Spain, and non-compliance can lead to administrative sanctions, fines, and even closure of the establishment in case of serious risk to the safety of people.

1.2.1.2. *Definitions*

An important aspect of this document lies in the definitions it provides, and it's worth starting by reviewing some of these.

a) **Industrial establishment:** "An industrial establishment is understood to be one intended for use under distinct ownership and whose primary purpose is industrial. Industrial establishments can consist of one or several buildings, parts thereof, and open spaces." (BOE, 2014)

b) **Industrial storage:** "Industrial storage refers to any enclosed or non-enclosed area exclusively intended for storing products, located within an industrial establishment or auxiliary to it, or, in the absence of specific applicable legislation, one whose use is derived from an industrial activity related to transportation, as outlined in Article 3.4, section f), of Law 21/1992 on Industry, such as logistics warehouses or goods distribution warehouses." (BOE, 2014)

c) **Passive fire protection:** "This refers to protection resulting from the construction requirements of establishments. Its purpose is to prevent the occurrence of a fire, impede or delay its spread, and facilitate both fire extinguishment and evacuation." (BOE, 2014)

d) **Active fire protection:** "This refers to the collection of means, equipment, and systems, whether manual or automatic, specifically designed to actively and directly act in fire protection through detection, control, or extinguishment, facilitating occupant evacuation and preventing the fire from spreading." (BOE, 2014)

e) **Equivalent safety techniques:** "This refers to the adoption of technical solutions that differ wholly or partially from the technical specifications indicated in this regulation, but offer an equal or greater level of safety." (BOE, 2014)

f) **Performance-based design:** "This refers to the adoption of a set of technical solutions that differ wholly or partially from the technical specifications indicated in this regulation and have been specifically designed for a particular location, taking into account all relevant factors related to it (such as operating conditions and intended use). The proposed set of technical solutions must ensure that the level of safety provided is equal to or greater than what would be achieved by applying the specifications indicated in this regulation." (BOE, 2014)

g) **Fire sectors and areas.**

Fire sector: Bounded space within a building where a fire can be contained to prevent its spread to other sectors or fire areas.

Fire area: Open space delimited by a perimeter within which it is separated from other zones. The elements within this area must be arranged in a way that prevents propagation to adjacent zones or buildings. (BOE, 2014)

1.2.1.3. *Basics*

This regulation provides a set of guidelines to achieve its objectives, ensuring that industrial establishments are designed, constructed, maintained, and operated in accordance with the specified fundamental requirements:

- a) Interior spread: Fire propagation within the building must not exceed a set maximum.
- b) Exterior spread: The risk of fire spreading outside the building itself or to others will be similarly limited.
- c) Occupant evacuation: The establishment must be adequately equipped for occupant evacuation or access to a safe space within it, under secure conditions.
- d) Fire protection facilities: The establishment shall be equipped with necessary equipment and installations to detect, control, and extinguish fires, as well as to transmit alarms.
- e) Firefighter intervention: Measures will be taken to facilitate the action of firefighting and rescue teams.
- f) Structural fire resistance: The load-bearing structure must maintain its fire resistance to ensure at least the time required for compliance with the mentioned basic requirements.

1.2.1.4. *Inherent Risk Level*

"Inherent Risk Level" (IRL), in Spanish, "Nivel de Riesgo Intrínseco" (NRI) of a fire sector or area refers to the level of danger it faces in the event of a potential fire. This is derived from factors such as the quantity of flammable materials present, their susceptibility to ignition, how these materials are distributed, and the nature of activities taking place in that space.

The IRL is classified as low, moderate, or high. Additionally, it is further subdivided into values ranging from 1 to 8, based on the weighted and adjusted fire load density (Q_s) present in the specific fire sector or area.

IRL		Q_s (MJ/m ²)
LOW	1	$Q_s \leq 425$
	2	$425 < Q_s \leq 850$
MEDIUM	3	$850 < Q_s \leq 1275$
	4	$1275 < Q_s \leq 1700$
	5	$1700 < Q_s \leq 3400$
HIGH	6	$3400 < Q_s \leq 6800$
	7	$6800 < Q_s \leq 13600$
	8	$Q_s > 13600$

Table 1. Intrinsic risk level based on weighted and adjusted fire load density (Q_s)

The weighted and corrected fire load density (Q_s) in each of the fire sectors or areas can be obtained using one of the possible methods outlined below:

a) Calculation of Q_s from the combustibility data of the materials present.

$$Q_s = \frac{\sum(q_i G_i C_i)}{A} R \text{ (MJ/m}^2\text{)}$$

Where:

Q_s = Weighted and corrected fire load density of the fire sector or area, measured in MJ/m².

q_i = Calorific power, in MJ/kg, of each of the combustible materials present in the fire sector or area.

G_i = Mass, in kilograms, of each of the combustible materials present in the fire sector or area.

C_i = Dimensionless coefficient that weighs the degree of hazard based on the combustibility of each of the combustible materials present in the fire sector or area.

R = Dimensionless coefficient that corrects the degree of inherent hazard from the industrial activity carried out in the fire sector or area (production, assembly, transformation, repair, storage, etc.).

A = Constructed area of the fire sector or fire area, measured in square meters.

b) Calculation of Q_s based on fire load density data from zones with manufacturing activities and other similar processes.

This method is used for fire sectors or areas with specific manufacturing and other similar processes, which are not of particular interest for this project, and the calculation using this process will not be extensively developed.

c) Calculation of Q_s based on fire load density data from storage areas.

For fire sectors or areas dedicated to storage, the following expression can be used:

$$Q_s = \frac{\sum(q_{vi}h_iS_iC_i)}{A} R \text{ (MJ/m}^2 \text{)}$$

Where:

q_{vi} = fire load, contributed by each cubic meter of each storage area with different material types present in the fire sector or area, in MJ/m³.

h_i = height of each material storage, in meters.

S_i = constructed area of each material storage, in square meters.

d) Calculation of Q_s by combining various of the aforementioned methods.

If there are several activities within the same building, you can utilize the combination of two or more of the previously mentioned equations.

1.2.1.5. *Construction Requirements for Industrial Establishments*

Regarding the construction requirements of industrial establishments, there is an emphasis on the importance of compartmentalizing them into fire sectors when located within buildings, or fire areas if situated in open spaces. Each industrial establishment must include at least one fire sector or, if applicable, a fire area. Furthermore, it is stipulated that the maximum allowable constructed area for each fire sector is determined by factors such as the intrinsic risk level and the specific configuration of the sector, as detailed in a corresponding table.

Intrinsic risk level	Configuration			
	Type A _v (m ²)	Type A _H (m ²)	Type B (m ²)	Type C (m ²)
Low 1	2.000	6.000	12.000	Unlimited
Low 2	1.000	4.000	8.000	12.000
Medium 3	500	3.500	7.000	10.000
Medium 4	400	3.000	6.000	8.000
Medium 5	300	2.500	5.000	7.000
High 6	Not Allowed	2.000	4.000	6.000
High 7		1.500	3.000	5.000
High 8		Not Allowed	Not Allowed	4.000

Table 2. Maximum allowable constructed area for each fire sector

Certain significant considerations apply to this configuration depending on the intrinsic risk level:

Except in cases of high risk, in situations where more than 50% of the accessible perimeter of the industrial establishment corresponds to its façade, the maximum allowable constructed areas, as detailed in the table, may be multiplied by 1.25.

When fixed automatic sprinkler systems covering the entire sector are installed, the maximum allowable constructed areas indicated in the table may be multiplied by 2. Alternatively, the use of other fixed automatic fire suppression systems will also be accepted instead of sprinklers, provided these systems are suitable for the location and the risk being protected.

Both of the previous multipliers can be applied simultaneously. Thus, if both situations occur concurrently, the factor for increasing the maximum area of the fire sector would be 2.5.

In type C configurations, the fire sector can have any area, as long as the entire sector is equipped with a fixed automatic fire suppression system and the distance to other establishments, as well as to property boundaries with potential for building on them, is greater than 10 meters, free from flammable goods or intermediate elements capable of spreading fire.

The following table displays the minimum fire resistance of construction components that establish boundaries between adjacent fire sectors, such as walls and ceilings:

Intrinsic risk level	Type A _v		Type A _H		Type B		Type C	
	Sub-level floor (basement)	Above-grade floor						
Low	EI 120	EI 90	EI 120	EI 90	EI 90	EI 60	EI 60	EI 30
Medium	Not Allowed	EI 120	EI 180	EI 1200	EI 120	EI 90	EI 90	EI 60
High	Not Allowed	Not Allowed	Not Allowed	EI 180	EI 1800	EI 120	EI 120	EI 90

Table 3. Fire resistance of construction elements delimiting fire sectors

A few important considerations and clarifications to consider from this section are as follows:

The symbols E, I, and R represent Flame Integrity, Thermal Insulation, and Load-Bearing Capacity, respectively, with their values expressed in minutes. In cases where partition elements also serve as load-bearing structures, their values should meet at least the respective REI values, as per the figures specified in the table.

For above-grade buildings with a single floor and a lightweight roof, if the total area of the fire sector is protected by a fixed automatic fire suppression system and a smoke and heat control system the values in Table 3 can be reduced to the values indicated below:

Intrinsic risk level	Type A _H	Type B	Type C
Low	EI 60	EI 30	EI 30
Medium	EI 90	EI 30	EI 30
High	EI 120	EI 30	EI 30

Table 4. Adaptation for single-story above-grade buildings with lightweight roofing, equipped with a fixed automatic fire suppression system and smoke and heat control system.

The specifications that products used as cladding or surface finishes must meet at the very least are as follows:

For habitable areas in general, C-s2, d0 will be required for ceilings and walls, and Cfl-s1 for floors.

In industrial establishments, the use of active fire protection systems is required. In this context, it's worth providing a concise definition of fixed automatic fire suppression systems. These systems are designed to initiate agent discharge without requiring human intervention. The following systems fall under this category:

1. Fixed automatic fire suppression systems with automatic sprinklers and water mist
2. Fixed automatic fire suppression systems with water mist
3. Fixed automatic fire suppression systems with physical foam

4. Fixed automatic fire suppression systems with powder
5. Fixed automatic fire suppression systems with gaseous extinguishing agents
6. Fixed automatic fire suppression systems with condensed aerosols

In the subsequent segments, we will delve into the detailed descriptions of the most pertinent active fire protection systems for our case study.

1.2.1.5.1. Fire detection and alarm systems

Fire detection and alarm systems will consist of devices for automatic activation (detectors) and/or devices for manual activation (manual alarm buttons). These components will be interconnected with a control and indication panel, as well as alarm devices.

In the fire sectors of industrial establishments where storage activities are conducted, detection and alarm systems will be installed. These systems will incorporate devices for both automatic and manual activation, including detectors and manual alarm buttons. This arrangement will be applied in the following scenarios:

- a) AV or AH type configurations: with sectors of 150 m² or larger.
- b) B type configurations: with areas of 1,000 m² or larger and a medium intrinsic risk level, or areas of 500 m² or larger with a high intrinsic risk level.
- c) C type configurations: with areas of 1,500 m² or larger and a medium intrinsic risk level, or areas of 800 m² or larger with a high intrinsic risk level.

1.2.1.5.2. Fire water supply systems

As per this regulation, it will be necessary to install a water supply system whenever it is required to provide service under the calculated flow rate, pressure, and reserve conditions for one or multiple fire protection systems, or when any of the existing provisions demand it.

In the case of coexisting multiple fire protection systems, the calculation of flow rate, pressure, and water reserve must consider the following criteria:

1. The flow rate, pressure, and water reserve must be sufficient for the simultaneous operation of the protection systems in a localized fire.
2. It is not necessary to consider multiple fire sources when calculating flow rate, pressure, and water reserve, as the systems are designed to act in a single location.
3. In areas with multiple protection systems, the flow rate and pressure are calculated to meet the demand of the zone with the highest protection requirements.
4. The calculated flow rates and reserves are minimum values, but they can be dimensioned larger to increase safety or address more demanding situations.

5. If multiple establishments share a water supply system for their fire protection systems, it must comply with the aforementioned requirements, be designed for maximum demand scenarios, and ensure proper maintenance and accessibility.

1.2.1.5.3. Fire extinguishers

The most notable aspect in this section is the requirement for the installation of portable fire extinguishers in all fire sectors of industrial establishments, except in areas with automated storage where access is restricted due to operational activity.

1.2.1.5.4. Equipped Fire Hydrant Systems

Fire hydrant systems will be installed in fire sectors under the following circumstances:

- a) AV type configuration with sectors of 300 m² or larger.
- b) AH or B type configurations: with sectors of 150 m² or larger.
- c) AH or B type configurations: with areas of 500 m² or larger and a medium intrinsic risk level, or areas of 200 m² or larger with a high intrinsic risk level.
- d) C type configurations: with areas of 1,000 m² or larger and a medium intrinsic risk level, or areas of 500 m² or larger with a high intrinsic risk level.
- e) D type configurations: with areas of 5000 m² or larger with a high intrinsic risk level.

Just as with fire extinguishers, the absence of equipped fire hydrant systems can be justified in areas with automated storage where human access is restricted due to operational activity.

1.2.1.5.5. Dry Standpipe Systems

Dry standpipe systems will be installed in industrial establishments where the evacuation height is 15 meters or higher, and these columns will include outlet valves on all floors.

1.2.1.5.6. Fixed Automatic Fire Suppression Systems

In fire sectors where storage activities are conducted, automatic sprinkler systems will be implemented under the following circumstances:

- a) AV type configuration with sectors of 300 m² or larger and a medium intrinsic risk level.
- b) AH type configuration: with areas of 1000 m² or larger and a medium intrinsic risk level, or areas of 600 m² or larger with a high intrinsic risk level.

- c) B type configuration: with areas of 1500 m² or larger and a medium intrinsic risk level, or areas of 800 m² or larger with a high intrinsic risk level.
- d) C type configuration: with areas of 2000 m² or larger and a medium intrinsic risk level, or areas of 1000 m² or larger with a high intrinsic risk level.

When a sector involves both manufacturing and permanent storage activities, the installation of these systems will be necessary when the following equation is satisfied:

$$\frac{A_m}{A_{mm}} + \frac{A_s}{A_{ms}} \geq 1$$

In which:

A_m : Manufacturing área

A_{mm} : Area where installation is mandatory for manufacturing

A_s : Storage area

A_{ms} : Area where installation is mandatory for storage

1.2.1.5.6.1. Fixed water spray fire suppression systems

Fixed water spray fire suppression systems will be installed in cases where the structure needs to be cooled to ensure its stability due to the configuration, contents, process, and location of the hazard, and to prevent the effects of radiant heat emitted by nearby hazards. These systems will also be installed in sectors and fire areas where their implementation is required according to current regulations governing fire protection in specific industrial sectors or activities.

1.2.1.5.6.2. Fixed physical foam fire suppression systems

Foam systems shall be installed in sectors and fire areas where their installation is mandatory as per the prevailing regulations governing fire protection in industrial, sector-specific, or specific activities. Moreover, their installation is warranted in cases where within a fire sector, zones involve the handling of flammable liquids that could potentially propagate to other sectors in the event of a fire.

1.2.1.5.6.3. Fixed powder fire suppression systems

Powder extinguishing systems shall be implemented in fire sectors where their installation is mandatory as per the prevailing regulations governing fire protection in industrial, sector-specific, or specific activities.

1.2.1.5.6.4. Fixed gas extinguishing agent fire suppression systems

Gas extinguishing systems shall be installed in the fire sectors of industrial establishments, where enclosed spaces house electronic equipment, data centers, control or measurement centers, and similar facilities, and protection with water-based systems could potentially damage such equipment. Additionally, they shall be installed in fire sectors where their installation is mandated by the prevailing regulations governing fire protection in industrial, sector-specific, or specific activities.

However, the installation and use of these systems will only be permissible when the safety and evacuation of individuals are guaranteed. Otherwise, an alternative type of fixed extinguishing system should be considered for installation.

1.2.1.5.7. Smoke and heat control systems

In this regulation, we find of special interest the aspects related to Ventilation and smoke and combustion gas exhaust in industrial buildings in section 7 of Annex II. According to the characteristics that determine the movement of smoke, based on the typology of the building, the removal of generated heat, along with smoke and combustion gases, from the fire sectors of industrial establishments, must be carried out accordingly.

Regarding industrial buildings intended for storage activities, those considered to have medium intrinsic risk and a built area ≥ 1000 m², or high intrinsic risk and a built area ≥ 800 m², will have smoke evacuation systems.

For those with a smaller surface area, the following regulations will apply:

1. Ventilation will be natural unless the sector's location prevents it; in such cases, forced ventilation may be used.
2. Openings will be evenly distributed in the upper part of the sector, either on high areas of the façade or the roof.
3. Openings must be operable manually or automatically.
4. Additionally, openings for air intake must be provided in the lower part of the sector, in the same surface area proportion as required for smoke exhaust openings, and openings of sector access doors may be considered.

Fire sectors with storage activities located on underground floors must have an aerodynamic surface area of 0.5 m²/100 m² of the building, and 0.5 m²/150 m² when located above ground.

1.2.1.5.8. Emergency lighting

An important aspect within the RSCIEI pertains to the provision of emergency lighting for evacuation routes in fire sectors. The installation of such lighting is mandated under various circumstances:

- a) Fire sectors located below ground level are required to have emergency lighting.
- b) On any above-ground floor, emergency lighting is obligatory when the occupancy level (P) is equal to or exceeds 10 individuals, and the sectors are classified as medium or high intrinsic risk.
- c) Regardless of the floor or risk category, emergency lighting is obligatory when the occupancy level (P) reaches 25 individuals or more.

1.2.1.5.9. Signaling of protective means

Manual fire protection devices (such as extinguishers, alarm buttons, fire hose reel systems, and hydrants) must be clearly marked for easy identification. This signage should adhere to the requirements outlined in Section 2a of Annex I of the RIPCI.

Ventilation and smoke and combustion gas exhaust in industrial buildings

In this regulation, we find of special interest the aspects related to ventilation and smoke and combustion gas exhaust in industrial buildings in section 7 of Annex II. According to the characteristics that determine the movement of smoke, based on the typology of the building, the removal of generated heat, along with smoke and combustion gases, from the fire sectors of industrial establishments, must be carried out accordingly.

Regarding industrial buildings intended for storage activities, those considered to have medium intrinsic risk and a built area ≥ 1000 m², or high intrinsic risk and a built area ≥ 800 m², will have smoke evacuation systems.

For those with a smaller surface area, the following regulations will apply:

1. Ventilation will be natural unless the sector's location prevents it; in such cases, forced ventilation may be used.
2. Openings will be evenly distributed in the upper part of the sector, either on high areas of the façade or the roof.
3. Openings must be operable manually or automatically.

4. Additionally, openings for air intake must be provided in the lower part of the sector, in the same surface area proportion as required for smoke exhaust openings, and openings of sector access doors may be considered.

Fire sectors with storage activities located on underground floors must have an aerodynamic surface area of 0.5 m²/100 m² of the building, and 0.5 m²/150 m² when located above ground.

1.2.2. NFPA 1 (NFPA, 2021)

The National Fire Protection Association (NFPA) is a global self-funded nonprofit organization which plays a fundamental role in defining standards and guidelines that for safety in fire and emergency situations internationally and specially in the United States. This leading organization has established a comprehensive set of codes and regulations, among which, and the focus of this section, is the NFPA 1, Fire Code.

The NFPA 1 provides a comprehensive perspective on fire prevention, human safety, and property protection based on the expertise of industry experts and professionals in the field. Its guidelines have been widely adopted in various sectors and environments, ensuring high and consistent standards for fire protection in buildings and structures. It provides detailed guidelines for the implementation of fire protection systems, sprinkler systems, ventilation systems, and other aspects related to safety in the industry.

1.2.2.1. *General Safety Requirements*

1.2.2.1.1. *Fundamental Requirements*

This section of the regulation outlines fundamental requirements for the construction, arrangement, equipment, maintenance, and operation of buildings and structures, aiming to ensure an appropriate level of safety in fire, explosion, and hazardous conditions. It focuses on safeguarding human life, property, and public well-being from both actual and potential hazards.

Key points include the need to use materials with a fire reaction class of A1 in elements such as frames, panels, and metal floors, and the significance of repairing structurally damaged elements to maintain structural integrity.

Additionally, it establishes the responsibility of the owner, operator, or occupant to comply with the code, notify occupancy changes, and provide compliance evidence. In the case of fire prevention inspections in existing buildings, a minimum schedule is specified, and the obligation to maintain records of maintenance and testing of fire protection systems and other equipment is underscored.

1.2.2.1.2. Building Evacuation

Individuals must leave a building promptly when notified or directed by the AHJ due to emergencies like fires. The section also covers situations where overcrowded premises must be evacuated as directed by the AHJ. It outlines the importance of complying with evacuation procedures during fire alarms, fire drills, system testing, or maintenance, and highlights that non-fire incidents also require adherence to emergency action plans triggered by mass or emergency notifications. This section underscores the critical role of timely and orderly evacuation in ensuring safety during various emergency scenarios.

1.2.2.1.3. Fire Drills

Section 10.5 of the regulation addresses emergency egress and relocation drills. These drills must be conducted in accordance with the provisions of the Code or NFPA 101, in cooperation with local authorities. The frequency of drills should be sufficient to familiarize occupants with procedures and establish them as routine. During drills, emphasis should be on orderly evacuation rather than speed.

Drills should occur at expected and unexpected times under varying conditions to simulate unusual situations that can arise in actual emergencies. During drills, participants should relocate to a predetermined area and remain there until a recall or dismissal signal is given. Furthermore, maintaining a written record of each drill is required, completed by the responsible person and stored in an approved manner.

1.2.2.1.4. Reporting of Fires and Other Emergencies

Upon discovering any unwanted fire, regardless of its size, the person must immediately inform the fire department. Facilities with established on-premises firefighting organizations and approved procedures coordinated with the AH do not need to notify the fire department.

Furthermore, the owner, manager, occupant, or anyone in control of the building or premises must promptly notify the fire department upon discovering an unwanted fire or evidence of a previously extinguished one. No person should impose regulations or orders that cause unnecessary delays in reporting a fire.

Deliberate or malicious false fire alarms are prohibited, where the person knows that no actual fire exists. Unauthorized discharge of hazardous materials notification should follow Chapter 60. Anyone intentionally making false or misleading statements, with the intention to mislead fire department personnel or interfere with their operations, is in violation of this Code.

1.2.2.1.5. Tampering with Fire Safety Equipment

Individuals are prohibited from disabling or making inaccessible any portable or fixed fire-extinguishing system, fire-warning system, or device. However, such systems may be temporarily made inoperative or inaccessible during emergencies, maintenance, drills, testing, alterations, or renovations.

It is forbidden to render a fire protection system or device inoperative during an emergency unless directed by the incident commander. Unauthorized removal, unlocking, destruction, or tampering with locked gates, doors, barricades, chains, enclosures, signs, tags, or seals required by the AHJ according to this Code is also prohibited, except by a person authorized by the AHJ.

1.2.2.1.6. Emergency Action Plans

These plans are required for various occupancies, such as high-rise buildings, healthcare facilities, assembly spaces, and more, as specified by the AHI or Chapter 60.

The plan requirements include procedures for reporting emergencies, occupant and staff responses, evacuation and relocation procedures tailored to the building's occupancy, appropriate use of elevators, fire drill design and conduct, details about building fire protection systems, and any additional items mandated by the AHJ.

Emergency action plans must be submitted to the AHI for review when mandated. Additionally, these plans should be regularly reviewed and updated as required by the AHJ to ensure they remain current and effective.

1.2.2.2. *Smoke Partitions*

Smoke partitions are mandated in locations specified throughout the Code to limit smoke transfer. These partitions should extend from the floor to the underside of the floor or roof deck above, even through concealed spaces and interstitial areas. They can also extend to the underside of a monolithic or suspended ceiling system if specific conditions are met, such as having a continuous membrane ceiling, a smoke-tight joint, and not using the space above the ceiling as a plenum.

Doors within smoke partitions need to comply with several provisions, including being self-closing or automatic-closing. Louvers in doors are prohibited. The clearance of doors should follow NFPA 80 standards. Additionally, shutters protecting openings should automatically close upon activation of approved smoke detectors according to NFPA 72.

For air-transfer openings within smoke partitions, specific requirements are outlined. Approved smoke dampers tested to UL 555S standards should limit smoke transfer. The dampers' leakage and elevated temperature ratings are also specified as at least Class II and 250°F (140°C) respectively.

1.2.2.3. *Smoke Barriers*

Smoke barriers are necessary to subdivide building areas to contain and control the spread of smoke.

Continuity is crucial for smoke barriers. They must extend either from an exterior wall to another exterior wall, between floors, or from one smoke barrier to another, or through a combination of these configurations. Additionally, smoke barriers are expected to be continuous through concealed spaces like those found above ceilings and within interstitial areas. In cases where an occupied space lies beneath an interstitial space, the smoke barrier may not need to extend through it, provided the construction assembly forming the bottom of the interstitial space effectively resists smoke passage.

A noteworthy provision allows a fire barrier to serve as a smoke barrier if it meets the criteria outlined in Section 12.9. This provision enhances flexibility and efficiency in fire safety measures by allowing dual functionality for certain barriers.

1.2.2.4. *Automatic Sprinklers*

This section delves into the installation, maintenance, and requirements for automatic sprinkler systems, a crucial aspect of fire protection measures.

General prescriptions:

- Automatic sprinklers must be installed and maintained in full operational condition as stipulated by this Code or referenced codes and standards.
- Installations should adhere to NFPA 13, NFPA 13R, or NFPA 13D, as appropriate for the context.
- Existing systems must comply with the relevant sections outlined.
- Sprinkler piping for hazardous areas can be directly connected to a domestic water supply system if it can deliver 0.15 gpm/ft² (6.1 mm/min) throughout the entire enclosed area.
- Indicating shutoff valves, supervised as per 13.3.1.8 or NFPA 13, should be installed for sprinkler piping serving hazardous areas.

This section also highlights that, in areas protected by automatic sprinklers, other sections mandating automatic heat-detection devices are not required. Also, clarifies that alternative permitted systems still need to meet the applicable provisions of the Code that pertain to required systems.

It provides some supervision guidance:

- Signals must be supervised in accordance with NFPA 72, indicating conditions that could hinder sprinkler system operation.
- Supervisory signals should sound and be displayed either within the building or at an approved remote location.
- Alarm signals should be transmitted to approved alarm receiving facilities, remote or central stations, or the fire department.
- Automatic sprinkler systems should be installed as required by this Code or referenced codes and standards in the following scenarios:
 - Basements exceeding 2500 ft² (232 m²) in new buildings.
 - New buildings housing emergency services.
 - New buildings three or more stories in height above grade.

Temperature ratings and color coding:

Maximum Ceiling Temperature		Temperature Range		Glass Bulb Color
°F	°C	°F	°C	
100	38	135-170	57-77	Orange or red
150	66	175-225	79-107	Yellow or green
225	107	250-300	121-149	Blue
300	149	325-375	163-191	Purple
375	191	400-475	204-246	Black
475	246	500-575	260-302	Black
625	329	650	343	Black

Table 5. Sprinklers temperature ratings and color coding from NFPA 1

1.2.2.5. *General Fire Protection*

Sprinkler Systems: Sprinkler systems in storage buildings must adhere to the specifications in Section 13.3, emphasizing the importance of automatic fire suppression systems.

High-Expansion Foam: Additional high-expansion foam systems, when used alongside automatic sprinklers, should follow NFPA 11 guidelines, with specific requirements. High-expansion foam systems must activate automatically and have provisions for detection, pumps, and other components to operate on standby power.

Manual Protection: This section highlights the role of manual fire protection measures.

- **Portable Fire Extinguishers:** The provision of portable fire extinguishers is based on Section 13.6, with considerations for using hose lines instead of extinguishers in certain situations.

- **Hydrants:** Private hydrants, according to Section 13.5, must be installed if public hydrants are absent or beyond a certain distance.

Fire Organization: Rapid entry provisions for emergency responders are outlined, allowing quick access to the premises during fire or emergencies.

Training: Facility emergency personnel need specialized training due to the unique hazards associated with storage fires. The training covers pile and building collapse potential, sprinkler system operation, controlling valves, emergency systems operation, material handling during firefighting, evacuation procedures, and more.

Fire Watch: A fire watch must be maintained when the sprinkler system is out of service to ensure ongoing fire safety.

Alarm and Security Services: Automatic sprinkler and foam systems must have approved alarm service, which can be central, auxiliary, remote, or proprietary, with certain exceptions based on occupancy and guard service. The alarm service should conform to NFPA 72. Additionally, security services must comply with NFPA 601 if provided.

1.2.2.6. *Components of egress means*

This section deals with the various components of means of egress in a building. Here are the main points:

Permitted Components:

Doors:

- Doors must comply with applicable regulations and be operable from the egress side without the need for keys, special devices, or prior knowledge.
- Locks on doors must allow easy and swift opening from the egress side, without requiring keys, tools, or complex operations.
- Doors must not require more than one turn or movement to open from the egress side, ensuring efficient exit.
- Doors must be clearly identifiable as exits, either through their design, specific signage, pictograms, or other visual methods.
- Doors must not be obstructed or blocked when occupants are in the building, ensuring clear access to exits.
- Doors must be single-swinging and not subject to special conditions, such as unlocking devices or complex electronic requirements.
- Opening and closing devices on doors must be easy to operate, and the force required to open the door must not be excessive.
- If doors have glass, it must comply with fire resistance and safety standards specified by the code.

Staircases: Stairs are crucial pathways for vertical movement within a building during evacuations. The requirements aim to ensure that stairs are safe, accessible, and effective in facilitating the evacuation process. Modifications, like grated treads and landings, are allowed. Stairs with non-combustible grated steps and landings are permitted. Grated steps are designed to prevent the accumulation of debris and promote visibility, minimizing slip hazards. Stairs providing access to industrial equipment in accordance with Section 40.2.5.3 are also allowed. This recognizes that in some cases, specific industries may require unique stair designs to access equipment while ensuring safety.

Horizontal Exits: In specific cases, one horizontal exit door should be swinging while the other can be an automatic sliding fire door, remaining open when the building is occupied.

Existing and approved horizontal sliding fire doors must meet all of the following conditions:

- Held open by fusible links.
- Fusible links rated not less than 165°F (74°C).
- Fusible links located no more than 10 feet (3050 mm) above the floor.
- Fusible links in immediate proximity to the door opening.
- Fusible links not located above a ceiling.

Smoke Barriers:

- **Purpose and Function:** Smoke barriers are intended to create barriers that impede the flow of smoke from one area to another, thus facilitating safer evacuation and

- reducing the potential for smoke inhalation. These barriers enhance overall life safety during fire emergencies.
- **Continuous and Secure:** Smoke barriers must be continuous and securely constructed to form an effective barrier against smoke migration. Gaps, holes, or other openings that could compromise their effectiveness should be minimized or eliminated.
 - **Construction Materials:** The materials used for smoke barriers must have appropriate fire-resistance and smoke-resistant properties to withstand the conditions of a fire and prevent smoke penetration. The code may specify the required fire-resistance ratings for these materials.
 - **Integrity and Maintenance:** Smoke barriers must be maintained in good condition and should not be impaired or compromised by modifications, repairs, or other actions that could undermine their effectiveness. Regular inspections and maintenance are crucial to ensure their integrity.
 - **Doors and Openings:** Smoke barrier doors and openings must be equipped with components that ensure their effectiveness. This may include self-closing mechanisms, latching devices, and smoke seals to prevent smoke passage.
 - **Activation and Closure:** Smoke barriers should activate automatically in response to fire alarms or other triggering events. This ensures that the barrier is deployed when needed to contain smoke and protect occupants.
 - **Integration with Fire Protection Systems:** Smoke barriers may be part of a larger fire protection system, including smoke detection and alarm systems. Their integration with other fire safety measures ensures a comprehensive approach to smoke control and evacuation.

Ramps:

- **Purpose:** Ramps offer accessible routes, especially for those who can't use stairs.
- **Slope:** Ramps have specific slope requirements for safe and comfortable use.
- **Traction:** Surfaces must prevent slipping, even when wet.
- **Width:** Ramps should be wide enough for safe movement.
- **Handrails:** Handrails prevent falls and provide stability.
- **Industrial Access:** Ramps for equipment are allowed.
- **Integration:** Ramps are integrated with evacuation plans.

Exit Passageways:

- **Purpose:** Exit passageways provide protected paths for occupants to reach safety.
- **Enclosed Design:** Passageways are enclosed to shield occupants from smoke, fire, and heat.
- **Width and Accessibility:** Passageways have specific width requirements to ensure easy and swift evacuation.
- **Continuity:** Exit passageways provide uninterrupted routes between exits, facilitating safe movement.
- **Fire Resistance:** Materials used in construction meet fire resistance standards.
- **Integration:** Exit passageways are a crucial part of the overall means of egress plan in the building.

Fire Escapes:

- **Purpose:** Fire escapes serve as alternative evacuation routes, especially in multi-story buildings where other means of egress might be compromised.
- **Standards for Existing Escapes:** Fire escapes should adhere to specific design, construction, and safety standards outlined in the section.
- **Maintenance:** Regular maintenance and inspections are necessary to ensure the fire escapes' continued usability and safety.
- **Integration:** Fire escapes are integrated into the overall means of egress plan for the building.

This section also discusses capacity, quantity, arrangement, travel distance, discharge from exits, lighting, emergency lighting, exit signage, initiation of fire alarm systems, and corridors. It emphasizes the regulations for storage facilities, specifying permitted components, modifications, and standards to ensure safe egress in case of emergencies.

Some of the most remarkable aspects are the following:

The quantity of egress means must comply with either of the following:

- In occupancies with low-hazard storage, a single egress means is allowed from any floor or area.
- In occupancies with ordinary-hazard storage, a single egress means is allowed from any floor or area, provided that the exit can be reached within the allowable common path distance. All buildings or structures that do not meet the criteria and are used for storage, as well as all sectors within them considered separately, must have a minimum of two separate egress means, spaced apart as much as practicable. **New Buildings:** Floors or parts thereof with an occupant load exceeding 500 people in new buildings must have the minimum quantity of separated and spaced egress means specified. **Elevated Risk Areas:** Areas with high-risk contents must comply with the requirements outlined.

For structures exclusively occupied during daylight hours, egress routes may be illuminated by windows arranged to provide the required lighting level in all parts of the egress routes during those hours, when approved by the competent authority.

Emergency lighting must be provided in occupancies for storage that are normally occupied. However, this requirement does not apply to spaces occupied solely during daylight hours and benefiting from natural lighting.

Section 11.8 addresses the specific requirements for high-rise buildings in terms of fire protection and life safety measures. It covers various aspects, including but not limited to:

- **Height Considerations:** The section defines what constitutes a high-rise building in terms of height criteria.

- **Structural Fire Protection:** High-rise buildings may require enhanced structural fire protection measures, such as fire-resistant materials and fireproofing for supporting elements.
- **Fire Alarm Systems:** High-rise buildings often have more complex fire alarm systems that may include features like voice evacuation systems, floor plan annunciators, and firefighter communication systems.
- **Elevator Operation:** Specific provisions might apply to elevator operation and their use during fire events, including firefighter service, recall procedures, and emergency power requirements.
- **Stairwell Pressurization:** This section might require stairwell pressurization systems to prevent smoke infiltration during evacuations.
- **Fire Department Access:** High-rise buildings must have designated areas for fire department operations, such as staging areas, access points, and standpipe connections.
- **Emergency Lighting and Communication:** High-rises might need enhanced emergency lighting systems and communication devices to facilitate safe evacuation and coordination during emergencies.
- **Fire Protection Systems:** The section may outline requirements for automatic sprinkler systems, fire pumps, and fire department connections specific to high-rise buildings.
 1. **Automatic Sprinkler Systems:** High-rise buildings often require automatic sprinkler systems that cover all areas, including common spaces, tenant spaces, and other designated areas. The installation and maintenance of these systems must adhere to stringent standards to ensure their effectiveness.
 2. **Fire Pumps:** Fire pumps might be mandated to provide adequate water pressure and flow for the sprinkler system to effectively suppress fires at various heights within the building.
 3. **Fire Department Connections:** High-rise buildings are likely to have fire department connections that provide a direct supply of water to the fire protection systems. These connections enable firefighters to supplement water supply if needed.
 4. **Standpipe Systems:** Standpipe systems, which consist of pipes and outlets for firefighting hoses, are crucial for delivering water to upper floors. High-rise buildings may require standpipe systems to be installed in stairwells or other accessible locations.
 5. **Fire Control Room:** Some high-rise buildings might require a dedicated fire control room where fire alarm and fire protection systems are monitored and controlled. This central control room aids in managing fire safety systems efficiently during emergencies.
 6. **Fire Command Center:** In line with NFPA 1's requirements, a fire command center might be established in high-rise buildings to facilitate communication and coordination among emergency responders, building management, and occupants during fire incidents.
- **Means of Egress:** High-rise buildings may have unique egress requirements, including wider exits, additional stairways, and fire-rated corridors.

1.3. Types of fires in warehouses

As seen, the presence of various types of combustible materials in spaces designated for storage carries an inherent risk: the possibility of fires. The consequences of fires in industrial warehouses can be devastating, ranging from material losses and disruptions in the supply chain to risks to the safety of workers and nearby individuals.

In order to effectively combat this risk, it is crucial to understand the different types of fires that can arise in these environments. The fire classification according to NFPA 10 (National Fire Protection Association) provides us with an essential guide to comprehend and address these situations appropriately.

In this section, therefore, the main types of fires that can occur are developed, along with the particular challenges posed by each, as well as the preventive measures and most suitable extinguishing strategies.

1.3.1 Type of combustible

A primary classification of significance that we can make is the one presented by (NFPA, 2022) NFPA 10 Standard. The classification is based on the burning fuel. (TARGET FIRE PROTECTION)

Class A Fires: Fires of ordinary solid combustibles.

Class A fires are among the most prevalent and can involve materials like wood, plastic, paper, and fabrics. These fires can rapidly propagate if there's an adequate supply of combustibles, oxygen, and heat. Especially in commercial and industrial spaces strict maintenance is key to mitigate fire risks.

Class B Fires: Fires of flammable or combustible liquids.

Class B fires involve flammable liquids like paint, gasoline, oils, solvents, and alcohol and are some of the most dangerous fires possible. These fires can arise in locations storing or utilizing such liquids, such as garages, warehouses, hospitals and laboratories. Flammable liquids have low flash points, making them susceptible to ignition from even a small spark or open flame. Preventing Class B fires necessitates proper storage to minimize risks, limiting the quantity of flammable liquids present, maintaining distance from ignition sources, and strictly avoiding open flames in areas where such liquids are stored.

Class C Fires: Fires involving energized electrical equipment.

Class C fires in the United States are categorized as fires that involve energized electrical equipment. These are normally situations created by electrical appliances, machinery, or devices that are more often commonly present. These types of fires create unique risks

due to the presence of electrical energy, which can potentially lead to electric shock or additional hazards for responders.

Class D Fires: Fires involving combustible metals.

Class D fires involve fires with combustible metals. These fires are relatively uncommon due to not all metals being flammable. The primary concern for Class D fires revolves around smaller metal deposits, like shavings or powders. Thick sheet metals and solid metals pose lower fire risks. Industries engaging in metalwork, especially cutting, face a higher risk of Class D fires.

Certain metals like potassium, titanium, and magnesium can be combustible. Workspaces with common metal shavings or fine deposits should be regularly cleaned to control metal concentrations. Sparks and open flames must be kept well away from these areas.

Class K/F Fires: Fires involving fats, oils, and cooking oils.

These fires involve fats, oils, and cooking oils and are commonly found in restaurants and commercial kitchens. They typically occur when fats and oils are heated to high temperatures for cooking. Neglecting pans containing oils or grease can lead to these fires. Class K/F fires have a high flash point, which differentiates them from other types of fires like Class B fires. Prevention is crucial, especially in busy commercial kitchens where strict fire safety measures should be implemented. If signs of a potential Class K/F fire are observed, such as smoke or smell, immediate action should be taken to turn off the heat source before the oil ignites.

This classification helps to choose the extinguishing agent for each type of fire and to tackle it in the most effective way possible. In a warehouse, there is often a combination of several of these types, although at times there may be a higher proportion of one type or another.

1.3.2 According to the origin or cause

Another classification can refer to the origin that has led to the fire. In this case, the origin can vary significantly, and some of the most common ones are listed. To determine the risk, probability, and severity associated with each type, this project relies on a study carried out by the NFPA over a five-year period (Alternatives in Engineering, Inc., 2020). During this time, U.S. fire departments intervened in an average of 1,210 warehouse fires per year, resulting in 19 civilian injuries, three deaths, and a cost of \$155 million in direct property damage each year.

Intentionally set fires accounted for the primary cause of fires and the most significant destruction, causing 32% of overall property damage. Subsequently, the following warehouse fire hazards were identified:

- Electrical and lighting

- Trash and rubbish fires
- Heating equipment
- Exposure fires
- Combustible liquids/highly flammable materials
- Cigarette-related fires
- Automatic Storage Retrieval Systems

Warehouse Electrical Distribution & Lighting Equipment Fires

Electrical distribution and lighting equipment issues accounted for 18% of warehouse fires, leading to 38% of civilian injuries according to this study. Wiring, cables, and related equipment were common causes, along with lamps and bulbs. To prevent such fires, avoid leaving unnecessary items plugged in, keep flammable materials away from outlets, and never use extension cords as permanent solutions.

Trash & Rubbish Fires in Distribution Centers

In distribution centers, about 170 trash and rubbish fires occur annually, often due to excessive waste from packaging. Proper employee training is crucial to prevent these fires, as neglecting to dispose of trash promptly can lead to serious injuries and business disruptions. Accumulated trash can also obstruct exit pathways, emphasizing the need to keep exits clear and unblocked at all times.

Distribution Warehouse Heating Equipment Fires

Heating equipment fires in distribution warehouses, which include fixed or portable space heaters, boilers, and chimneys, result in approximately 90 fires annually. To prevent these fires, avoid using portable space heaters and consider upgrading your heating system. Regular inspections and maintenance for your heating equipment and designated safe areas for portable heating equipment are important measures to mitigate the risk of fires.

Warehouse Exposure Fires

Warehouse exposure fires, originating from fires outside the building, constitute 7% of all warehouse fires and 7% of the total direct property damage. These external fires can involve nearby buildings, vehicles, and outdoor objects like trash, dumpsters, and trees. The danger lies in their potential to go unnoticed, making proper detection crucial. Preventive measures include properly disposing of cigarette butts in sealed receptacles, avoiding placing flammable items near exterior outlets, cords, and lighting, and maintaining fire-safe surroundings.

Flammable & Combustible Liquid Fires in Warehouses

Flammable and combustible liquid fires pose significant hazards in warehouses, especially when gas lines, propane, and other flammable liquids are used in heating, cooling, equipment, and appliances. These fires can be explosive and quickly ignite upon contact with sparks or open flames. Warehouses also store large quantities of flammable inventory and hazardous materials. To prevent such fires, thorough employee training on

proper storage, handling, and use of these substances is essential. Strict adherence to protocols and safety measures is crucial to mitigate the risks associated with these highly dangerous fires.

Smoking Materials & Cigarette Fires in Warehouses

Smoking materials and cigarette fires are a notable risk in warehouses, causing around 60 fires annually and \$17 million in direct property damage according to the NFPA study. Although smoking is less common in workplaces, it remains a concern in designated outdoor areas. Mitigation involves locating smoking zones away from structures and flammable items, ensuring proper cigarette disposal, and using signage to remind smokers of safety protocols. Proper management of these areas can effectively reduce the risk of warehouse fires.

Fire Risks of Automatic Storage Retrieval Systems (ASRS)

The implementation of Automatic Storage Retrieval Systems (ASRS) in warehouses enhances efficiency but introduces new fire risks. In these automated setups, goods are stored in open plastic bins that burn more intensely than traditional materials. The robotic arms' cables can fray and create sparks when entangled with equipment, while the heightened stacking of racks hampers fire sprinkler effectiveness. These factors necessitate careful consideration and fire prevention measures when integrating ASRS into warehouse operations.

1.3.3 According to the growing rate

Another way to classify fires is based on the speed of fire growth, which depends on the characteristics of the combustible materials and how they are arranged or stored.

It is worth mentioning the different stages of a fire (Figure 9) to get a better understanding of how they evolve.

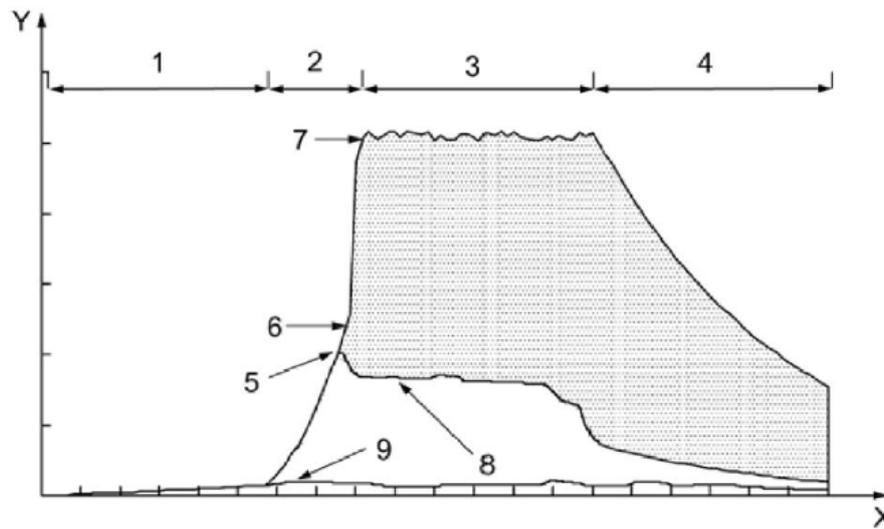


Figure 9. Fire stages and growing rates (Normalización Española, 2017)

Legend:

- 1- Incipient
- 2- Growth
- 3- Fully developed
- 4- Decay
- 5- Sprinkler activation
- 6- Rapid widespread combustión
- 7- Controlled by ventilation
- 8- Controlled by sprinklers
- 9- Flameless combustion
- X- Time
- Y- Heat generation

In the majority of instances, the pace at which fires typically unfold within buildings is delineated through exponential curves, referred to as t-squared curves, which can be of slow, moderate, fast, or ultra-fast growth.

Growth	Typical Real Fires
Slow	Highly packed wooden products
Moderate	Solid wood products Wood elements with small amounts of plastics
Fast	Wood pallets stored in height Products stored in cardboard boxes on pallets
Ultra-fast	Plastic materials stored in height

Table 6. Growing rates fire classification

The most significant growth rates in fires within logistics warehouses vary primarily between moderate growth, which could occur in ground-level storage areas next to loading docks, and ultra-fast growth that could be reached in high-storage areas of plastic products. Fires with moderate growth also help to characterize situations in which shelves are not fully occupied by combustible products.

ESFR sprinklers are designed with the objective of early fire suppression. However, in accordance with Chapter C.2.8 of UNE-EN ISO 16733-1 (Normalización Española, 2017), it is proposed to consider that the fire grows exponentially until the activation of the sprinklers, maintaining the maximum power reached from that moment onward.

2 Smoke control systems in warehouses

2.1 General description

(COLT, 2004) When a fire occurs, the consequences, as seen so far, can be highly dangerous, both in terms of economic impact, environmental effects, and the safety and health of the individuals involved, as well as the firefighters and professionals. A Smoke Control System can be crucial in mitigating this risk and the potential impact of the fire and the inherent smoke-related issues.

2.1.1 Purposes of smoke control systems

Some of the most evident advantages offered by these systems can include:

Safety: It is one of the primary objectives, allowing for the reduction of toxic smoke caused by fire and enabling safer and faster evacuation.

Visibility: Improved visibility enables quicker and more effective action to follow evacuation and safety protocols in such scenarios.

Property Protection: Smoke, aside from visibility and toxicity issues, exponentially increases the spread of fire by transmitting heat and being corrosive. Therefore, controlling smoke with these systems as soon as possible is vital to reducing damages.

Firefighter Accessibility: By maintaining controlled smoke conditions, firefighters can enter the facility more effectively, locate, and extinguish the fire more rapidly.

Business Continuity: By reducing damage and downtime caused by fire, smoke control systems can help maintain operability and business continuity. Occupants are provided with a clear escape path, permitting them to exit the building far more quickly and safely, potentially allowing greater travel distances to be accepted.

2.1.2 Components

Some of the most common elements that constitute a smoke control and evacuation system include:

1. Smoke vents or fans for smoke exhaust installed on roofs or facades.
2. Fans, grilles, or air inlets for supplying clean and fresh air to the affected area.
3. Smoke barriers or containment barriers.
4. Control system: pneumatic or electric.

2.1.3 Working steps

2.1.3.1 *Early stages of a fire*

In a large industrial building, conventional methods of containing a fire, like closing doors and windows, are not as effective due to the abundant oxygen supply and natural ventilation. Unlike a home fire where sealing off a room can limit its spread, industrial fires can't be easily contained. Instead, the smoke from the fire tends to rise into the roof space during the initial stages.

2.1.3.2 *Smoke characteristics*

Smoke in a large building can spread horizontally at a speed of up to 5m/s, much faster than an average person's walking pace of 1-2m/s or running speed of 7.5m/s. As the roof space of the building becomes filled with smoke, it will eventually start descending. The rate of this descent depends on factors like the type of materials burning and the layout of the building.

2.1.3.3 *Smoke logged*

In a closed environment, such as an unventilated building with a volume of 10,000m³, smoke can quickly fill the space in a matter of minutes. While the smoke primarily consists of air drawn into the fire, it can carry enough toxic elements and suffocating agents to cause disorientation and incapacitation within seconds, potentially leading to fatalities within minutes.

2.1.4 Basic design principle

The basic principle of this fire safety system consists of limiting the spread of smoke, extracting heat and smoke, and replenishing with clean air.

In order to achieve this, the basic design requires these elements:

1. **Smoke exhaust vents or fans:** Installed on roofs or walls to expel smoke from the building.
2. **Clean air supply:** Deliver fresh air to the affected area to improve visibility and assist in smoke control.
3. **Smoke containment barriers:** Direct smoke towards exhaust vents and prevent it from spreading to other areas.

4. **Control system:** Can be pneumatic or electric and acts to open and close exhaust vents and fans based on smoke conditions.

2.1.5 Components

2.1.5.1 *Natural smoke vents*

Natural smoke vents can be use not only during a fire event by limiting the spread of smoke and heat but also providing day-to-day ventilation benefits.

These vents are strategically positioned on rooftops for efficient smoke and heat extraction, and at lower levels for introducing fresh air.

They are designed to operate in a fail-safe manner, ensuring that they automatically open when control or power sources are removed.

In the presence of a larger fire, the hotter and more buoyant smoke enhances the effectiveness of these vents.

A common problem with this system is the decrease in performance when external wind affects to the difference in pressure that allows the extraction of the contaminated air. In this case mechanical ventilation is an interesting alternative.

2.1.5.1.1 *Types of natural smoke vents (cottes, 2020)*

The selection of the type of smoke exhaust vent can depend on various factors, such as design, additional functions, physical or mechanical properties, or price, among others. Some of the most common types of natural smoke exhaust vents can include the following:

Lamella exhaust vents (Figure 10)

This type of ventilator stands out for its lightweight design and high-quality materials. It offers versatility in terms of defining various possibilities and finishes, resulting in excellent thermal and acoustic insulation, integration with common building elements, and significant natural light and daily natural ventilation capabilities. Lamella vents can be adapted to any type of façade or roof. The main advantages of lamella exhaust vents include their versatility, lightweight construction, and their contribution to the energy efficiency of a building.



Figure 10. Lamella exhaust vent (cottes, 2020)

Compartmental exhaust vents (Figure 11)

This type of ventilator, designed exclusively for roof installation, is notable for its ability to integrate a base or adaptation socket, which enhances both investment and energy performance while optimizing installation costs. In addition to its high capacity for ventilation and smoke extraction, these vents also provide significant natural light to buildings.



Figure 11. Compartmental exhaust vent (cottes, 2020)

Architectural Solution Vents (Figure 12)

These vents are designed to meet the needs of unique and special spaces. They offer high technical performance and can be seamlessly integrated into various architectural projects where design is a priority. They contribute to energy efficiency and create pleasant environments in industrial facilities and distinctive projects. Incorporating these vents not only enhances safety but also demonstrates a commitment to sustainability and significant cost savings, synergizing with other building elements like lighting and cooling systems.



Figure 12. Architectural Solution Vents (cottes, 2020)

2.1.5.2 Mechanical smoke vents

Mechanical ventilation systems for smoke control require consistent power sources and are designed to extract a fixed volume of smoke regardless of fire size.

Structural considerations, such as fan weight, must be addressed, and a dedicated air inlet system is necessary.

Noise can be an issue, especially when integrated with voice alarm systems. Unlike natural smoke vents, these systems have distinct features and challenges.

	Natural smoke ventilation	Mechanical smoke ventilation
Advantages	<ul style="list-style-type: none"> - Fail safe function - Self-regulating - Silent - No time or temperature limits - Lightweight 	<ul style="list-style-type: none"> - Not wind pressure sensitive - Suitable for ducting
Disadvantages	<ul style="list-style-type: none"> - Sensitive to wind effects 	<ul style="list-style-type: none"> - Noise and weight - Maintained electrical supply - Dedicated air inlet supply

Table 7. Natural and mechanical smoke ventilation

2.1.5.3 Inlet

For an effective smoke ventilation system, having an inlet air supply is crucial. This creates a chimney effect that maintains a steady airflow. Extract vents remove air and gases, which are replaced by the inlet vents, often called 'make up air'. This approach is especially suitable for spacious single-story buildings with limited doors and windows.

Natural inlet vents play a vital role in smoke control systems. They provide fresh air by positioning inlets low within the building, typically at least 1.5 meters below the smoke layer's height. If this isn't feasible, smoke curtains can be employed. Inlet air can be sourced from adjacent non-fire zones at roof level or through the automatic opening of vents, windows, and doors. Inlet velocities must stay under 5m/s to ensure effective escape and evacuation.

2.1.6 Special considerations

2.1.6.1 High bay storage areas

It is worth mentioning the special case of high bay warehouses, in which the risk of fire escalation is heightened due to the rapid upward spread of fire along vertical racks.

To ensure an effective fire safety approach, sprinklers must be integrated to manage the fire's growth. A smoke control system complements sprinklers by evacuating smoke, minimizing damage, and aiding firefighting efforts.

It is of special interest in this type of areas to take into account some considerations such as, the nature of the goods stored, the packaging used, the system of storage, the surface area of supporting combustion materials and, as it will be shown later, the type of sprinkler system installed.

2.1.6.2 Interaction of sprinklers & vents

In this section, a preliminary approach to the main issue that this document aims to study will be developed, which is the interaction between sprinklers and smoke ventilation systems.

Firstly, the main issues that can arise are, on one hand, the delay that can be caused in the activation of sprinkler systems due to heat extraction through smoke and heat evacuation systems, and on the other hand, the oxygen supply that this airflow and air renewal can entail, resulting in a fire intensification and thus greater difficulty in extinguishing it.

It is not clear if these effects are entirely accurate, and there are many differing opinions on this matter. While it seems that in regular installations, these effects might not be so apparent, it is worth mentioning that with fire suppression systems like ESFR, there is an

additional issue concerning the impact that these air currents and pressure changes can have on the proper functioning of the systems.

2.2 Spanish perspective

2.2.1 UNE 23585 (Normalización Española, 2017)

This standard serves the purpose of offering building design professionals a suitable analytical and computational approach to ascertain the necessary requirements for Temperature Control and Smoke Evacuation Systems within a specific building and its designated fires. The objective is to effectively manage smoke and combustion gases produced during the most adverse scenarios of anticipated fires, while also regulating their temperature.

Some of the objectives of this standard are:

- Ensure smoke-free access and evacuation pathways by either preventing smoke infiltration or creating a smoke-free layer at a safe height in specific areas of the route.
- Aid firefighting efforts by establishing the mentioned smoke-free layer within the fire area.
- Manage the thermal power of smoke to lower the risk of sudden widespread combustion (flashover) and the overall fire progression.
- Minimize the thermal impact on the building's load-bearing structural elements and other construction components.
- Safeguard equipment, furniture, accessories, and furnishings.
- Mitigate damage caused by hot gases and the thermal breakdown of materials.

This Spanish standard defines a Smoke Control and Temperature Evacuation System (SCTEH) as a setup comprising smoke vents, mechanical extraction equipment (fans), and clean air inlet openings (Figure 13). These components are designed to create a layer free of smoke above the fire floor level during the worst-case fire scenarios. Additionally, they maintain an acceptable average temperature within the smoke layer. This system enhances safety by facilitating the evacuation and rescue of individuals, protecting the building's belongings and structure, and enabling firefighting efforts in the early stages of a fire.

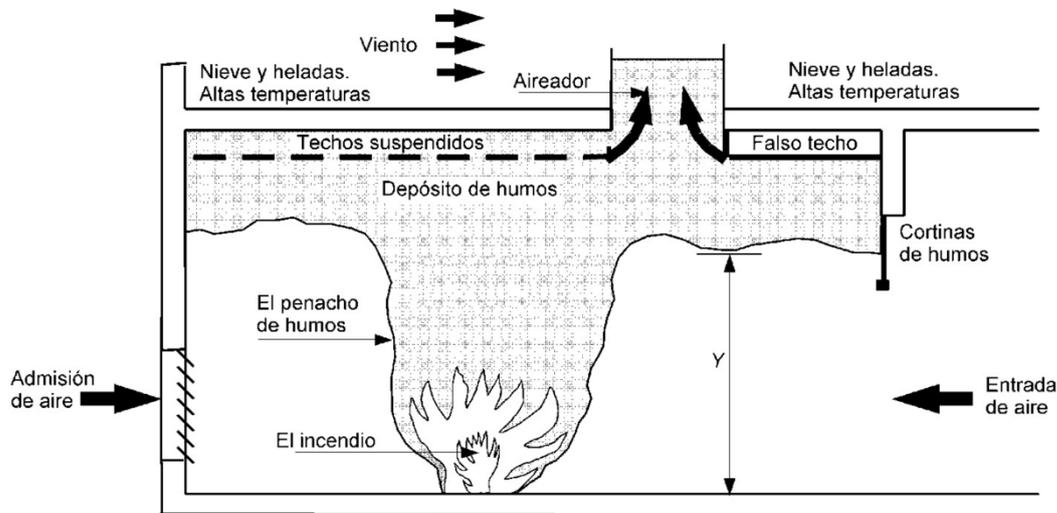


Figure 13. Smoke Control and Temperature Evacuation System

2.2.1.1 Application of the Smoke Control and Fire Safety Management

The SCTEH system is designed to fulfill specific objectives related to evacuation and fire protection. Depending on the objective prevailing the procedure may vary.

- a) For protecting evacuation routes, the SCTEH should be activated by fire detection systems. Activation components must be both automatic and manually controlled, with manual control taking precedence over any other system.
- b) For the protection of properties and/or assets and firefighting operation, if an automatic fire extinguishing system with sprinklers is present, the SCTEH should be activated as detailed in the section “Performance with a sprinkler suppression system”. In the absence of an automatic fire extinguishing system with sprinklers, the provisions in point a) apply.

When manual activation is involved, certain requirements apply. There should be a provision for authorized personnel familiar with the SCTEH (such as security management personnel or firefighting services) to activate or deactivate the system.

Manual controls should ideally be accessible from outside the building or from a protected area outside the fire sector designated for the SCTEH. Adequate signage and information near the manual control should aid firefighting services in locating it. Additionally, basic SCTEH operation information and diagrams of the smoke reservoirs should be provided nearby.

2.2.1.2 Design fire model for high-rise storage building

The table below provides a concise overview of key equations and definitions for determining the fire area surface, perimeter, and released heat flux, taking into account the type of sprinklers commonly used in these buildings, subject to certain limitations.

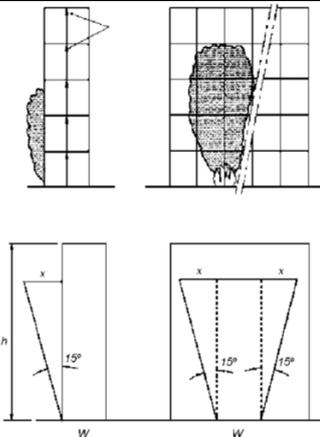
High-rise storage building			
Storage with products on shelves. (w = width of the shelf) (h = height of the shelf) (x = $2/3 \cdot h \cdot \tan 15^\circ = 0,18 \cdot h$) SILOS: (w = width of the shelf, for calculation, maximum 3 m) (Y = smoke free height) (x = $Y \cdot \tan 15^\circ = 0,27 \cdot Y$) Y \geq 2/3h			
	Fire area (Af) m ²	Fire Perimeter (P) m	Released heat flux (qf) kW / m ²
Ceiling sprinklers, regardless of their type	$4/31h (w + x)$	$2 (w + 4x)$	qf (bajo) = 250 qf (alto) = 625
Intermediate sprinklers	$2/3h (w + x)$	$w + 4x$	
Without sprinklers	81	36	qf (bajo) = 250 qf (alto) = 1250

Table 8. High-rise storage building equations and definitions

2.2.1.3 Smoke reservoirs and fire curtains

In situations where a fire is located directly beneath a smoke reservoir, the standard imposes certain limitations on the maximum surface area of the reservoir. This area should not exceed 2,000 m² when employing natural smoke exhaust vents or 2,600 m² when utilizing mechanical smoke exhaust vents. These restrictions are intended to optimize the effectiveness of smoke extraction and management in such specific scenarios.

Regarding smoke curtains and other characteristic elements forming part of the boundaries of a smoke reservoir, the following provisions apply:

- These elements must have a depth that is at least 0.1 m greater than the calculated height of the floating smoke layer base. This consideration accounts for any deflection or displacement of these elements.
- The smoke curtain, when in a deflected position, should not exhibit gaps larger than those on either side when in the non-deflected position.
- For hanging smoke curtains designed to seal openings between a smoke reservoir and adjacent floors (such as open floors connected to an atrium), the curtains must remain in contact with the lower part of the opening, extending from the top to the bottom.

In situations where each smoke reservoir within a building is separated by walls or smoke curtains, the following requirements come into play:

1. In cases of natural smoke extraction, the vents in adjacent zones should open automatically.
2. With mechanical smoke extraction, if each zone is equipped with its own SCTEH system it is crucial that once an SCTEH is operational in one smoke zone, other actions that might influence SCTEH operation are not triggered by the detection systems in adjacent smoke zones due to smoke spread.
3. If mechanical smoke extraction is applied and neighboring smoke zones are connected by ducts to a common extraction fan or a set of fans, smoke control dampers in an adjacent smoke zone may open if triggered by detection systems due to smoke expansion. This is contingent upon ensuring that the extracted volumetric flow remains sufficient for each individual zone and adhering to requirements for maximum air intake velocities. Alternatively, when an SCTEH is operational in a smoke zone, measures must be taken to prevent other actions affecting SCTEH operation from being triggered by detection systems in adjacent smoke zones due to smoke spread.

2.2.1.4 Air inlet

In order to replace the air and smoke expelled to the exterior by the extraction systems, a supply of clean and cool air is necessary. This can be achieved through the following methods:

- a) intake openings constantly open
- b) intake openings with automatic opening
- c) natural smoke and heat exhaust vents in adjacent smoke reservoirs

To consider two reservoirs as adjacent, they need to share both a corner and a side for the purpose of calculating the $A_v C_v / A_i C_i$ ratio.

For the proper functioning of air intake, a series of requirements must be met:

Automatic Closure Mechanism: Openings for air intake must be equipped with mechanisms that automatically open when the smoke and heat extraction system is activated.

Manual Activation: Each automatically opening air intake should also have the capability to be manually activated.

Emergency Power: Automatic air intake systems for life safety purposes must have a fail-safe operation mechanism or a secondary/emergency power supply.

Air Velocity Limit: The air velocity through any door or evacuation route, used for air intake, should not exceed 5 m/s in systems with mechanical or natural smoke extraction, to avoid discomfort or distortion of the smoke layer.

Contamination Prevention: Systems using smoke extractors from adjacent smoke reservoirs for air intake should ensure a minimum separation distance of 5 meters to prevent contamination of incoming air with smoke.

2.2.1.5 Interactions between different zones or smoke compartments

- a) Each smoke zone or compartment is separated from the others and forms a fire compartment.**

In a building when each smoke zone is separated from the others, creating individual fire compartments, mechanical ventilation can be achieved by connecting ducts from one or more smoke zones to extraction fans, serving all connected smoke zones while maintaining fire compartmentalization at all times.

The volumetric flow to be extracted must be calculated for the worst-case scenario of a possible design fire within the relevant connected compartment. Fire location is detected by a detection system, which activates the smoke control dampers located at openings between the smoke zone and the working duct leading to the extraction fan(s). This setup ensures that only the zone where the fire is detected is connected to the extraction duct, while other smoke zones remain isolated from the extraction duct.

- b) Each smoke reservoir is separated from the others by walls and/or smoke curtains.**

When smoke reservoirs are separated by walls or smoke curtains, either a common mechanical SCTEH or individual SCTEHs, whether natural or mechanical, can be

employed. However, due to the shared boundaries, smoke might escape into neighboring zones during a fire. While this shouldn't endanger evacuation or firefighting efforts, it should activate detection systems. This situation could affect SCTEH functionality if neighboring systems are triggered. This applies even if a fire starts under structural features or smoke curtains. For exclusively naturally ventilated SCTEHs, activation can be based on water flow mechanisms complying with standards, except when protecting evacuation routes.

In cases where smoke reservoirs in a building are separated by walls or smoke curtains (Figure 14), specific requirements come into play:

- a) If replacement air supply is distributed within the same fire compartment across multiple smoke zones, air inlets and doors must adhere to the air inlet requirements.
- b) When employing natural smoke extraction, adjacent zone air inlets should automatically open.
- c) For mechanical smoke extraction with individual SCTEHs in each zone, ensure the operation of one SCTEH isn't influenced by detection systems in an adjacent zone.
- d) In scenarios where mechanical smoke extraction connects adjacent smoke zones through ducts to a fan, regulators in an adjacent zone can open upon detection, maintaining adequate airflow. Alternatively, ensure detection systems in adjacent zones don't affect SCTEH operation once it's initiated.



Figure 14. Smoke curtain (cottes, 2020)

2.2.1.6 Performance with a sprinkler suppression system

If a fire suppression system utilizing liquid, gas, or foam agents is present in the fire safety setup, the smoke control system needs to be configured for manual activation after the active protection system has been triggered. Steps should be taken to prevent inadvertent automatic activation. The design should guarantee effective smoke and heat dispersal in the event of suppression system breakdown or malfunction.

When both sprinklers and smoke control systems are in place, the ensuing requirements should be implemented based on the primary design objective under consideration:

• **Protection of evacuation routes and firefighting operations:**

Smoke and heat control systems are often used to protect evacuation routes, regardless of the expected arrival time of firefighting services. SCTEHs are not capable of handling very large fires on their own, but they can delay the spread of smoke and heat, which is beneficial for fire control. Quick-response sprinklers are more effective for safeguarding lives than regular-response sprinklers. The optimal approach to safeguarding occupants and firefighters during a fire is a combined system comprising SCTEHs assisted by sprinklers, controlling the fire to a manageable size for SCTEHs. This reduces threats to firefighters and the likelihood of disorientation in smoke.

In this case SCTEH should automatically activate through fire detection systems, with manual control as well. In case of automatically open, all the functions of the complete SCTEH must be achieved within 60 seconds after the signal.

• **Protection of Property and Assets and Firefighting Operations:**

Under these premises, the SCTEH must have both manual and automatic opening mechanisms. The manual operation is controlled by firefighting services, while the automatic activation responds to a water flow signal equivalent to the lowest sprinkler flow. The delay is set by authorities, typically around 10 minutes for system effectiveness. Additionally, conventional methods like compartmentalization, route limits, and sprinklers protect evacuation routes.

If a CMSA or ESFR sprinkler system is in place, SCTEH should be operated solely manually, according to the respective norms. Manual control by fire services from a secure location outside the fire compartment is still necessary.

Sprinklers are effective in preventing fires from becoming large. They assist firefighting teams by maintaining smaller fires, enabling more efficient and safer firefighting. SCTEH systems create smoke-free areas, aiding firefighting efforts, but they don't control fire growth, only delaying smoke intrusion. Sprinklers often control fires, but firefighters extinguish them, with sprinklers providing support.

SCTEHs are valuable for firefighting support. They enhance active firefighting rather than just property protection. Combining ventilation and sprinklers without firefighting is as effective as using only sprinklers. When fire service response is delayed, it's advisable to restrict ventilation until firefighters manually activate the SCTEH system.

For forced extraction systems, as opposed to natural ones, the aforementioned guidelines should be implemented, treating each smoke intake of the SCTEH as if it were a discharge ventilator. Designers of buildings with both SCTEH and sprinklers need to be cautious and prevent scenarios where smoke descent or localized smoke downwash might obstruct evacuation paths in different parts of the building. In spaces protected by ESFR sprinklers, automatic SCTEH activation that could negatively impact sprinkler operation will always be prohibited.

2.3 US perspective

2.3.1 NFPA 92 (NFPA, 2021)

The NFPA 92 standard applies to design, acceptance testing, installation, operation, and periodic testing of smoke control systems.

The purpose is to establish requirements to achieve various objectives, such as:

- Preventing smoke from entering stairwells, egress paths, elevators, etc.
- Maintaining safe conditions in smoke refuge areas during evacuations.
- Stopping the spread of smoke from a designated area.
- Providing suitable conditions for emergency response personnel.
- Contributing to life protection and property loss reduction.

2.3.1.1 Key Design Aspects and Approaches for Smoke Control

- **Smoke Containment Systems:** The design of smoke control systems aims to contain smoke within a specific zone or prevent it from entering another zone. Factors influencing the design pressure difference include whether the zone is sprinklered, ceiling height, and pressure differentials.
- **Smoke Management Systems:** The design basis for smoke management in large-volume and communicating spaces involves determining parameters such as design fires, space dimensions, occupancies, barriers, egress routes, and areas of refuge.
- **Temperature Ratings:** Equipment used in smoke control systems must have temperature ratings based on operational conditions, considering proximity to fire and effects of smoke dilution.

- **Design Approaches:** For smoke containment systems, various design approaches include stairwell pressurization, zoned smoke control, elevator pressurization, vestibule pressurization, and smoke refuge area pressurization. Smoke management systems for large-volume spaces can utilize methods like natural smoke filling, mechanical smoke exhaust, gravity smoke venting, and opposed airflow.
- **Minimum Design Smoke Layer Depth:** Smoke management systems require a minimum design depth for the smoke layer, either 20% of floor-to-ceiling height or based on engineering analysis.
- **Activation:** Smoke control systems must be activated using approved automatic means.
- **System Startup:** The smoke control system should become fully operational before the space reaches design smoke conditions. Time considerations include fire detection and HVAC system activation.
- **Duration:** Smoke management systems designed for occupant egress before smoke exposure must undergo a timed egress analysis and remain operational for the required duration.

2.3.1.2 Manual and automatic activation

Smoke control systems can be activated automatically through signals from fire detection devices or manually by authorized users. When multiple smoke zones are involved, the system responds based on the first signal received, ensuring efficient operation. For systems using heat-activated detectors, the control strategy can expand to accommodate additional zones, provided it stays within mechanical system design limits.

In large spaces where smoke stratification could occur, detection methods include using upward beams, detecting smoke at different levels, or using horizontal beams. Manual activation through fire alarm pull stations is allowed, but these stations should not be used for systems needing information about the fire's location. For systems like stairwell pressurization, activation via manual pull stations is acceptable.

In terms of control priorities, automatic activation takes precedence over other automatic controls. Equipment used for both smoke control and regular building operations can be overridden for smoke control purposes. However, specific controls such as static pressure high limits and duct smoke detectors are not automatically overridden.

Manual activation and deactivation are given priority over automatic controls. If equipment is automatically activated due to alarms or schedules, manual control can override it. Dedicated manual controls for smoke control must be clearly marked, and controls serving dual purposes should be thoroughly documented.

The Fire Safety Control System (FSCS) has the highest priority control over all smoke control systems and equipment. Response time is critical, and the smoke control mode should initiate within 10 seconds of receiving an activation command. Different smoke containment components have specific time limits for achieving their operational states, ensuring effective smoke management.

2.3.1.3 Equipment

- Smoke Dampers: Smoke dampers must be listed according to specific standards for smoke and fire dampers. (ANSI/UL 555 and ANSI/UL 555S)
- Makeup Air System: Coordination of supply and exhaust fan activation is necessary for systems with makeup air supplied by fans.
- Control Systems: Control systems should be listed as per specific standards, fully coordinate interlocks, prioritize smoke management mode, and provide manual control accessible to the fire department.
- Electrical Services: Electrical installations must comply with the National Electrical Code. (NIPA 70)
- Materials: Ducts conveying smoke and related equipment should adhere to standards, withstand pressures during smoke management, and be suitable for their intended use and temperatures. (NFPA 90A)

2.3.2 NFPA 204 (NFPA, 2021)

This American standard applies to venting systems design for emergency venting of combustion products from fires in buildings. Specific chapters cover different scenarios, including single-story non-sprinklered buildings, computer-based solutions, and sprinklered buildings.

The standard applies to various building types and building spaces with ceiling heights that allow for the development of a fire plume and smoke layer. It's applicable to cases where the hot smoke layer doesn't accelerate the fuel array's burning rate and for fires with specific heat release rates.

2.3.2.1 Fundamentals

The design objectives for a vent system during a fire include determining the minimum smoke layer height and the maximum smoke layer temperature that need to be achieved within a specific time period.

2.3.2.1.1 Design

When designing a vent system for a building and its contents, factors such as fire growth (limited-growth or continuous-growth), layout of curtained areas, depth of draft curtains, type of detectors, detector spacing, time interval for maintaining a clear layer, total vent area, distribution of vents, and air inlet area need to be selected and established.

Vent systems are designed to manage the smoke produced by a fire by exhausting it to the exterior, aiming to slow, stop, or reverse the descent of the smoke layer within the building.

2.3.2.1.2 Basics

Determination of Contents Hazard: The potential danger posed by combustible materials or flammable liquids within the building is considered by analyzing their fuel loading and expected rate of heat release during a fire. The heat release rate of the design fire is quantified as outlined in Chapter 8.

Smoke Production: The equations in the standard are based on the assumption that the base of the fire is at the bottom of the burning zone. Fire size and entrainment rates of potential fire scenarios are considered before determining the conditions of the design fire.

Vent Flows: The flow through vents is calculated based on buoyancy pressure difference, without considering pressure from gas expansion. Wind effects aren't accounted for in vent area calculations. Inlet air openings and their locations are taken into account in predicted vent flows. Inlet air should be introduced below the smoke layer boundary, and wall and ceiling leakage above the smoke layer boundary is excluded from vent flow calculations.

2.3.2.2 Vents design and classification

The mechanism for vent activation should be chosen considering a range of expected environmental conditions. Vents should be designed to open either individually or simultaneously, based on the type of detector activated. If the hazard is localized, vents should open directly above that area. Vents, their supporting structure, and actuation means should be designed for post-installation visual inspection.

2.3.2.2.1 Methods of Operation

Normally closed vents must automatically open during a fire to meet design or performance objectives. Vents should be designed to fail in the open position so that a component failure results in an open vent. Vents can be opened using gravity or other approved methods, and the opening mechanism should not be hindered by factors like snow, debris, or projections. All vents should also be operable manually, either internally or externally, based on approval by the relevant authority.

2.3.2.2.2 Dimensions and Spacing of Vents

The dimensions and spacing of vents should be designed to prevent plugholing (choking of airflow). The area of a unit vent should not exceed 2 times the design depth of the smoke layer. Spacing between vents within a curtained area must ensure that the center-to-center distance does not exceed 4 times the ceiling height. Horizontal spacing from walls or draft curtains to the nearest vent should not exceed 2.8 times the ceiling height.

The total vent area per curtained area should be determined based on design objectives and performance requirements relative to the design fire.

2.3.2.3 Air Inlets

Air inlets are necessary for supplying makeup air to vent systems, ensuring effective smoke management and control of fire-related conditions.

2.3.2.3.1 Construction and location

Air inlets, such as louvers, doors, dampers, windows, and other approved openings, should be constructed in a way that allows outdoor air to flow into the building.

Air inlets are to be strategically placed either in external walls below the smoke layer boundary's design level or in nonadjacent curtained areas, depending on building characteristics.

The size and spacing of air inlets are critical to their effectiveness. Proper sizing ensures that the necessary air exchange can occur, while spacing prevents potential obstructions. Additionally, air velocity should not exceed 1 m/sec (3.28 ft/sec) to maintain controlled airflow.

2.3.2.3.2 Methods of Operation

Air inlets should operate reliably during a fire event. They should be constantly open or automatically open upon fire detection to achieve design and performance objectives. Fail-safe mechanisms ensure that they remain open even if a component fails. The opening mechanisms should be resistant to environmental conditions and should not be obstructed.

2.3.2.4 Draft Curtains

Draft curtains are required when the space between walls exceeds specific limits, serving to enhance smoke control in buildings during fire events.

2.3.2.4.1 Construction and location

Draft curtains must effectively contain smoke by withstanding the maximum expected temperatures during the design interval time. This requirement is especially important when considering a design fire located close to the draft curtain.

Draft curtains should hang vertically from the ceiling, extending downward to a certain distance. It should be at least 20% of the ceiling height (H) from the ceiling to the floor in cases of flat or sawtooth roofs with flat ceiling areas. For sloped roofs, it's measured from the center of the vent to the floor. Each vent's height should be considered individually if they differ.

Spacing restrictions are in place to ensure draft curtains' effectiveness. Curtained areas' length and width must not exceed eight times the ceiling height. If draft curtains extend to a depth of less than 30% of the ceiling height, the space between them should be at least one ceiling height. These provisions ensure that draft curtains effectively guide smoke and control its spread in the event of a fire.

2.3.2.5 Mechanical Smoke Exhaust Systems

Mechanical smoke exhaust systems can be used instead of the natural vent systems. These two systems should not serve the same curtained area. Design of mechanical smoke exhaust systems should follow the guidelines provided next.

2.3.2.5.1 Design

Exhaust rates for each curtained area should be equal to or greater than the determined mass plume flow rates unless a lower rate prevents smoke from descending below the

design smoke layer boundary during the designated period. Mechanical smoke exhaust systems must function effectively under expected fire conditions. Smoke layer temperature is determined as per the specifications.

The minimum number of exhaust inlets must prevent plugholing, ensuring exhaust flow doesn't exceed the limits. Additional inlets beyond the minimum are permitted. Certain values are used in this calculation based on the inlet's location and characteristics.

Adequate intake air must be provided to compensate for the air exhausted by the mechanical smoke exhaust systems as shown previously.

2.3.2.6 Venting in Sprinklered Buildings

Venting in sprinklered buildings should be designed based on an acceptable engineering analysis, demonstrating compliance with established objectives.

In storage areas with draft curtains, the curtains should be placed over the aisle's longitudinal center. The aisle width should be at least 1.5 times the spacing between sprinklers in the direction perpendicular to the draft curtain. Sprinklers must be located on both sides of the curtain, complying with NFPA 13's sprinkler placement requirements concerning walls. An exception to the aisle width requirement applies when a full-height partition replaces the draft curtain.

2.4 Comparison between both perspectives

2.4.1 Activation type: manual or automatic

The Spanish regulation present sections within the building equipped with air handling systems with two main functions: smoke and heat extraction, and replacement with clean air. The operation of this system involves simultaneously opening all systems within the same sector or zone.

This can happen in two ways: through manual activation or automatic activation.

As seen, the automatic mode consists of receiving a signal on the control panel sent from the Fire Protection Central (PCI), whether it's a detection or flow signal, and commanding the simultaneous opening of all air handling units within the alarm zone. This action can take place immediately upon receiving the signal or after a set delay to ensure more effective operation.

The control panel features an emergency button that, when pressed, results in the same operation as the automatic mode; this is considered manual operation. Therefore, the main difference between this activation method and the automatic one is that the activation signal doesn't come from a detection system but is initiated by a human (firefighters or authorized personnel) to activate the system.

In the case of the American regulations, a distinction is made between the SCTEH systems in buildings with and without sprinklers. For the purpose of this document, we'll focus on buildings where both systems coexist.

In this scenario, we find that the opening system, whether automatic or manual, differs from the Spanish approach in that it doesn't open ventilation systems collectively but rather individually.

Regarding automatic opening, it occurs after the thermal fuse of each unit breaks. In the case of manual opening, professionals must activate it individually from the roof. The regulation stipulates that the mode of operation should be automatic or remote, but it notes that the manual system helps reduce entry time for firefighters from the roof.

Concerning the impact of using both fire safety systems, the regulation states that the operation of ventilation systems prior to sprinklers can be detrimental and thus reduce the effectiveness of the sprinkler system.

What is proposed in this situation is to open the air handling units at a higher temperature than the sprinklers, which brings us to a potential issue: the non-opening of these systems. Sprinklers are designed to act only in the area affected by the fire, whereas air handling units are meant to release smoke, which might result in non-activation of units in areas not directly impacted by flames but containing smoke.

Hence, it's evident that in general scenarios, both regulations prioritize the use of automatic systems over manual ones, without preventing manual usage when necessary.

Therefore, the primary difference we've observed thus far is that automatic activation in the American system occurs individually, triggered by the temperature at the precise point where the unit is located. In contrast, in the Spanish regulation, the system is activated collectively upon receiving an activation signal from the PCI central.

This difference raises the key question of the efficacy of individual versus collective opening and the negative impact of each when sprinklers are present.

In the case of using ESFR sprinkler systems, the situation differs. In the UNE-EN 12845:2016+A1:2021 regulation, it's indicated that the appropriate way to combine these systems is solely through manual activation by firefighting teams. Just as inefficiencies have been seen in the method proposed in the American regulation, the Spanish norm also allows for potential ineffectiveness due to imprecise manual activation timings.

At this point, it's also important to remember that this project primarily focuses on property protection and damage reduction, given that it involves storage facilities with minimal human presence and a high potential fuel load. Thus, it might not be unreasonable to prioritize the proper functioning of the fire control system over the smoke evacuation system, while still aiming to optimize both.

The Spanish regulation itself has undergone changes over the years to better adapt to these new systems and to incorporate the knowledge gained over time. A clear example is the update of the UNE 23585 standard in 2017, where, for the first time, the presence of these American sprinklers was considered and modifications were made.

It shifted from considering activation mode based on the type of risk and protection objective (people or property) to solely focusing on the type of sprinkler system, control or ESFR, and the protection objective. If prioritizing property protection, the standard suggests activating SCTEH after the flow signal with a 10-minute delay for control-type sprinklers, and for ESFR, it maintains the manual activation system.

This change, along with the numerous mentions in different regulations, might suggest that delayed system activation is also a viable tool to consider.

2.4.2 Fire curtain

Both Spanish and American regulations emphasize the necessity of utilizing these systems and outline similar requirements, albeit with some differences.

While UNE standards detail the characteristics, placement, and interaction with smoke reservoirs, NFPA 204 delves into draft curtains, emphasizing their construction, positioning, and effectiveness in enhancing smoke control.

UNE 23585 imposes restrictions on the maximum surface area of smoke reservoirs when a fire occurs beneath, aiming to optimize smoke extraction. This aspect is not specifically addressed in NFPA 204.

This area should not exceed 2,000 m² when employing natural smoke exhaust vents or 2,600 m² when utilizing mechanical smoke exhaust vents.

Some characteristics of this barriers are:

- Depth at least 0.1 m greater than the calculated height of the floating smoke layer base.
- When in a deflected position, should not exhibit gaps larger than those on either side when in the non-deflected position.
- For hanging smoke curtains designed to seal openings between a smoke reservoir and adjacent floors the curtains must remain in contact with the lower part of the opening, extending from the top to the bottom.

The American perspective provides, clarifications regarding the use of draft curtains and ESFR systems. It mentions that, generally, draft curtains are not utilized in ESFR sprinkler systems, except for specific scenarios where exceptions are justified.

It then clarifies that in cases where ESFR sprinkler systems coexist with standard-response sprinkler systems, a draft curtain made of noncombustible material and with a minimum depth of 2 feet (600 mm) must separate these areas. An unobstructed aisle measuring at least 4 feet (1.2 m) beneath the draft curtain should be maintained to ensure proper separation.

3 Sprinklers systems in warehouses

3.1 Basics of sprinkler systems

A sprinkler is an active fire protection device designed to activate in case of a fire when a certain temperature is reached. Its purpose is to reduce, control, or even suppress the fire or its spread.

3.1.1 Components and Operation

This device is generally composed of various parts that work together to fulfill its purpose as effectively as possible (Figure 15).



Figure 15. Sprinkler parts (firewize)

1. Heat-Sensitive Glass Bulb (
2. Figure 16): This is the main component that reacts to temperature increase. It is filled with a glycerin-based liquid that expands when heated. The glass bulb is designed to break when it reaches a specified temperature.



Figure 16. Sprinklers glass bulb color grading (Day-Impex Ltd)

2. Plug or Seal: Once the glass bulb breaks due to heat, a plug or seal is released, blocking the water passage in the sprinkler system.
3. Water: The sprinkler system is connected to a pressurized water source. When the glass bulb breaks and the plug is released, water starts flowing through the system.
4. Deflector: Just beneath each sprinkler, there is a flower-shaped metal device called a deflector. The deflector is responsible for distributing water in a specific pattern based on the direction where water dispersal is needed. This ensures that water reaches the fire-affected area effectively.
5. Frame: The frame provides structural support for the sprinkler components, ensuring that they are properly aligned and positioned.
6. Thread: The thread connects the heat-sensitive glass bulb to the frame. It holds the bulb securely in place until the glass breaks due to increased temperature.

There are also sprinklers that use a heat-sensitive fusible instead of a glass bulb that works similarly. It is located at the end of an arm or tube and when the ambient temperature rises, the fusible element melts, which in turn releases the arm or tube, allowing the sprinklers to activate.

3.1.2 Types

There are many ways to classify the different types of sprinklers, including activation type, response time, extinguishing agent nature, sprinkler arrangement, or extinguishing capacity. Next, we will look at some of these classifications that are of particular interest to the industry, especially for warehouses.

Automatic sprinklers: When the sensors detect the presence of fire, because of heat or smoke, these sprinklers activate automatically and spray the fire extinguisher agent over the affected area. In this category are found the Early Suppression Fast Response (ESFR) sprinklers, which will be of greater interest for this project and are therefore detailed in more depth at the end of this section.

Manual sprinklers: in this case, these sprinklers require a person to activate them manually through a manual valve or manual activation device.

Foam sprinklers: if the nature of the fire involves ether fats or liquid fuels these sprinklers are the most frequently used, by applying a mixture of water and foam to extinguish the fire.

Powder sprinklers: when the origin of the combustion comes from an electrical source or metals these sprinklers use extinguishing powder to extinguish specially these kinds of fires.

Carbon dioxide sprinklers: these sprinklers use carbon dioxide to extinguish fires. They are very effective for fires in enclosed spaces and, also, for electrical equipment fires.

3.1.2.1 Early Suppression Fast Response sprinklers

The Early repression Fast Response (ESFR) sprinklers are of special interest for the present document because they are normally used to fight fires in high-threat areas, such as storages with high shelves and artificial structures with veritably high ceilings.

The main difference between ESFR sprinklers and other types of automatic sprinklers under the same category as commercial standard sprinklers, CMDA or CMSA, is that while those end for fire control, ESFR sprinklers concentrate on fire repression. Rather of trying to control the fire until the fire department can extinguish it, this system is designed to snappily spark and attack the fire directly. These can be achieved thanks to their capacity of furnishing a large quantum of water at high speed and pressure, is known as the extinguishing capacity, and measured by the K- factor (Figure 17), which is represented as the next equation.

$$K = \frac{Q}{\sqrt{P}}$$

Where:

Q is the flow through the sprinkler orifice in gpm (L/min).

P is the pressure at the sprinkler orifice in psi (bar).

The units for K are $\text{gpm}/\text{psi}^{0.5}$ ($[\text{L}/\text{min}]/\text{bar}^{0.5}$).



Figure 17. K-Factor comparison for automatic sprinklers. [5]

Also, this kind of sprinkler presents other advantages particularly convenient for warehouses, such as, the possibility, thanks to their extinguishing capacity, of avoiding the use of intermedial sprinklers that, when using those of lower capacity, must be installed in different highs, especially in these kinds of unusual tall buildings. These sprinklers are normally placed in the racks used for the storage which leads to a much

expensive, fixed and complicated installation, and opens up the possibility of accidental damage with heavy loads and machinery moving around them.

According to the UNE 12845 (Normalización Española, 2021) and NFPA 13 (NFPA, 2022) standards these sprinklers can be installed up to a 13,7m high, which enables a higher capacity of the building. There are also specialized companies such as FM Global who considers the capacity of these systems to work from up to 16,8m.

(ESFR Sprinklers: A Strong Line of Defense in Storage Applications, 2022) ESFR sprinklers are highly effective tools for safeguarding high-challenge environments. Unlike conventional sprinklers, ESFR sprinklers are designed not only to control but to suppress fires by directly attacking and extinguishing the blaze. While typical spray sprinklers aim to control fires by wetting and cooling the area to lower heat and prevent flashover, ESFR sprinklers focus on sharply reducing a fire's heat release rate and preventing its resurgence through direct and substantial water application to the burning fuel surface. In essence, ESFR sprinklers are engineered for early and effective fire suppression rather than just containment. (Figure 18)

It's important to highlight that there is a third category beyond control and suppression when it comes to fire response: extinguishment. Extinguishment refers to completely and thoroughly extinguishing a fire without the need for additional firefighter actions to search for remaining hot spots or fuel sources that might rekindle. While sprinklers designed for control or suppression can occasionally achieve extinguishment, their primary design goals and capabilities (specifically for various types of fires) remain technically separate.

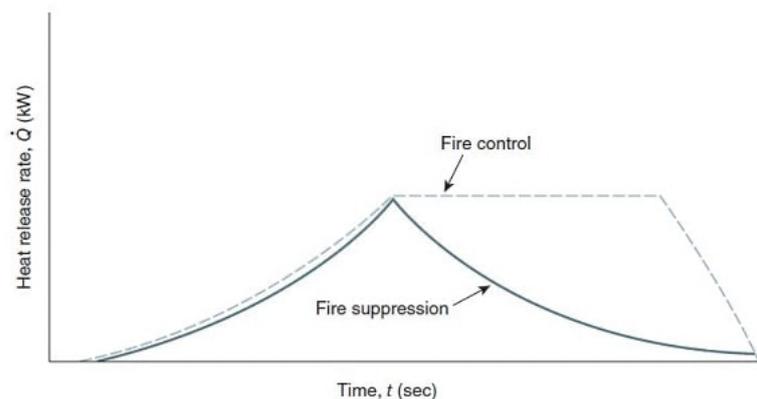


Figure 18. Heat release rate vs Time. Fire suppression and fire control (NFPA, 2022)

ESFR sprinklers achieve their effective fire suppression through several key features. Firstly, their deflectors are designed to create larger and heavier water droplets capable of penetrating the fire plume. This distinct feature is discussed in more detail in a previous blog post.

Secondly, ESFR sprinklers are engineered to deliver water directly onto the fire. This is accomplished by concentrating extra water density within a two-foot radius around the sprinkler axis, resulting in a concentrated application of water below the sprinkler.

Tightly spaced placement also contributes to their efficacy. NFPA 13 (NFPA, 2022) outlines that ESFR sprinklers can be positioned as closely as 15 feet (4,57 m) apart in light or ordinary hazard occupancies, with tighter spacing between 10 to 12 feet (3 to 3,66 m) depending on ceiling height. This arrangement ensures a high density of sprinklers, ready to swiftly combat a fire.

Moreover, ESFR sprinklers generate a substantial water flow, evidenced by the required pressure, water supply, and the sprinkler's K-factor, indicating the orifice size. According to NFPA 13 (NFPA, 2022), ESFR sprinklers must have a minimum K-factor of 11.2, which implies a large orifice. Adjustments beyond this minimum are made to match the hazard level. This engineering approach addresses challenges like safeguarding tall storage, high ceilings, and flammable materials, partially achieved by increasing orifice size and water flow volume.

ESFR sprinklers are also classified as "fast-response" sprinklers due to their more sensitive thermal elements. This design doesn't alter the sprinkler's activation temperature—determined by the solder or fluid in the bulb, not the element's size. Instead, it enhances the sprinkler's ability to swiftly respond to temperature changes.

The rapid-response feature inherent in ESFR sprinklers plays a pivotal role in achieving early fire suppression. Fires have the ability to vaporize minute water droplets and create air currents that disperse water once it reaches a certain size. Consequently, ESFR sprinklers are equipped with fast-response elements to ensure prompt fire suppression taking action before the fire escalates to a significant extent.



Figure 19. Fast-response and a standard-response sprinkler (ESFR Sprinklers: A Strong Line of Defense in Storage Applications, 2022)

The key difference distinguishing fast-response and standard-response sprinklers lies in their bulbs or links. (Figure 19) The fast-response bulb, depicted on the right, possesses a slimmer profile compared to its standard counterpart. This characteristic enhances its sensitivity to temperature changes, further contributing to the sprinkler's swift activation.

3.1.2.1.1 Benefits of ESFR sprinklers

An ESFR sprinkler system offers distinct advantages compared to standard spray sprinklers, particularly in certain scenarios. The early suppression feature minimizes fire damage, and swift fire suppression often translates to reduced overall water damage, particularly when fire hoses are involved. ESFR sprinklers excel in handling challenges that other storage sprinklers struggle with, often negating the need for in-rack sprinklers integrated within storage racks.

Warehouses, densely packed with highly flammable materials, pose intricate fire protection challenges. These settings can experience rapid and intense fires, capable of vaporizing and dispersing water droplets from sprinklers. Such fires might trigger adjacent sprinklers prematurely, diminishing the effectiveness of the nearest sprinkler due to decreased water pressure.

3.2 Spanish perspective

3.2.1 UNE 12845 (Normalización Española, 2021)

3.2.1.1 Introduction

This European standard outlines stipulations and offers suggestions concerning the arrangement, setup, and upkeep of immobile fire sprinkler systems in both architectural and industrial settings within Europe. It encompasses particular prerequisites for sprinkler systems that are an integral part of life safety measures.

An automated sprinkler system is engineered to identify and suppress an early-stage fire using water, or to manage the fire until alternate extinguishing methods can be employed. This system comprises a source of water (or multiple sources) and one or more installations of sprinklers. Each installation is comprised of a primary control valve and an interconnected network of pipes furnished with sprinkler heads. These sprinkler heads are positioned on ceilings or rooftops, and where needed, among shelves, beneath racks, and inside ovens and stoves.

The sprinklers activate at predetermined temperatures, releasing water onto the area below affected by the fire. The flow of water through the alarm valve sets off a fire alarm. The designated operational temperature is usually chosen to match the surrounding

conditions. Only sprinklers in proximity to the fire, those adequately heated, will be triggered.

The sprinkler system is formulated to encompass all sections of the property, with a few specific exceptions. It is not prudent to assume that the existence of a sprinkler system entirely obviates the necessity for alternative firefighting techniques. It is of paramount importance to contemplate comprehensive fire protection strategies for the entire property.

3.2.1.2 Classification of Activities and Fire Risks

This system applies to buildings and areas that require fire protection and are classified as Light Risk, Ordinary Risk, or Extra Risk. The classification is based on the activity and the amount of flammable material present. Examples of activities are provided in Annex A.

When interconnected areas with different risk levels exist, the stricter design criteria must extend to at least two rows of sprinklers within the area with the lowest risk level.

The Light Risk (LR) in Spanish “Riesgo ligero” (RL) category includes activities with low levels of flammable material and combustion, with compartments no larger than 126 m² and a fire resistance of at least 30 minutes.

Ordinary Risk (OR) in Spanish “Riesgo ligero” (RO) encompasses activities where flammable materials are processed or manufactured with an average fire load and combustion.

Extra Risk in the Process category applies to activities involving materials with a high fire load and combustion, which could lead to rapid or intense fire spread.

Extra Risk in the Storage category refers to the storage of items where the storage height exceeds certain established limits.

3.2.1.3 Storage classification

Storage configuration is classified as follows:

ST1: Free or block stacking.

ST2: Self-supporting pallets in single rows, with aisles of no less than 2.4 meters in width.

ST3: Self-supporting pallets in multiple rows (including doubles).

ST4: Palletized shelving (beam pallet racking).

ST5: Solid or open shelves with a width of 1 meter or less.

ST6: Solid or open shelves with a width greater than 1 meter and up to 6 meters.

In this Project, cases of ST2, ST3, and ST4 categories are of particular interest, which are especially common in industrial storage warehouses. Similarly, it will be assumed, as shown later, that the warehouse load consists of unexpanded plastic in cardboard boxes. Below is the table that characterizes these scenarios according to this standard.

Tabla P.3 – Plástico no expandido en cajas de cartón, almacenamiento ST2, ST3 o ST4

Aplicaciones de almacenamiento:				
ST2/ST3 Palés autoportantes				
ST4 Estantería paletizada				
Mercancías:				
Plásticos: No expandidos en cajas de cartón				
Altura de almacenamiento máxima	Altura de techo máxima			
	m			
m	9,1	10,7	12,2	13,7
Presión de funcionamiento mínima de rociador				
bar				
Rociador colgante ESFR factor K nominal 200				
7,6	3,5	5,2	5,2	6,2 + 1 nivel de en estantería
9,1	†	5,2	5,2	6,2 + 1 nivel de en estantería
10,7	†	†	5,2	6,2 + 1 nivel de en estantería
12,2	†	†	†	6,2 + 1 nivel de en estantería
Rociador colgante ESFR factor K nominal 240				
7,6	2,4	3,6	3,6	4,3 + 1 nivel de en estantería
9,1	†	3,6	3,6	4,3 + 1 nivel de en estantería
10,7	†	†	3,6	4,3 + 1 nivel de en estantería
12,2	†	†	†	4,3 + 1 nivel de en estantería
Rociador montante ESFR factor K nominal 200				
7,6	3,5	5,2	†	†
9,1	†	5,2	†	†
Rociador montante ESFR factor K nominal 240				
7,6	2,4	3,6	†	†
9,1	†	3,6	†	†
Rociador colgante ESFR factor K nominal 320				
7,6	1,7	2,4	3,1	3,5
9,1	†	2,4	3,1	3,5
10,7	†	†	3,1	3,5
12,2	†	†	†	3,5
Rociador colgante ESFR factor K nominal 360				
7,6	1,4	2,1	2,7	3,5
9,1	†	2,1	2,7	3,5
10,7	†	†	2,7	3,5
12,2	†	†	†	3,5
† No aplicable.				

Table 9. Unexpanded plastic in cardboard boxes in ST2, ST3, and ST4 storage configurations UNE 12845 (Normalización Española, 2021)

3.2.1.4 Water Supply

Some guidance is provide for water supply for this safety systems.

Duration: Water supplies must provide the required pressure and flow for the system. For other firefighting systems, additional considerations apply. Each water supply must sustain the system for the following minimum durations:

- Light Risk (LR): 30 minutes
- Ordinary Risk (OR): 60 minutes
- Extra Risk (Process) (ER-P): 90 minutes
- Extra Risk (Storage) (ER-S): 90 minutes

Continuity: Water supplies should be unaffected by conditions like frost, drought, or floods. Measures must ensure their reliability. Ideally, users control water supplies; if not, reliability is guaranteed by the controlling entity.

Water Quality: Water must lack fibrous or suspended materials that could accumulate in pipes. Saltwater should not be retained; freshwater is preferred. In the absence of freshwater, saltwater is permissible if the system remains loaded with freshwater under normal conditions.

3.2.1.5 Spacing and Placement of Sprinklers

All requirements for the spacing of sprinklers should be considered horizontally, unless otherwise specified.

A minimum open area under the deflector of ceiling and roof sprinklers must be maintained, as follows:

1. For Light Risk (RL) and Ordinary Risk (RO):
 - 0.3 m for flat spray sprinklers
 - 0.5 m for all other cases
2. For Extra Risk (Process) (REP) and Extra Risk (Storage) (REA):
 - 1.0 m

Maximum Sprinkler Coverage:

- RL: 21 m²
- RO: 12 m²
- REP and REA: 9 m²

3.2.1.6 Sprinkler Flow Rate and Temperature

Sprinkler Flow Rate: The water flow rate of a sprinkler should be calculated using the formula:

$$Q=K \times \sqrt{P}$$

Where: Q is the flow rate in liters per minute, K is a constant, P is the pressure in bars.

Sprinkler Temperature Ratings

When choosing sprinklers, it's important to select a temperature rating that is at least 30°C above the highest expected ambient temperature but not lower. In spaces lacking proper ventilation, situated beneath skylights or glass ceilings, it might be necessary to use sprinklers with higher operating temperatures, potentially up to 93°C or 100°C. Extra attention should be paid to sprinkler ratings near equipment emitting radiant heat, such as drying ovens and heaters.

Glass Bulb Sprinklers		Fusible Sprinklers	
Nominal Operating Temperature (°C)	Liquid Color Code	Nominal Operating Temperature within Range (°C)	Fork Arms Color Code
57	Orange	57 a 77	No Color
68	Red	80 a 107	White
79	Yellow	121 a 149	Blue
93	Green	163 a 191	Red
100	Green	204 a 246	Green
121	Blue	260 a 302	Orange
141	Blue	320 a 343	Black
163	Purple		
182	Purple		
204	Black		
227	Black		
260	Black		
286	Black		
343	Black		

Table 10. Sprinklers temperature ratings and color coding from UNE 12845

3.2.1.7 Interaction with other measures

Consideration must be given to the potential interaction between sprinkler systems and other measures. Therefore, the thermal response of sprinkler systems should not be inhibited. The effective operation of other fire safety measures might rely on the more efficient functioning of the sprinkler equipment, and in such cases, the overall fire safety measures must not be compromised. This aspect deserves particular attention when Extra Risk systems are involved.

The efficient operation of sprinkler systems relies on the swift suppression or control of fires in their early stages. With the exception of sprinklers located on shelving, sprinklers typically operate by the horizontal flow of hot combustion gases from the fire through the sprinklers. As a result, nothing should hinder this horizontal flow of combustion gases.

3.2.1.8 High-Rise Systems

This section outlines regulations for using sprinkler systems in multi-story buildings where the height difference between the highest and lowest sprinkler exceeds 45 meters.

These rules apply to buildings with activities classified as no riskier than RO3. For buildings with higher risks, specialized fire engineering solutions are required, and seeking expert advice is recommended. High-rise sprinkler systems must meet the protection requirements set for Ordinary Risk Group III.

3.2.1.9 ESFR Sprinklers

ESFR sprinklers are ceiling-mounted sprinklers designed to suppress fires within storage risks. Designing and installing ESFR sprinkler systems require careful attention, as their design principles and operating characteristics significantly differ from standard sprinkler protection. Deviations from the standard in design and installation might result not only in reduced effectiveness but also in complete system failure. Hence, all requirements in this annex must be met without exception when applying ESFR protection.

Specification and Installation: This annex specifies requirements and recommendations for designing and installing ESFR sprinkler systems in buildings. It covers activities, storage arrangements, installation design, building requirements, and the management of protected buildings. This ensures the satisfactory performance of ESFR sprinkler systems.

Not Covered: Protection of aerosols, flammable and combustible liquids, stacked rubber tires, and candle storage falls outside the scope of this annex.

Terms and Definitions:

- **ESFR Sprinkler:** A heat-sensitive device designed to react to a predetermined temperature by automatically releasing a water spray pattern with specified density over a designated area to provide early fire suppression.
- **Suppression Mode:** Achieved when a balance is struck between burning goods and sprinkler discharge, keeping the ceiling temperature from rising, eliminating horizontal fire spread, and suppressing fire on vertical surfaces of burning goods.
- **Classification of Articles:** The standard classification system in EN 12845 is replaced by four different plastic categories for ESFR system design: not expanded in cartons, not expanded exposed, expanded in cartons, and expanded exposed. Different criteria apply based on plastic content and volume.
- **Ceiling Height:** Measured from the floor to the underside of the roof. For corrugated metal roofs with depth under 75 mm, measurements can be taken at the lowest point of corrugation.
- **Activities and Fire Risks:** ESFR sprinklers can be used to protect storages as guided by specified tables. Certain conditions, like untested storage or certain configurations, restrict ESFR use. ESFR protection can be used in conjunction with manually operated smoke ventilation systems, operated solely for heat and smoke ventilation by the fire service.

ESFR sprinklers should not be utilized to safeguard areas where any of the following conditions are present:

- a) Goods and storage configurations that have not been evaluated or tested by the appropriate authority for ESFR sprinkler protection.
- b) Open-top containers capable of retaining water.
- c) Automated heat and smoke ventilation.
- d) Solid shelves larger than 2 m² per shelf.

In this section it is clarified that ESFR sprinkler protection may be used alongside manually operated smoke ventilation systems, which are only suitable for heat and smoke ventilation purposes and operated by the fire service.

Coverage area of ESFR sprinkler

Ceiling Height (m)	Sprinkler Spacing (m)		Sprinkler Coverage (m ²)	
	Min (m)	Max (m)	Min (m ²)	Max (m ²)
≤ 9	2.4	3.7	6	9
> 9 ≤ 13.7	2.4	3	6	9

Table 11. Coverage area of ESFR sprinkler in UNE 12845

3.3 US perspective

3.3.1 NFPA 13 (NFPA, 2022)

3.3.1.1 Scope and Purpose

Scope: This standard establishes the minimum requirements for designing and installing automatic fire sprinkler systems and exposure protection sprinkler systems. It does not cover water mist fire protection systems, which are regulated by NFPA 750.

Purpose: The purpose of this standard is to provide a reasonable level of protection from fire to life and property. It does so by setting design, installation, and testing criteria for sprinkler systems based on engineering principles, test data, and field experience. The installation of sprinkler systems and private fire service mains requires knowledgeable and experienced personnel.

This standard applies to various components including water supplies, sprinklers, fittings, piping, valves, materials, and accessories. Buildings protected by automatic sprinkler systems should have sprinklers in all areas, unless permitted otherwise. The standard also applies to "combined service mains" that carry water for fire service and other uses. Following the aim of this project a special attention will be paid to the sprinklers systems.

3.3.1.2 Classification of Activities and Fire Risks

Extra Hazard (Group 1) (EH1): Occupancies with very high quantity and combustibility of contents, or the presence of dust, lint, or other materials. These situations lead to rapidly developing fires with high heat release rates and minimal flammable liquids.

Extra Hazard (Group 2) (EH2): Occupancies with moderate to substantial amounts of flammable or combustible liquids, or those with extensive shielding of combustibles.

Light Hazard: Occupancies with low quantity and combustibility of contents, resulting in fires with relatively low heat release rates.

Ordinary Hazard (Group 1) (OH1): Occupancies with low combustibility, moderate quantity of combustibles, and stockpiles of contents not exceeding 8 ft (2.4m). Fires in these areas have moderate heat release rates.

Ordinary Hazard (Group 2) (OH2): Occupancies with moderate to high quantity and combustibility of contents. Stockpiles of contents with moderate heat release rates should not exceed 12 ft (3.7m), and those with high heat release rates should not exceed 8 ft (2.4m).

Low-Piled Storage:

- Solid-piled, palletized, rack storage, bin box, and shelf storage of Class I through Class IV commodities up to 12 ft (3.7 m) in height.
- Solid-piled, palletized, rack storage, bin box, and shelf storage of Group A plastic commodities up to 5 ft (1.5 m) in height.

High-Piled Storage:

- Solid-piled, palletized, rack storage, bin box, and shelf storage of Class I through Class IV commodities more than 12 ft (3.7 m) in height.
- Solid-piled, palletized, rack storage, bin box, and shelf storage of Group A plastic commodities more than 5 ft in height (1.5 m).

3.3.1.3 Sprinkler classification and identification

Max Ceiling Temperature °F (°C)	Temperature Rating °F (°C)	Temperature Classification	Glass Bulb Colors	Color Code
100 (38)	135-170 (57-77)	Ordinary	Orange or Red	Uncolored or Black
150 (66)	175-225 (79-107)	Intermediate	Yellow or Green	White
225 (107)	250-300 (121-149)	High	Blue	Blue
300 (149)	325-375 (163-191)	Extra High	Purple	Red
375 (191)	400-475 (204-246)	Very Extra High	Black	Green
475 (246)	500-575 (260-302)	Ultra High	Black	Orange
625 (329)	650 (343)	Ultra High	Black	Orange

Table 12. Sprinklers temperature ratings and color coding from NFPA 13

3.3.1.4 Sprinkler Location Requirements

The placement, spacing, and positioning of sprinklers must adhere to the following principles:

- Sprinklers must be installed throughout the premises.
- Sprinklers should be situated to cover areas within the allowable protection range per sprinkler.
- Sprinklers must be positioned and located to ensure effective activation time and even distribution.
- Sprinklers can be excluded from specific areas as permitted by the standard.

- If sprinklers are tested and results show that variations from clearance requirements to structural elements do not compromise their ability to control or suppress fires, their placement and positioning can adhere to the test outcomes.
- Exceeding the specified maximum clearance between sprinklers and ceilings is allowed, given that tests or calculations prove that the sprinklers perform with comparable sensitivity and effectiveness to those meeting standard requirements.

3.3.1.5 Installation Requirements for ESFR

Early suppression fast-response (ESFR) sprinklers must be selected, positioned, and spaced according to the guidelines in this chapter.

ESFR sprinklers are limited to wet pipe systems, unless explicitly listed for deployment in dry systems or preaction systems.

ESFR sprinklers may only be installed in buildings where the roof or ceiling slope above the sprinklers doesn't exceed a pitch of 2 in 12, corresponding to a roof slope of 16.7 percent.

Draft Curtains

For situations where ESFR sprinkler systems coexist with standard-response sprinkler systems, a draft curtain of noncombustible material and a depth of at least 2 ft (600 mm) is required to separate these regions. Maintaining a clear aisle of at least 4 ft (1.2 m) beneath the draft curtain is necessary for proper separation.

Protection Areas per Sprinkler: The protection area of coverage per ESFR sprinkler is determined based on specific criteria outlined in the standard. There are maximum (100 ft² or 9.3 m²) and minimum (64 ft² or 5.9 m²) allowable protection areas, with deviations allowed for structural obstructions. Additionally, certain exemptions apply to sprinklers placed above solid structural members in unobstructed construction.

Sprinkler Spacing: The maximum distance between ESFR sprinklers is determined by storage and ceiling height, with different limits for various conditions.

- Storage height \leq 25 ft (7.6 m) and ceiling height \leq 30 ft (9.1 m): Maximum 12 ft (3.7 m) between sprinklers.
- Storage height $>$ 25 ft (7.6 m) or ceiling height $>$ 30 ft (9.1 m): Maximum 10 ft (3.0 m) between sprinklers.

Ceiling Height (m)	Sprinkler Spacing (m)	Sprinkler Coverage (m ²)
	Max (m)	Max (m ²)
≤ 9.1	3.7	9
> 9.1	3	9

Table 13. Coverage area of ESFR sprinkler in NFPA 13

Deviations from maximum sprinkler spacing are permitted to accommodate structural obstructions, ensuring proper coverage while maintaining safety standards. Similar allowances are made for situations where branch lines run parallel to trusses and bar joists.

Distance from Walls: The standard specifies the maximum and minimum distances between ESFR sprinklers and walls. The maximum distance is linked to the allowable distance between sprinklers and is based on specific conditions. The minimum distance requires sprinklers to be located a minimum of 4 inches (100 mm) away from walls.

Minimum Sprinkler Spacing: ESFR sprinklers are required to be spaced a minimum of 8 ft (2.4 m) apart on center. Certain exemptions apply for buildings with unobstructed construction and sprinklers placed above adjacent solid structural members. Adjusted sprinkler spacing is permitted under specific conditions, including the use of baffles to ensure proper water distribution.

Deflector Position: ESFR sprinkler deflector positioning is crucial for effective fire suppression. The standard specifies the maximum and minimum distances between the sprinkler deflector and the ceiling for different types of sprinklers based on their nominal K-factors. Pendent sprinklers with different K-factors must be positioned within specific distance ranges, as well as upright sprinklers. The guidelines address situations where obstructed construction is present, allowing for the installation of branch lines across beams while positioning sprinklers in the bays, not under the beams. Additionally, the orientation of sprinkler deflectors must be parallel to ceilings or roofs.

Obstructions to Sprinkler Discharge ESFR: The arrangement of sprinklers in relation to obstructions is critical to ensure unobstructed water distribution for fire suppression. The standard provides guidelines for dealing with obstructions at or near the ceiling, such as beams, ducts, lights, and top chords of trusses and bar joists. Sprinklers need to be arranged according to specific tables and figures to ensure proper water coverage despite these obstructions. Special allowances are made for certain cases where obstructions are narrower than 24 inches (600 mm) and where sprinklers have special obstruction allowances based on their listings.

3.3.1.6 General Requirements for Storage

In this chapter, the guidelines are provided for determining essential aspects of fire protection within storage environments. These include identifying commodities, storage arrangements, storage heights, clearances, and general protection criteria. Storage conditions are addressed in relation to Chapters 21 through 25. Additionally,

miscellaneous and low-piled storage meeting criteria specified in Chapter 4 will be protected in alignment with referenced occupancy hazard criteria.

The protection of storage entails a comprehensive process involving the identification of commodity classes, storage methods, storage heights, clearances, and general protection criteria. Notably, ESFR sprinklers can effectively protect various commodities, including those falling under the category of Group A plastics. It's important to note that systems with multiple hazard classifications have distinct water supply requirements.

The classification of commodities hinges on the unique characteristics of individual storage units, considering factors such as packaging materials and pallets used. If specific test data from nationally recognized testing agencies are available, they can contribute to determining the classification. Commodity classification is categorized from the lowest, Class I, to the highest, exposed expanded plastic, Class IV. Moreover, commodities with lower classifications can protect those with corresponding lower classifications within the same list.

Commodity classes are defined based on diverse considerations, including packaging materials, combustibility, and constituent materials. Class I commodities encompass noncombustible products in various forms and arrangements. Class II commodities include noncombustible products housed within combustible packaging. Class III commodities are constructed from materials such as wood, paper, fibers, or plastics, with some allowances for plastic content. Class IV commodities are characterized by a combination of materials, including plastic, and possess specific classification criteria.

Roof Vents and Draft Curtains

The installation and use of roof vents and draft curtains are addressed within the context of fire protection. Roof vents, whether manually operated or automatic with higher temperature classifications than sprinklers, are permitted. However, ESFR sprinklers should not be used with automatic heat or smoke vents unless compatible mechanisms are in place. Generally, draft curtains are not employed in ESFR sprinkler systems, except for specific scenarios that warrant exceptions.

3.3.1.7 ESFR Requirements for Storage Applications

The provisions laid out previously extend to storage scenarios safeguarded by Early Suppression Fast-Response (ESFR) sprinklers. ESFR sprinklers designed per the criteria in this chapter can protect light hazard and ordinary hazard occupancies, as well as storage arrangements with specific design criteria.

Design areas typically encompass the most hydraulically demanding 12 sprinklers, distributed with four on each of the three branch lines, unless otherwise specified.

Protection of palletized, solid-piled, or rack storage of Class I through Class IV and Group A commodities adheres to the specifications detailed in the next table.

Table 23.3.1 ESRF Sprinkler Ceiling-Only Options for Solid Pile; Palletized; and Single-, Double-, and Multiple-Row Rack Storage

Commodity ^a	Maximum Ceiling/ Roof Height		ESFR Sprinklers — Pendent Orientation Minimum Operating Pressure psi (bar)				ESFR Sprinklers — Upright Orientation Minimum Operating Pressure psi (bar)	
			Nominal K-Factors				Nominal K-Factors	
			14 (200)	16.8 (240)	22.4 (320)	25.2 (360)	14 (200)	16.8 (240)
Class I through Class IV and cartoned nonexpanded Group A plastics	25 30 35 40 45	7.6 9.1 10.7 12.2 13.7	50 (3.4) 50 (3.4) 75 (5.2) — —	35 (2.4) 35 (2.4) 52 (3.6) 52 (3.6) —	25 (1.7) 25 (1.7) 35 (2.4) — 40 (2.8)	15 (1.0) 15 (1.0) 20 (1.4) 25 (1.7) 40 (2.8)	50 (3.4) 50 (3.4) 75 (5.2) — —	35 (2.4) 35 (2.4) 52 (3.6) — —
Cartoned expanded Group A plastics	25 30 35 40 45	7.6 9.1 10.7 12.2 13.7	50 (3.4) 50 (3.4) — — —	35 (2.4) 35 (2.4) — — —	— — — — —	— — — — —	50 (3.4) 50 (3.4) — — —	35 (2.4) 35 (2.4) — — —
Exposed nonexpanded, Group A plastics	25 30 35 40 45	7.6 9.1 10.7 12.2 13.7	50 (3.4) 50 (3.4) — — —	35 (2.4) 35 (2.4) — — —	— — — 75 (5.2) —	— — — 60 (4.1) —	— — — — —	— — — — —
Exposed expanded Group A plastics	25 30 32 35 40 45	7.6 9.1 9.8 10.7 12.2 13.7	— — — — — —	— — — — — —	— — — — — —	— 30 (2.0) ^b — — 60 (4.1) ^{b,c} —	— — — — — —	— — — — — —

^aSee 20.3.2 for information regarding protection of lower hazard commodities with higher hazard criteria.

^bThese options apply when all requirements in Section 27.4 are applied including vertical barriers.

^cThis option applies to palletized and solid pile storage in a closed array.

Table 14. Unexpanded plastic in cardboard boxes in ST2, ST3, and ST4 storage configurations NFPA 13 (NFPA, 2022)

The same way as in the previous chapter, it is of special interest the classification of commodity Class I through IV and cartoned Group A plastics with ESRF K(360) sprinkler system.

3.4 Comparison between both perspectives

It's worth noting a significant compatibility and synergy between both regulations that share many elements, provisions, and requirements. Especially for the most fundamental aspects, such as definitions or element classification, there are many similarities that facilitate cooperation among manufacturers and professionals from different countries. Despite this, there isn't complete compatibility, and many differences between these regulations can lead to uncertainties and issues.

Regarding zone classification:

Both regulations perform classification based on the potential risk posed by each zone.

In the Spanish classification system, activities and fire risks are categorized based on Light Risk (LR), Ordinary Risk (OR), and Extra Risk. The classification considers factors like the amount of flammable material, combustion levels, compartment size, and fire resistance. The LR category involves low flammable material and small compartments. OR includes average fire loads, while Extra Risk refers to high fire load and rapid spread.

The American classification system includes various hazard levels: Extra Hazard Group 1 (EH1), characterized by high combustibility and rapid fire development. Extra Hazard Group 2 (EH2) involves moderate to substantial flammable liquids or shielding of combustibles. Light Hazard signifies low combustibility, resulting in fires with limited heat release rates. Ordinary Hazard Group 1 (OH1) features low combustibility, moderate combustibles, and controlled stockpiles. Ordinary Hazard Group 2 (OH2) encompasses moderate to high combustibility and varying quantities of combustibles, with defined limits on stockpile dimensions.

Storage configuration is categorized in the Spanish perspective as ST1 to ST6, varying from free stacking to shelving with different widths and arrangements.

The American storage classification involves Low-Piled Storage and High-Piled Storage. Low-Piled Storage includes solid-piled, palletized, rack, bin box, and shelf storage up to 12 ft (3.7 m) in height for certain commodities. High-Piled Storage involves storage exceeding 12 ft (3.7 m) in height for specific commodities.

The classification of sprinklers by the color of the glass bulb, which each regulation does based on the activation temperature, varies slightly in the same way, although the similarity can be observed.

Color	American Temperatures (°C)	Spanish Temperatures (°C)
Orange	57-77	57
Red	79-107	68
Yellow	121-149	93, 100
Green	121-149	121
Blue	149-65	141
Purple	163-191	163, 182
Black	204-343	204, 227, 260, 286, 343

Table 15. Comparison of sprinklers classification by the color of the glass bulb

Regarding to ESFR sprinklers, the regulations are even more similar, as this is a very specific American sprinkler system. The Spanish regulation directly relies on the American one for its application.

Protection Areas per Sprinkler: The protection area of coverage per ESFR sprinkler is determined based on specific criteria outlined in the standard. There are maximum (100 ft² or 9.3 m²) and minimum (64 ft² or 5.9 m²) allowable protection areas, with deviations allowed for structural obstructions. Additionally, certain exemptions apply to sprinklers placed above solid structural members in unobstructed construction.

For instance, the distribution and spacing of the ESFR systems is the same for both. The maximum distance between ESFR sprinklers determined by storage and ceiling height is the following:

- Storage height \leq 25 ft (7.6 m) and ceiling height \leq 30 ft (9.1 m): Maximum 12 ft (3.7 m) between sprinklers.
- Storage height $>$ 25 ft (7.6 m) or ceiling height $>$ 30 ft (9.1 m): Maximum 10 ft (3.0 m) between sprinklers.

The same applies to the design criteria for ESFR systems, where both perspectives align for system selection based on the K-factor, ceiling height, and operating pressure. In this case, what needs to be taken into account are the distinct classifications these regulations provide for activities and risks.

Regarding the combined presence of SCTEH systems with ESFR systems in both regulations, there's a mention of the importance of proper utilization to ensure optimal performance when these systems work in tandem.

Spanish Regulation:

ESFR sprinkler protection can be combined with manually operated smoke ventilation systems that are solely intended for heat and smoke ventilation and are controlled by the fire service.

American Regulation:

The installation and usage of roof vents and draft curtains are considered within the fire protection context. Roof vents, whether manually operated or automatic with higher temperature ratings than sprinklers, are allowed. However, ESFR sprinklers should not be used with automatic heat or smoke vents unless compatible mechanisms are present. Draft curtains are generally not used in ESFR sprinkler systems, except for specific circumstances where exceptions are justified.

Both regulations acknowledge the integration of ESFR sprinklers with manual ventilation systems, the Spanish perspective emphasizes controlled by the fire service, while the American stance addresses the possibility compatible mechanisms that makes it possible to use automatic systems.

4 Assessment of the interaction between ESFR and smoke vents

4.1 Fire Dynamics Simulator (FDS)

Fire Dynamics Simulator (FDS) is an advanced computational tool used in the field of fire safety engineering. It is an open-source program developed by the National Institute of Standards and Technology (NIST). FDS operates as a computational fluid dynamics (CFD) model specifically designed to simulate fluid dynamics for fire scenarios. This is achieved through the numerical solution of the Navier-Stokes equations adapted to represent low-speed flows primarily induced by heat.

The simulation of the interaction between flames, smoke, and heat in fire scenarios is complex, and this program excels in addressing it. Therefore, the software's purpose is to accurately represent the behavior and interaction of heat and smoke produced in a fire.

This tool is particularly valuable due to its high precision and its wide range of design possibilities. Different types of fires can be simulated by varying the fire's origin, intensity, materials, location, environment, and even the effect of fire protection systems like smoke control and heat extraction systems or sprinklers can be simulated.

All of this makes this software a highly useful tool for many fire safety professionals, engineers, and researchers. It allows for a deeper understanding of fire development, propagation, and impact in a safe manner, reducing the need for expensive, hazardous, and environmentally detrimental experiments and tests. The accuracy of this system enables the design and evaluation of various fire safety measures in different scenarios within a reasonable timeframe.

To fully harness the potential of this program, it is used in conjunction with Smokeview, a visualization program. Smokeview enables the visualization of simulation results generated by FDS and allows for their reproduction according to set parameters, displaying results and graphs such as heat release rate or selected device outputs.

For all these reasons, FDS in conjunction with Smokeview has been chosen to conduct simulations that validate certain hypotheses and reflect on the obtained results.

4.2 Validation exercises FDS

To achieve the objectives of this project, a series of simulations using FDS software were conducted based on hypotheses presented in this section. These simulations aim to explore various fire scenarios in a logistics warehouse to observe the interaction between the active fire protection systems ESFR and SCTEH. The goal is to identify differences in system activation under varying circumstances.

Additionally, the effectiveness of smoke curtains under these conditions is being evaluated. These simulations serve to assess their impact and determine the necessity of such fire protection systems.

This initiative arises from observations of disparities among different global regulations and their historical modifications. These discrepancies and changes prompt questions about their foundations. These simulations are expected to provide clarity and insights into establishing the most appropriate criteria for the installation, operation, and functionality of these critical systems, particularly in facilities of this nature.

4.2.1 Initial Assumptions

- The logistics warehouse proposed to study has an area of 6,000 m² consisting of three smoke reservoirs of 2,000 m² each, as outlined in section 6.6.2.6 of the UNE 23585 standard and shown in 2.2.1.3 in this document.
- The analysis will be conducted with the following SCTEH:
 - Prescriptive design with smoke curtains delimiting the reservoirs, and replacement air supplied from adjacent reservoirs (**¡Error! No se encuentra el origen de la referencia.**).
 - Alternative design without smoke curtains, with replacement air provided from facade loading docks. All rooftop exhaust vents open after system activation. (**¡Error! No se encuentra el origen de la referencia.**).
- The SCTEH design will be based on Annex A and E of the UNE 23585 standard (2.2.1.2, 2.2.1.3 and 2.2.1.4). A smoke-free height of 2/3 as specified in Table 8 will be considered. The system design assumes maximum roof and storage heights according to the UNE 12845 sprinkler standard (Table 9).
- The system will be evaluated with a medium growth fire and an ultra-fast growth fire (**¡Error! No se encuentra el origen de la referencia.**). According to Chapter C.2.8 of the ISO 16733-1 (Normalización Española, 2017) standard, a constant fire power will be considered after ESFR sprinkler activation.
- ESFR K360 or similar sprinklers will be defined in the models to estimate their activation and subsequent fire curve evolution.
- The only participating combustion fuel will be GM 37 polyurethane foam (ANEX B. Characterization of the products released in the combustion reaction).
- Three types of SCTEH activations will be analyzed:
 - Manual activation after 15 minutes, assuming firefighting operations commence.

-
- Automatic activation upon fire detection by optical detectors. The smoke control system will activate within a maximum of 60 seconds, as specified in section 4.4.2 of the UNE 23585 standard (Normalización Española, 2017)(2.2.1.6 Performance with a sprinkler suppression system).
 - Automatic activation via a 182°C thermal detector beneath the exhaust vent (Option 1 in Figure 51. Flowchart for potential recommendations when vents or smoke vents must be installed)

- ANEX C. FM Datasheet 2-0).

The following table illustrates the eight proposed fire scenarios for analysis:

Scenario	SCTEH Activation	Smoke Curtains	Fire Growth
1	Manual at 15 min	No	Medium (0.01172 kW/s ²)
2	Manual at 15 min	No	Ultra-fast (0.1876 kW/s ²)
3	Manual at 15 min	Yes	Medium (0.01172 kW/s ²)
4	Manual at 15 min	Yes	Ultra-fast (0.1876 kW/s ²)
5	Automatic after detection + 60s delay	Yes	Medium (0.01172 kW/s ²)
6	Automatic after detection + 60s delay	Yes	Ultra-fast (0.1876 kW/s ²)
7	Automatic with 182°C thermal link + 60s delay	Yes	Medium (0.01172 kW/s ²)
8	Automatic with 182°C thermal link + 60s delay	Yes	Ultra-fast (0.1876 kW/s ²)

Table 16. Fire scenarios simulated.

The following images depict the scenarios simulated for cases 1 and 2 (Figure 20 and Figure 21; **Error! No se encuentra el origen de la referencia.**), where no curtains are present. The yellow rectangles represent the cargo within the logistics warehouse. At the top, there are eight blue rectangles representing smoke exhaust vents, in the center of the warehouse, there are twelve green dots representing the ESFR systems and on ground level a red rectangle that emulates the fire origin.

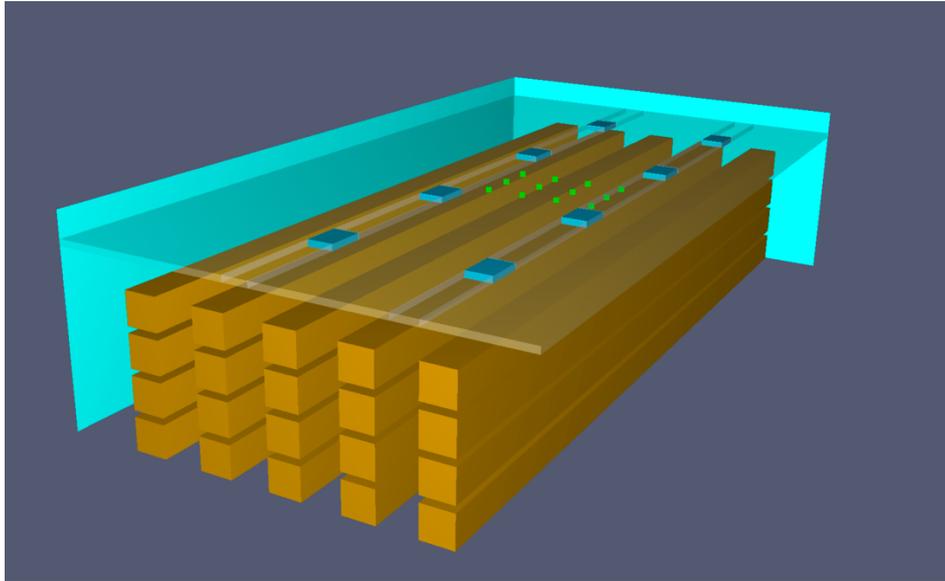


Figure 20. Axonometric view warehouse scenario 1 and 2.

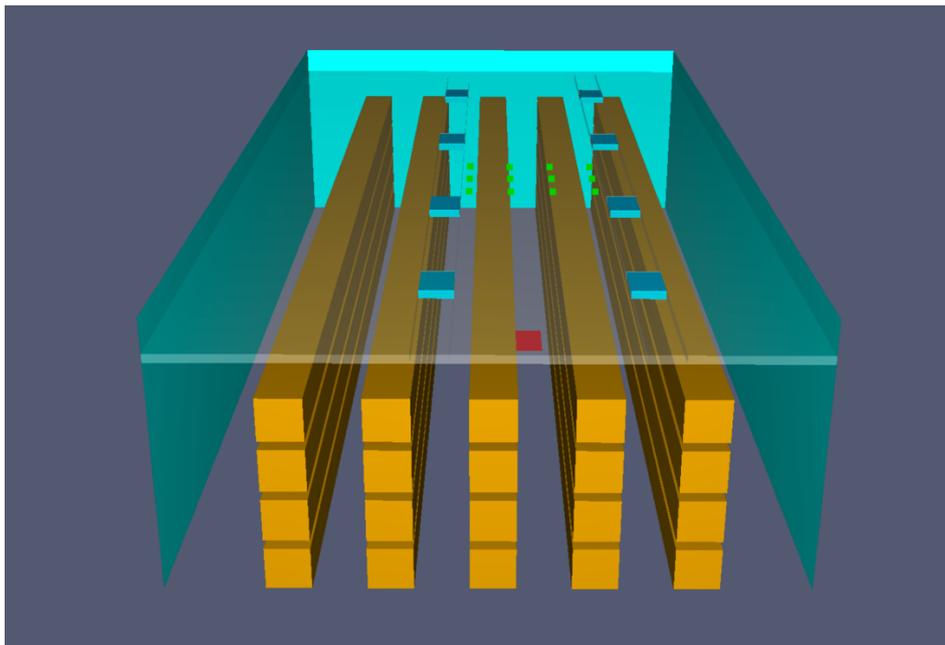


Figure 21. Left profile edge view warehouse scenario 1 and 2.

In the following images (Figure 22 and Figure 23), smoke curtains are shown covering the fire sector that will be used for the remaining scenarios.

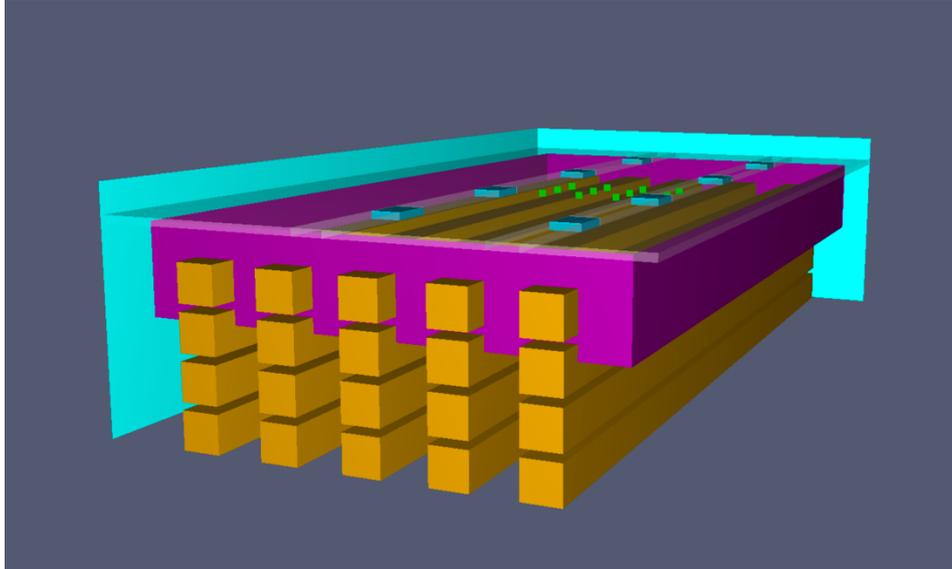


Figure 22. Axonometric view warehouse scenario 3, 4, 5, 6, 7 and 8.

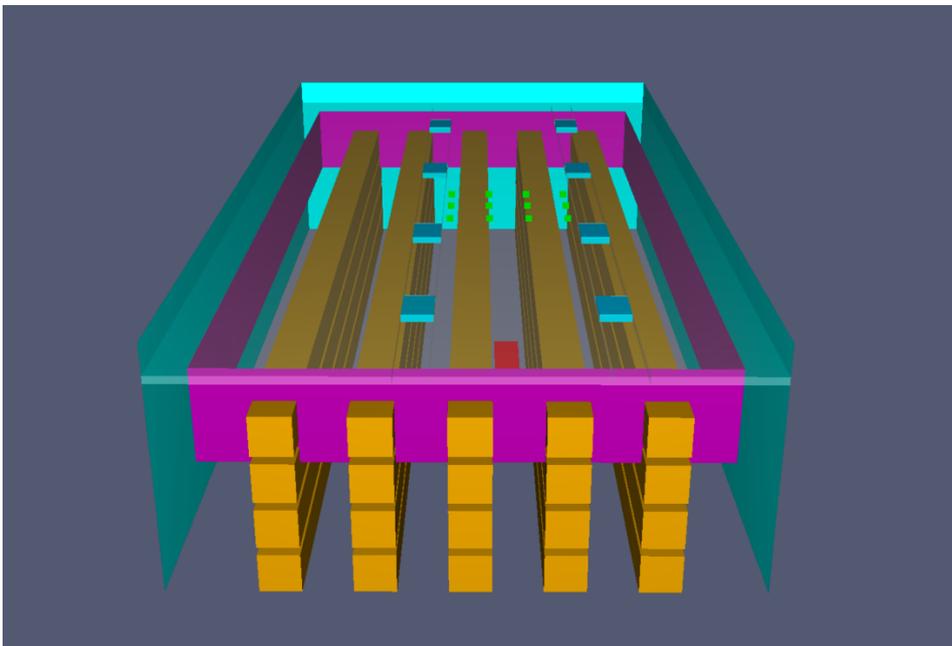


Figure 23. Left profile edge view warehouse scenario 3, 4, 5, 6, 7 and 8.

4.3 Perform FDS simulations.

4.3.1 Heat Release Rate graphs

The Heat Release Rate (HRR) refers to the amount of heat energy released per unit of time during a fire or combustion process. HRR is typically measured in watts (W) or kilowatts (kW) and is a crucial parameter for assessing fire behavior, evaluating fire protection systems, and understanding the potential impact of fires on structures and environments.

As observed in the section where the initial hypothesis was posed, the growth rate commonly seen in building types relevant to this project ranges from moderate to ultra-fast in the worst-case scenarios. This allows for a clearer understanding of the obtained results.

In cases 1, 3, 5, and 7, (Figure 26, Figure 28, Figure 30 and Figure 32) the growth rate is significantly slower (Figure 25), and the maximum HRR value is reached after 500 seconds, while in the remaining cases (Figure 27, Figure 29, Figure 31 and Figure 33), it occurs much earlier (Figure 24), around 150 seconds.

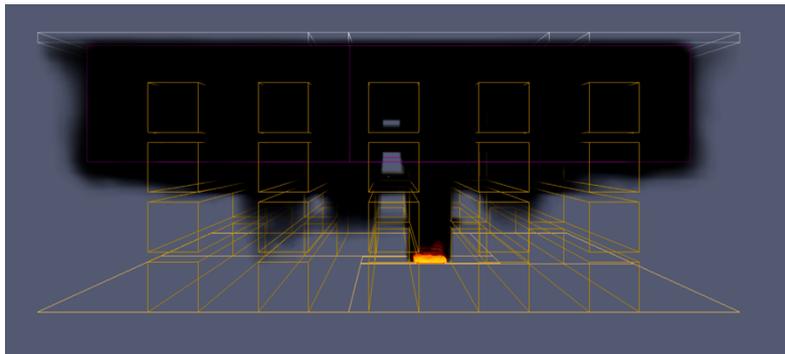


Figure 24. Snapshot in second 200 of ultra-rapid fire growth rate scenario

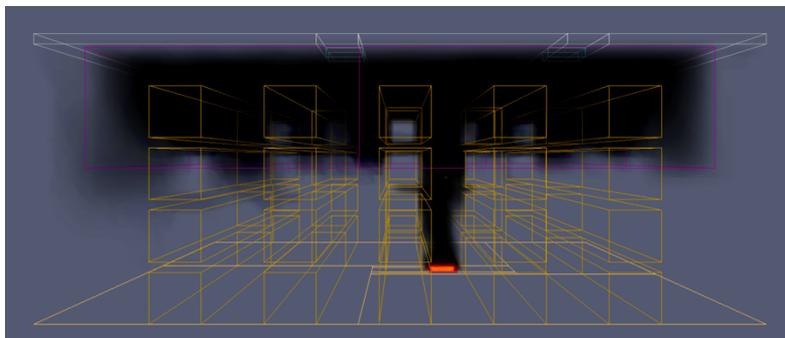


Figure 25. Snapshot in second 200 of medium fire growth rate scenario

Furthermore, as stipulated, this HRR value will remain constant for the rest of the simulation, regardless of sprinkler activation.

Similarly, it is noted that in scenarios where moderate fire growth was considered, the maximum reached value is around 3250 kW, whereas in the case of ultra-fast growth, this value hovers around 4750 kW.

Case 1

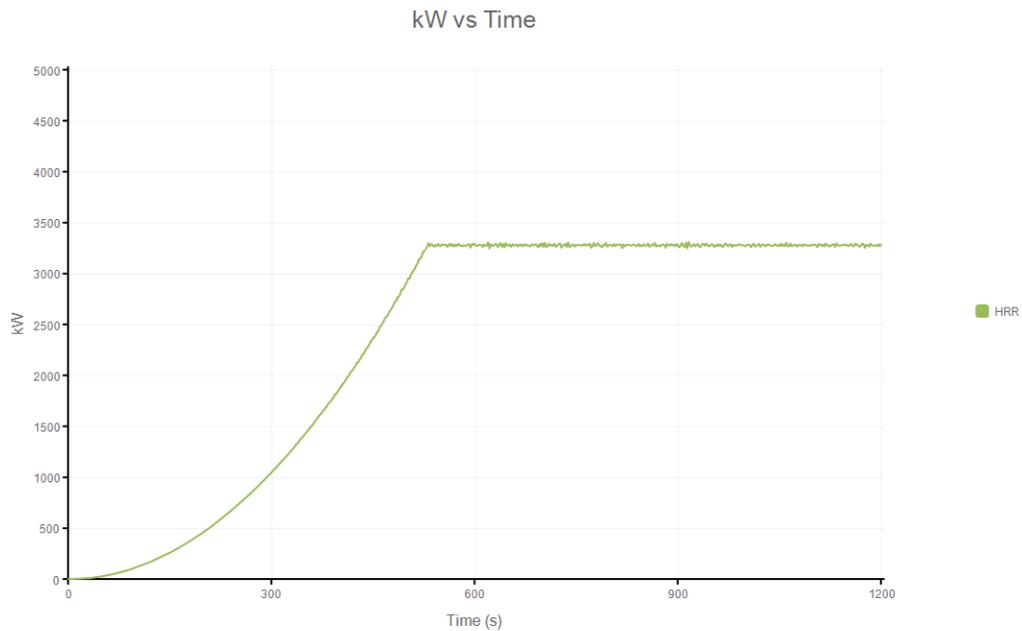


Figure 26. HRR Case 1

Case 2

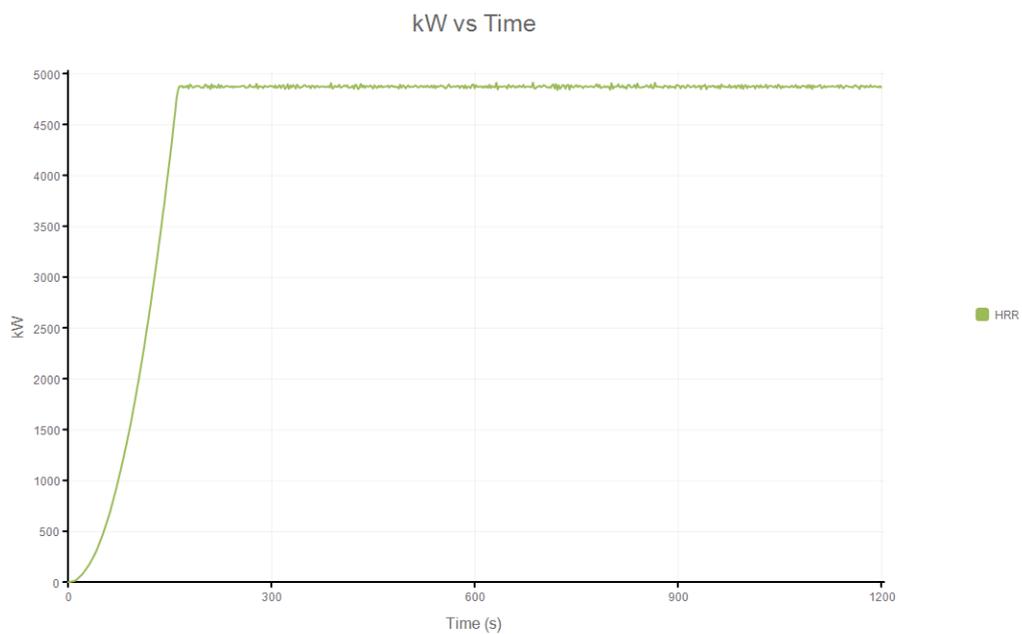


Figure 27. HRR Case 2

Case 3

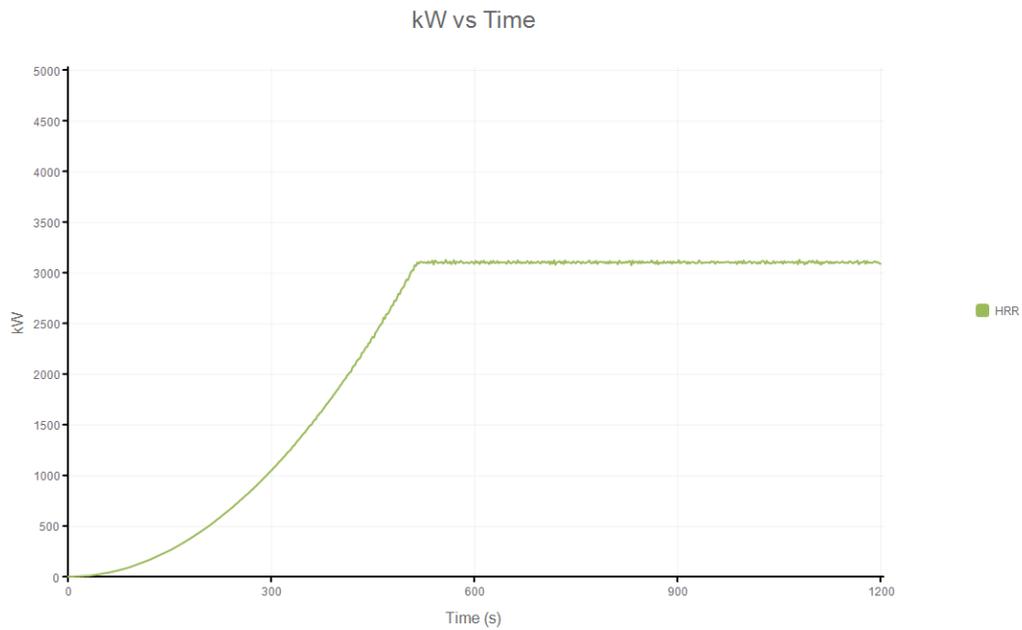


Figure 28. HRR Case 3

Case 4

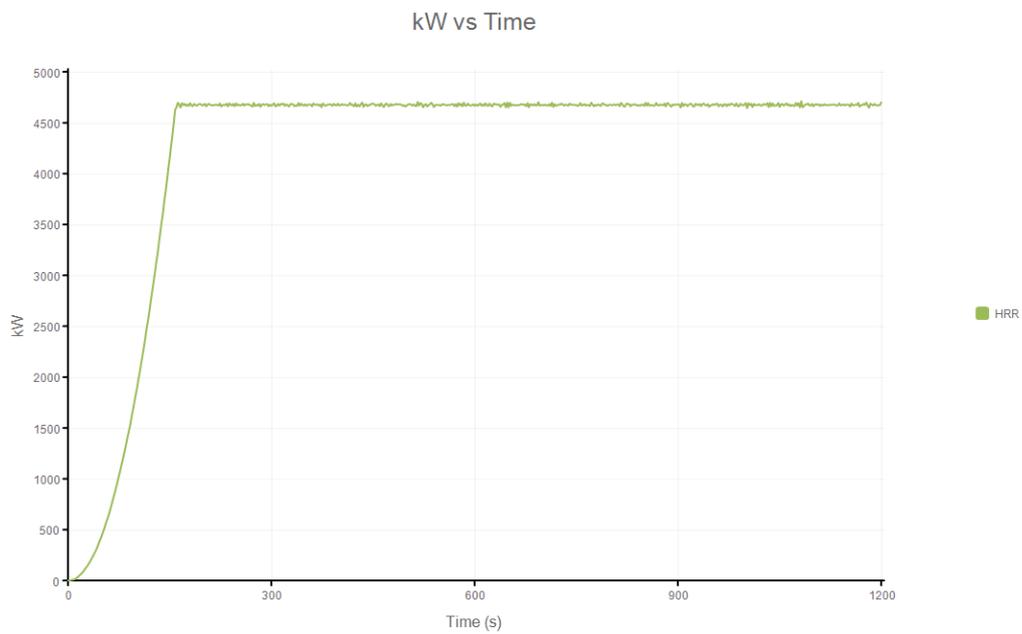


Figure 29. HRR Case 4

Case 5

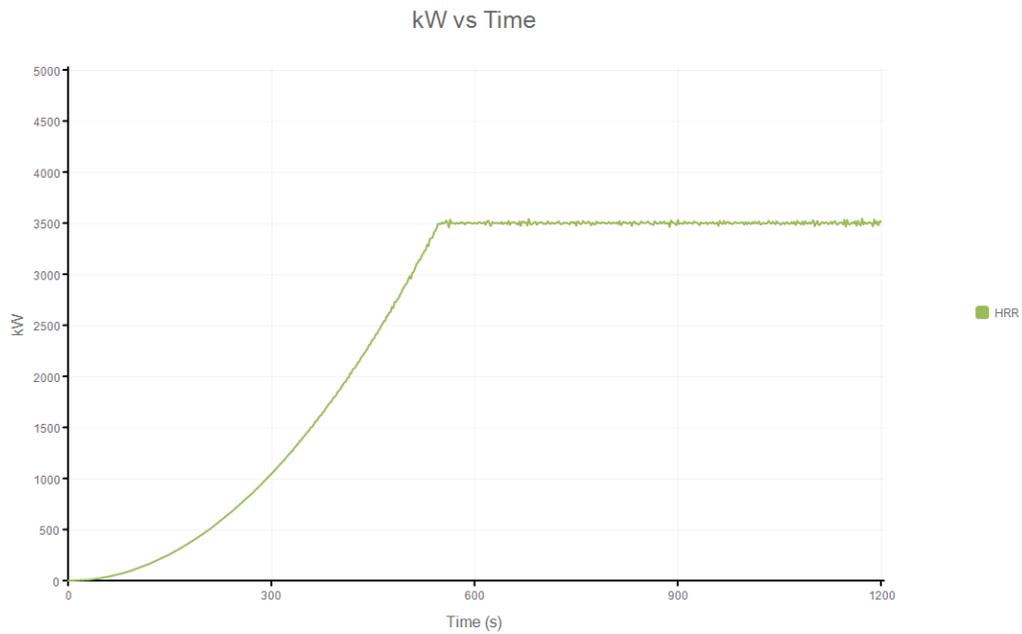


Figure 30. HRR Case 5

Case 6

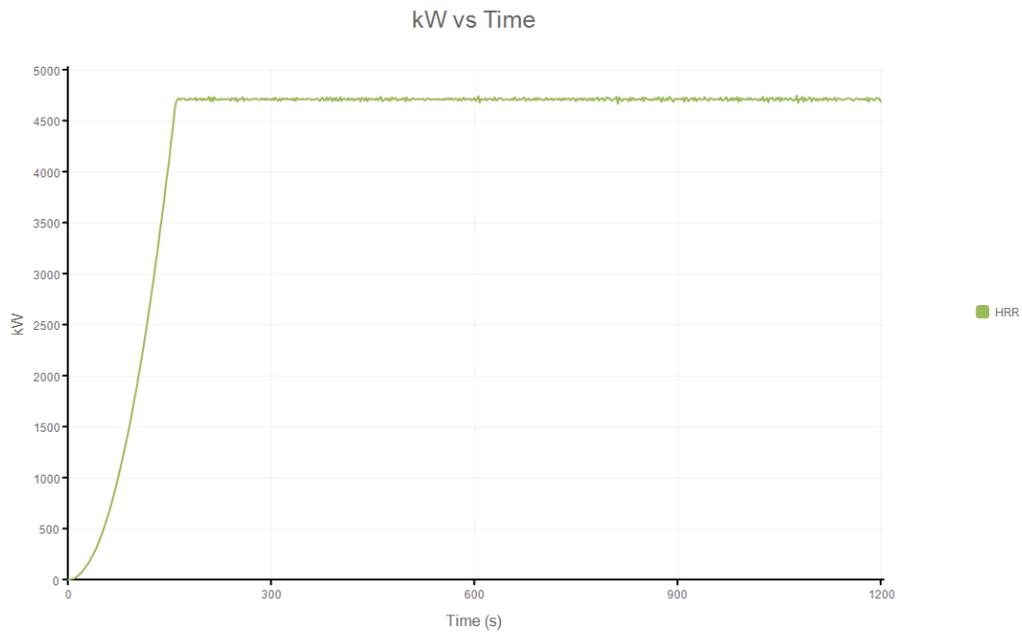


Figure 31. HRR Case 6

Case 7

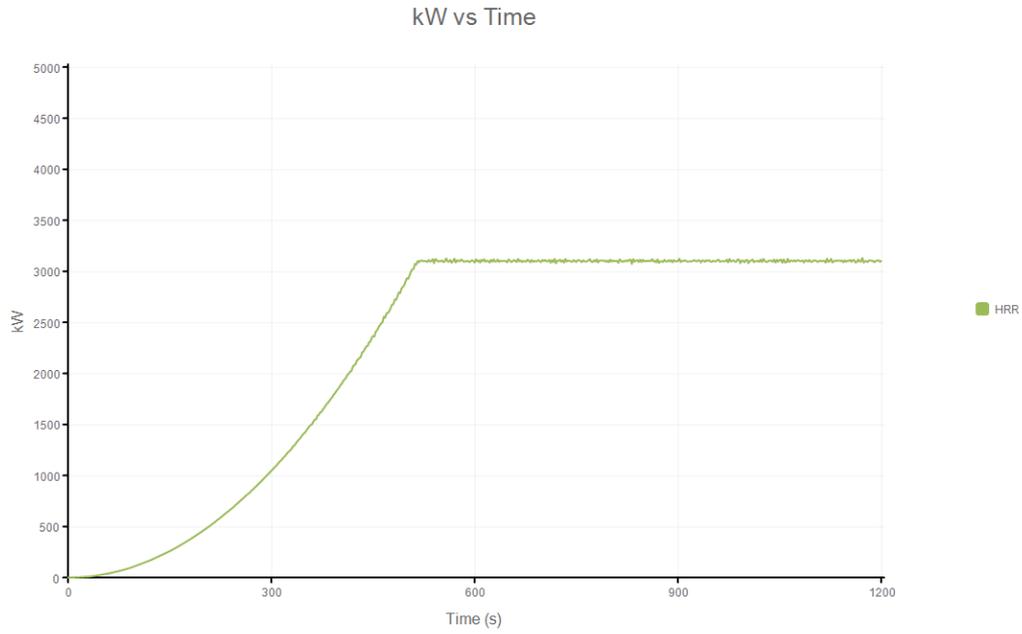


Figure 32. HRR Case 7

Case 8

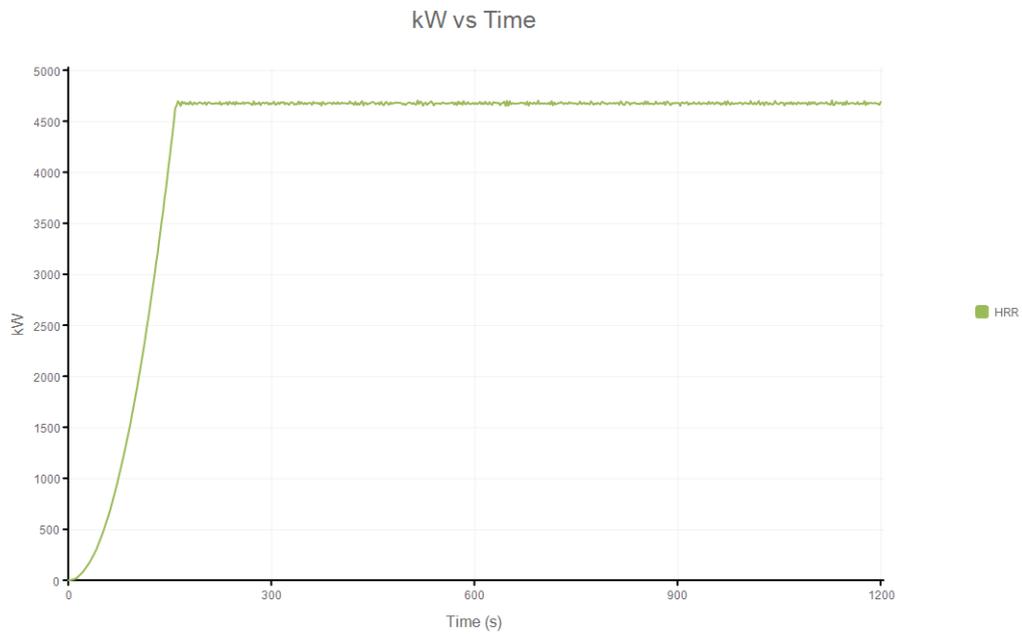


Figure 33. HRR Case 8

4.3.2 Sprinklers activation and time

The selected ESRs for these simulations have an activation temperature of 74°C. The charts presented in this section illustrate the temperature measurements at each sprinkler. This visualization enables the identification of activated sprinklers that have surpassed the activation temperature and when this occurred.

The images presented below depict a top-down view of the sprinkler distribution in relation to the simulated fire area. This helps in understanding the activation process or temperature variations among sprinklers due to their proximity to the fire source.

The main distinction between the two images is the fire area, which is larger for cases 2, 4, 6, and 8 (ultra-fast growth rate (Figure 24)) (Figure 35), and smaller for cases 1, 3, 5, and 7 (moderate growth rate (Figure 25)) (Figure 34).

The red area represents the extent of the fire, and the green-marked sprinklers are labeled for differentiation. Additionally, some extraneous elements are shown but are not pertinent to this section.

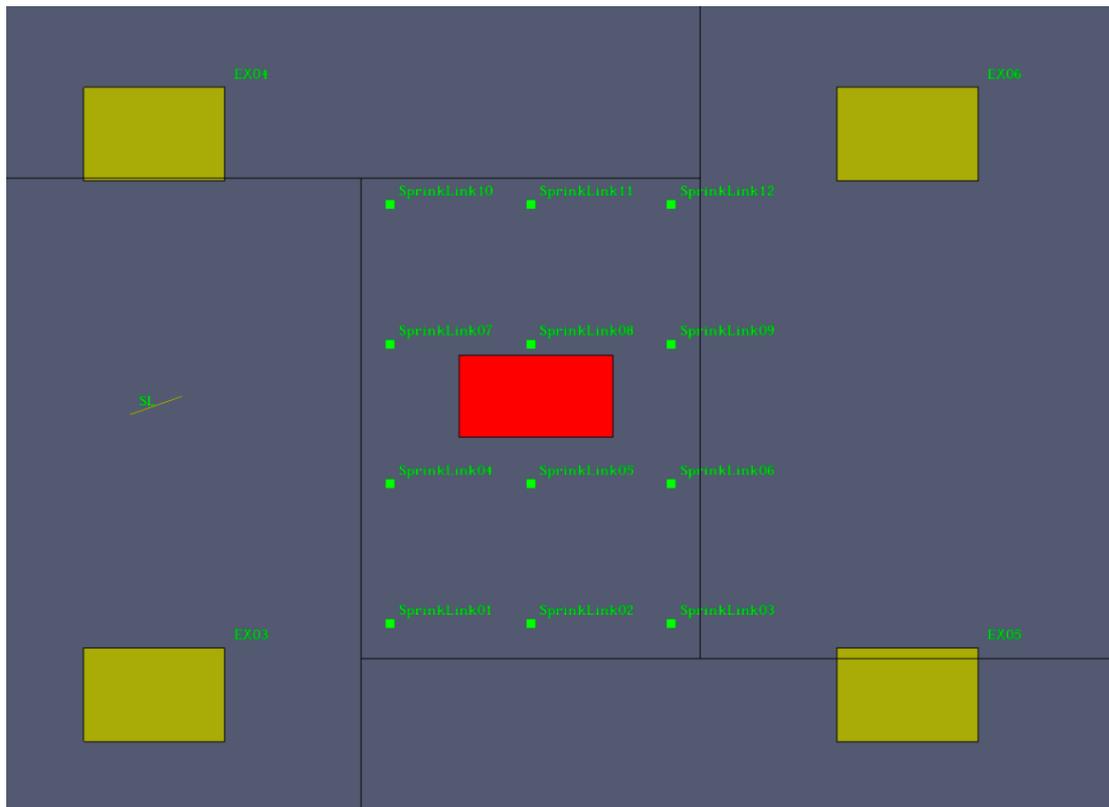


Figure 34. Top-down view of the sprinkler distribution in relation to the simulated fire area (moderate growth rate)

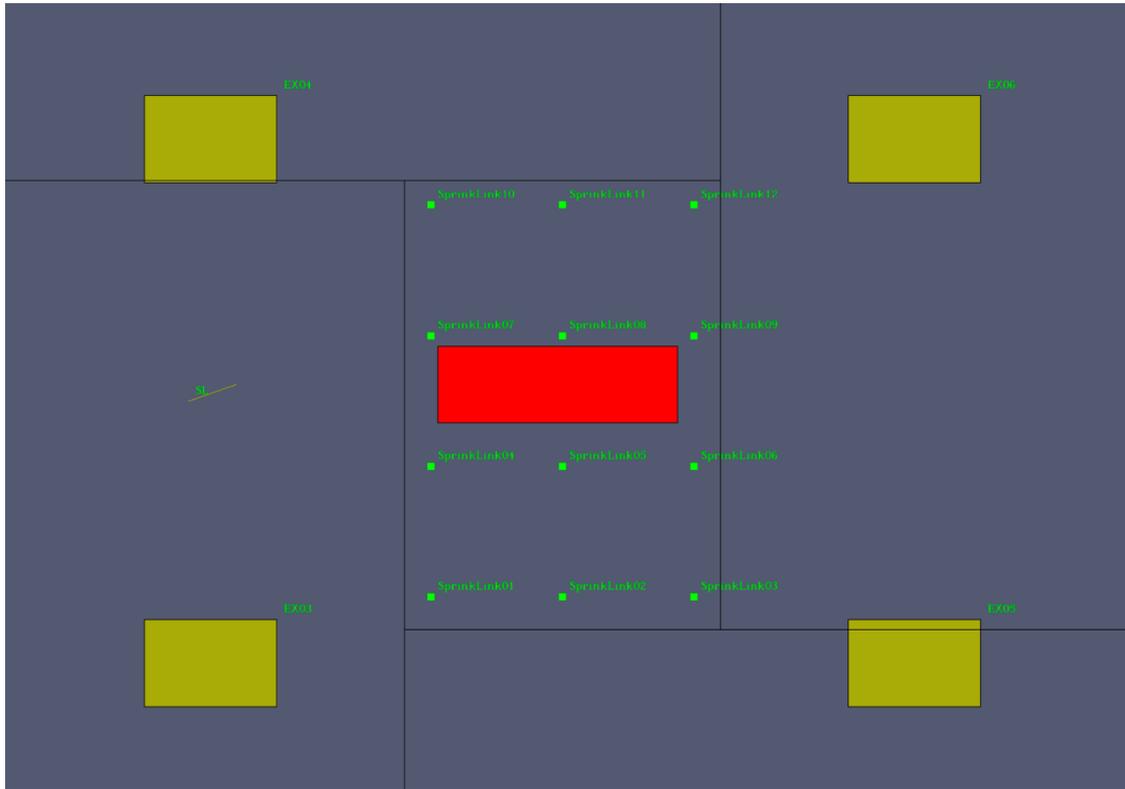


Figure 35. Top-down view of the sprinkler distribution in relation to the simulated fire area (ultra-fast growth rate)

Case 1:

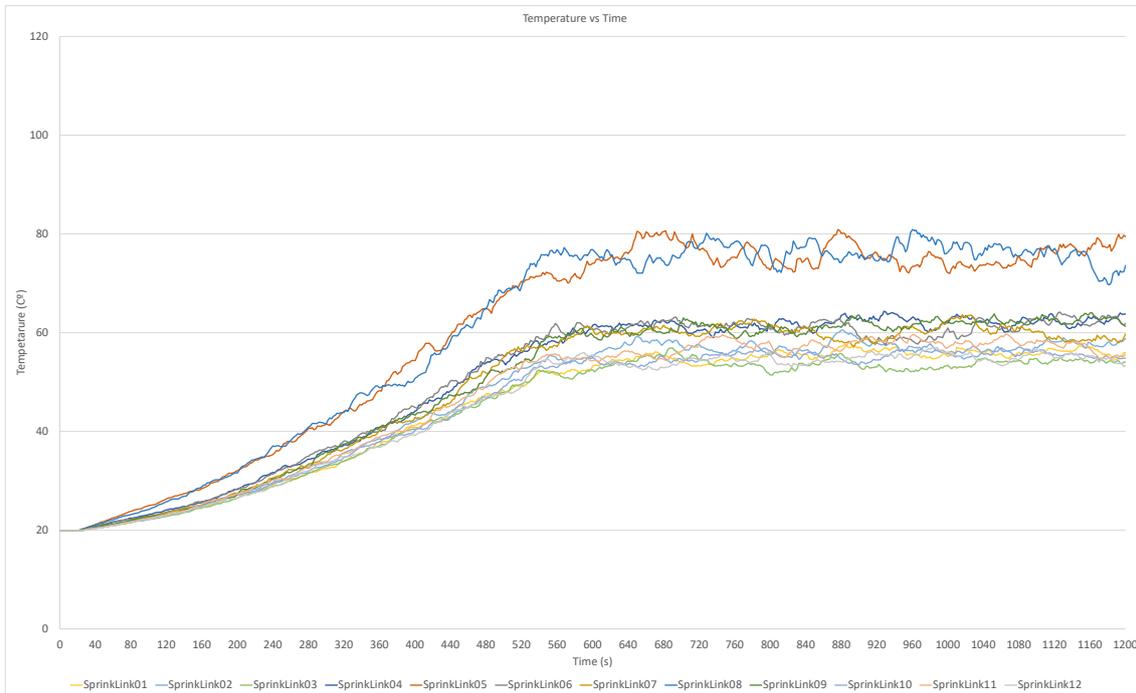


Figure 36. Sprinklers temperature vs time in Case 1

Activation time 1st sprinkler (Sprinkler08): 530s

Sprinklers activated: 8 and 5

(Figure 36) In this case, the first sprinkler to activate does so at 530 seconds. Only the activation of two sprinklers is required to control the temperature.

It's noticeable that the remaining sprinklers consistently maintain temperatures between 50°C and 60°C, while the two that activate fluctuate around 70°C and 80°C.

Case 2:

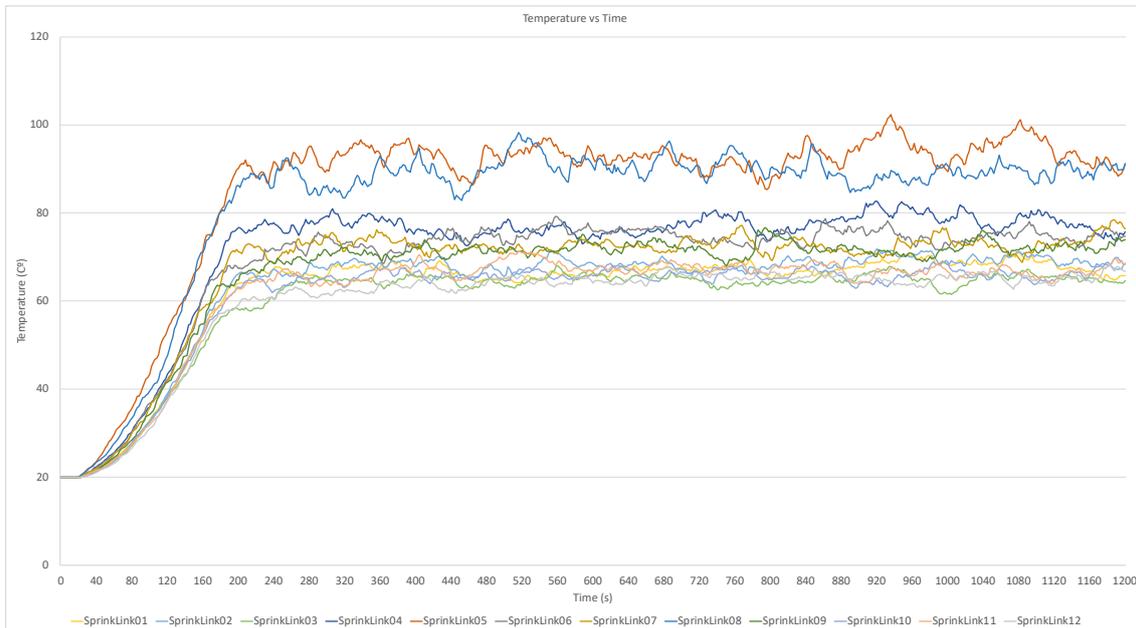


Figure 37. Sprinklers temperature vs time in Case 2

Activation time 1st sprinkler (Sprinkler05): 162s

Sprinklers activated: 4, 5, 6, 7, 8 and 9

(Figure 37) Under the same conditions as the previous section but with an ultra-fast growth rate, the activation time is considerably quicker, as expected, at just 162 seconds. This leads to the activation of six sprinklers.

Among these activated sprinklers, the two closest to the fire's center reach temperatures around 90°C, even exceeding 100°C. Meanwhile, the remaining sprinklers maintain temperatures between 60°C and 80°C.

Case 3:

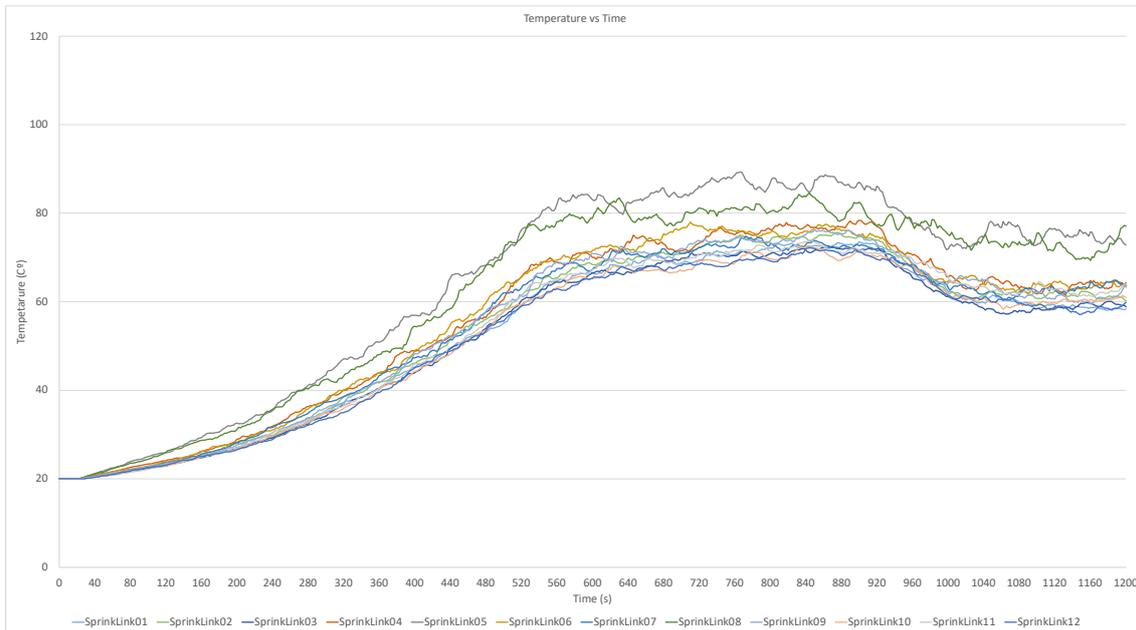


Figure 38. Sprinklers temperature vs time in Case 3

Activation time 1st sprinkler (Sprinkler08): 506s

Sprinklers activated: 2, 4, 5, 6, 7, 8 and 9

(Figure 38) This scenario simulates the same conditions as the first one, with the difference being the presence of smoke curtains to create compartments. In this case, we observe a slightly shorter activation time, at 506 seconds compared to the 530 seconds in the first case. Additionally, a greater number of sprinklers are activated (7) upon reaching the minimum activation temperature.

However, the temperature of the sprinklers is higher in this case. The sprinklers closest to the fire exhibit temperatures around 80°C to 85°C, while the rest range between 70°C and 80°C. Notably, these temperatures show a slight continuous increase instead of remaining stable, as in the first case.

A notable observation from the graph is that upon opening the smoke vents at the 900-second mark, there is a reduction in temperature across all sprinklers. This reduction stabilizes the temperatures once again, aligning more closely with those observed in the first case.

Case 4:

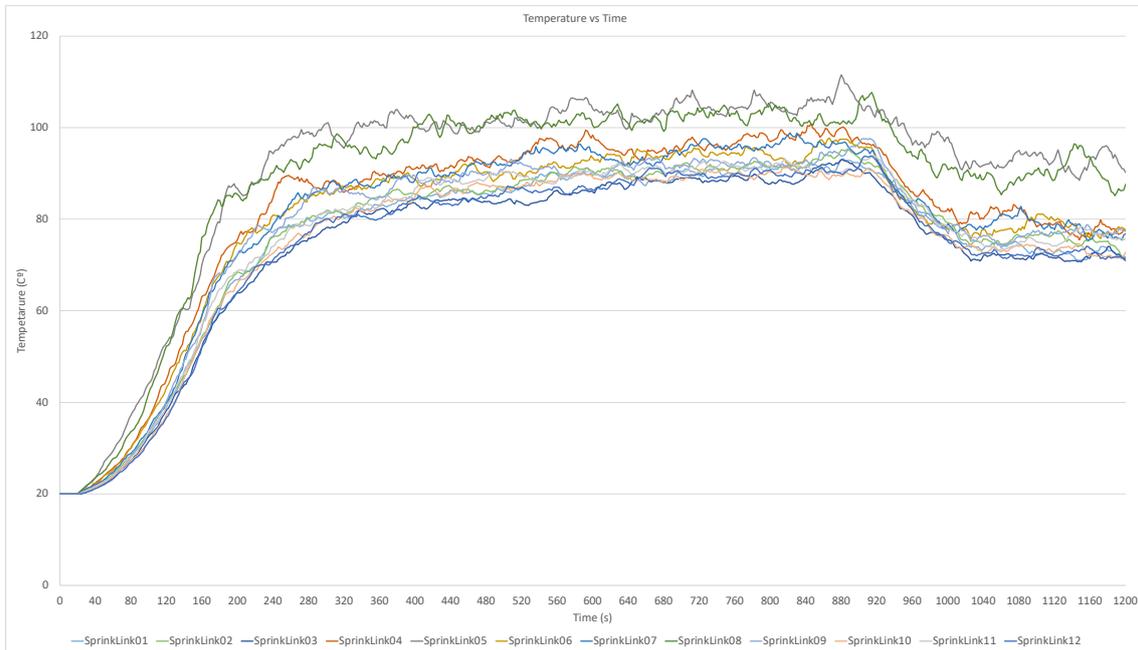


Figure 39. Sprinklers temperature vs time in Case 4

Activation time 1st sprinkler (Sprinkler08): 160s

Sprinklers activated: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12

(Figure 39) A similar situation occurs in this case as in the previous one. This scenario is comparable to the one in case 2, and like the previous case, more sprinklers are activated, all twelve in this instance. The activation of the first sprinkler is slightly quicker, but there's minimal difference since in both cases, the temperature rapidly increases.

The temperature reached by the sprinklers is also higher. Those near the source reach around 105°C, while the others range between 80°C and 100°C. It's evident that the temperature of the latter group increases over time until the activation of the SCTEH.

After the SCTEH activation beyond the anticipated 15 minutes, temperatures decrease and stabilize once more, aligning with those observed in case 2, as seen in the previous scenario.

Case 5:

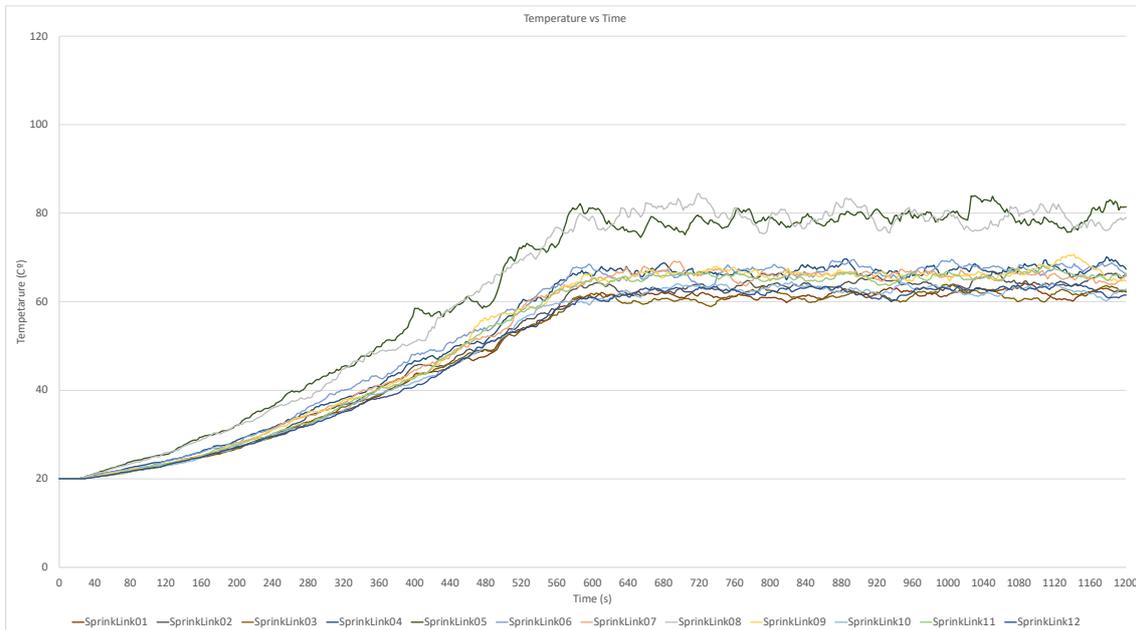


Figure 40. Sprinklers temperature vs time in Case 5

Activation time 1st sprinkler (Sprinkler08): 550s

Sprinklers activated: 5 and 8

(Figure 40) In this scenario, similar to the first one, only two sprinklers are activated. The first sprinkler activates at 550 seconds, which is even later than in the previous case.

The temperature maintained by the activated sprinklers is around 80°C, while the rest range between 60°C for the more distant ones and 67°C for the closer ones.

Case 6:

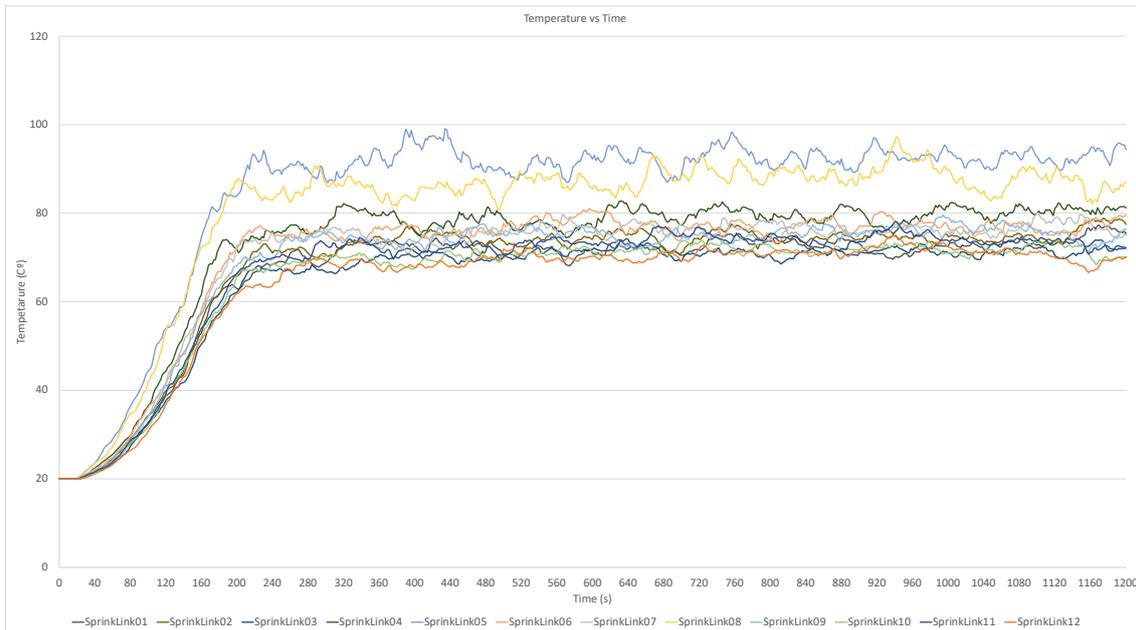


Figure 41. Sprinklers temperature vs time in Case 6

Activation time 1st sprinkler (Sprinkler08): 160s

Sprinklers activated: 1, 2, 4, 5, 6, 7, 8, 9, 11 and 12

(Figure 41) In this case, similar to the others with an ultra-fast growth rate, the first sprinkler activates at 160 seconds. Again, more sprinklers (10) are activated compared to the second scenario, where no curtains were present, though fewer than in the fourth scenario.

Temperatures fluctuate considerably and range between 80°C and 100°C for the nearest sprinklers, while the rest are between 70°C and 80°C, with values very similar to those observed in the second case.

Case 7:

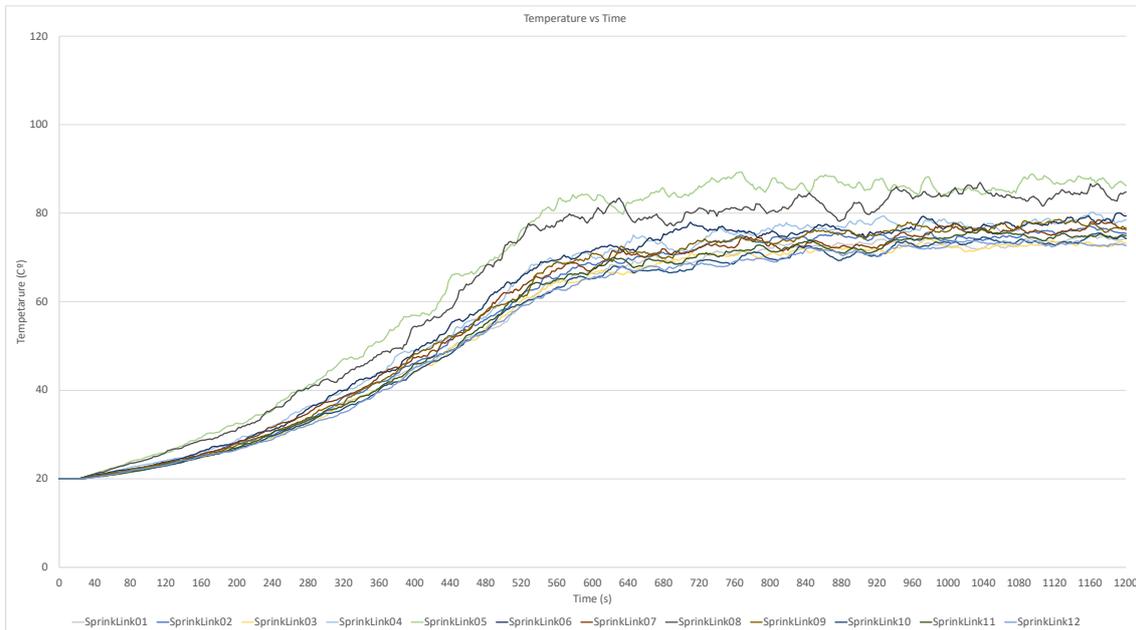


Figure 42. Sprinklers temperature vs time in Case 7

Activation time 1st sprinkler (Sprinkler08): 516s

Sprinklers activated: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11

(Figure 42) The activation time of the first sprinkler remains around the same time, at 516 seconds in this case. Unlike the previous cases, in this one, nearly all the sprinklers (11) are activated.

The temperature for the most affected sprinklers ranges between 80°C and 90°C, while the temperature for the rest stabilizes between 70°C and 80°C.

Case 8:

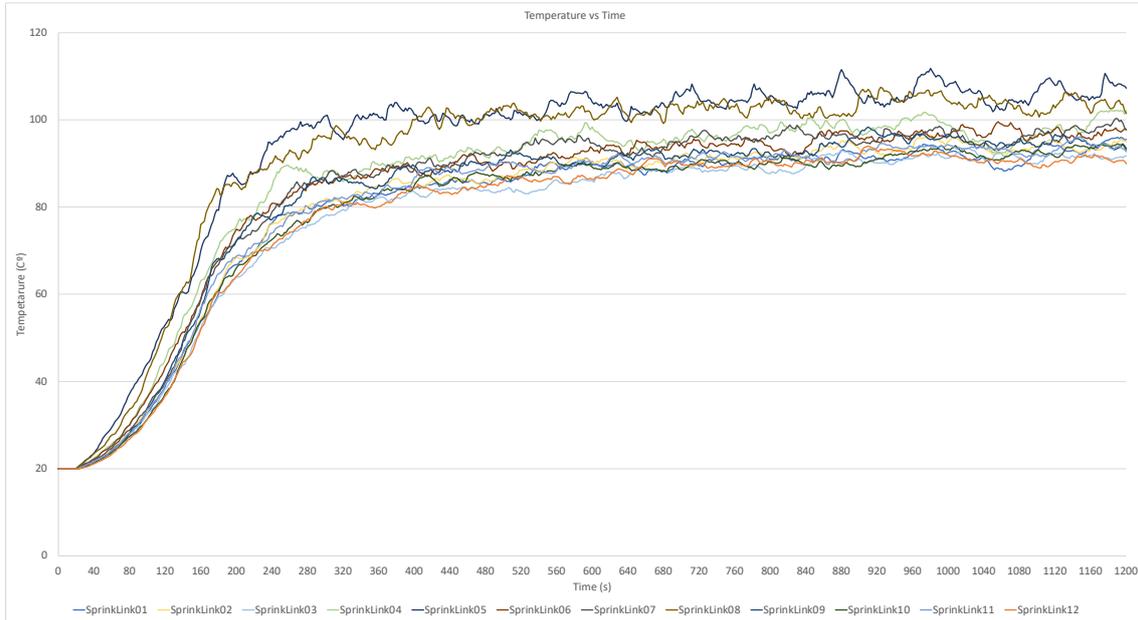


Figure 43. Sprinklers temperature vs time in Case 8

Activation time 1st sprinkler (Sprinkler08): 160s

Sprinklers activated: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12

(Figure 43) The activation time remains at 160 seconds, and once again, all the sprinklers (12) are activated.

In this case, the sprinklers with the highest temperature range between 100°C and 110°C, while the temperature of the rest falls between 90°C and 100°C.

4.3.2.1 Summary of the results

Case	1st Sprinkler Activation Time	Number of Activated Sprinklers	Temperature Range for Activated Sprinklers	Temperature Range for Rest of Sprinklers
2	162s	6	90-100°C	60-80°C
4	160s	12	80-100°C	80-100°C
6	160s	10	80-100°C	70-80°C
8	160s	12	100-110°C	90-100°C

Table 17. Sprinklers activation and temperatures in mediultra-fastm growth rate

Case	1st Sprinkler Activation Time	Number of Activated Sprinklers	Temperature Range for Activated Sprinklers	Temperature Range for Rest of Sprinklers
1	530s	2	70-80°C	50-60°C
3	506s	7	80-85°C	70-80°C
5	550s	2	70-80°C	60-67°C
7	516s	11	80-90°C	70-80°C

Table 18. Sprinklers activation and temperatures in medium growth rate

It can be observed that, firstly, in cases of medium growth compared to ultra-fast growth, the number of required sprinklers to effectively control the fire is significantly higher. This is attributed to the fact that, as evident from the attained temperatures, they are also notably higher in the latter scenario.

A similar pattern emerges for scenarios without curtains as opposed to those with curtains. In instances where smoke reservoirs exist, the temperatures recorded in this zone are higher, leading to the activation of a greater number of sprinklers.

When considering the "Automatic after detection + 60s delay" approach, it is evident for both fire types that a reduced number of sprinklers is necessary. Additionally, the temperatures reached are lower. This trend is particularly pronounced in medium fire growth scenarios, where the outcomes closely resemble those where curtains are not present.

Lastly, it is observed that the highest temperatures are recorded in scenarios employing a 180°C thermal detector. However, this temperature is not achieved largely due to the substantial ceiling height, the influence of sprinklers, and subsequently, it does not trigger the activation of the SCTEH systems.

4.3.3 Smoke reservoirs filling time

As stipulated in the UNE 23585 standard, for the SCTEH of a fire sector that utilizes air from an adjacent reservoir to function properly, that reservoir must be smoke-free.

In the conducted simulations, two different scenarios have been explored regarding this requirement. One scenario involves no curtains (Figure 44) and therefore no smoke reservoirs, while the other includes reservoirs.

Case	Filling Time of Smoke Reservoirs
1	No curtains
2	No curtains
3	260s
4	130s
5	No spillage
6	No spillage
7	250s
8	160s

Table 19. Filling Time of Smoke Reservoirs

Considering the activation time of the SCTEH in each case, the following observations can be made:

In both Case 3 and Case 4, when the smoke control systems are activated at the 15-minute mark, the adjacent reservoirs will have been filling with smoke starting at 4 minutes and 20 seconds and 2 minutes and 10 seconds, respectively. Consequently, the effectiveness of the systems cannot be guaranteed. (Figure 45)

On the other hand, in Case 5 and Case 6, the reservoirs do not become filled, allowing the utilization of air from the adjacent reservoirs. (Figure 46)

In the last two scenarios where a thermal link of 182°C is positioned beneath the smoke vents, smoke begins to spill into the adjacent reservoirs at 250 and 160 seconds, respectively. However, the SCTEH are never activated at any point during the simulation. (Figure 45)

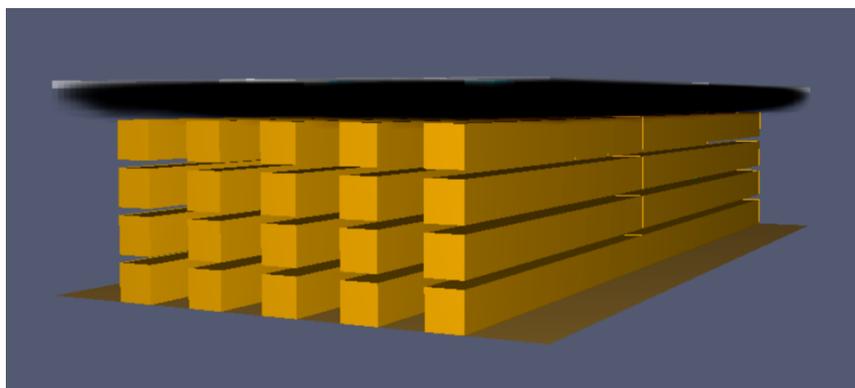


Figure 44. Smoke distribution with no curtains. Scenarios 1 and 2.

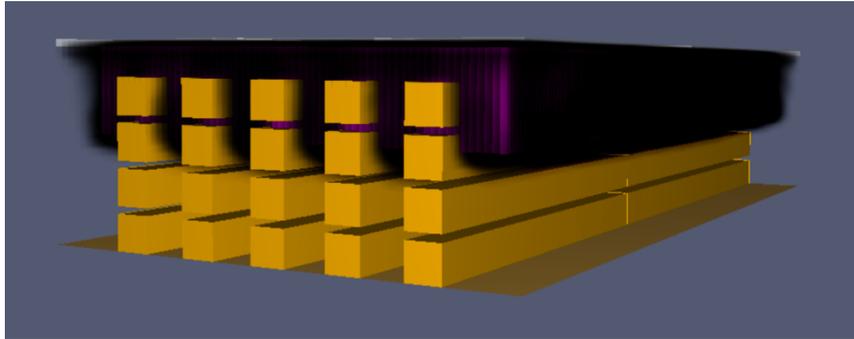


Figure 45. Smoke spillage over curtains. Scenarios 3, 4, 7 and 8.

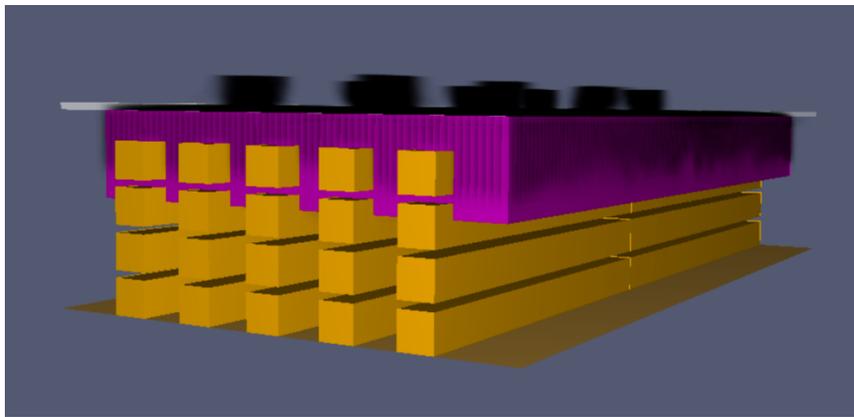


Figure 46. No smoke spillage over curtains and smoke evacuation through vents. Scenarios 5 and 6.

4.3.4 Mass of smoke evacuated through the exhaust vents

Simulation	Smoke Mass (Kg)	Time with open vents (s)
Case 1	14.021	300
Case 2	15.995	300
Case 3	30.385	300
Case 4	34.748	300
Case 5	85.029	1145
Case 6	111.687	1178
Case 7	-	0
Case 8	-	0

Table 20. Total smoke mass evacuated in each scenario

In the first two scenarios, where smoke curtains have not been used, the total amount of evacuated smoke is significantly lower compared to the other scenarios. For a more accurate comparison, cases 3 and 4 are analyzed, as they occur under identical conditions and with the same opening time for the evacuation systems. In this situation, the amount of evacuated smoke is doubled. This is easily understood by considering the presence of

a smoke reservoir in cases 2 and 4, where all the smoke accumulates, facilitating its extraction in larger quantities. In contrast, in cases 1 and 2, where smoke curtains are not used and the smoke disperses across the roof of the logistics warehouse, achieving the same evacuation amount through the extractors located in a specific area becomes more challenging.

Then, in cases 5 and 6, it can be observed that significantly larger amounts of smoke are expelled through the evacuation systems. This result can be understood by considering that the early activation time of the ESFR systems allows for preventing smoke accumulation and achieving nearly constant smoke evacuation while it is generated.

5 Conclusions

Having carried out this project and conducted the relevant simulations as proposed, certain conclusions can be drawn and new questions can be raised for future development.

The field of fire protection measures has witnessed substantial growth, refinement, evolution, and completion over time, with an abundance of information, regulations, and guidelines available on their utilization and application under various circumstances. Despite variations across different countries' regulations, they are complementary, allowing mutual learning and progress.

Nevertheless, not all conceivable scenarios are encompassed by existing regulations, and there is still room for improvement remains, particularly within specific domains like fire incidents in logistic warehouses. The advent of software tools like Fire Dynamics Simulator has enabled significant advancements and enhancements in understanding and addressing fire-related challenges.

5.1 Simulation results

In analyzing the outcomes of the simulations, we observe how the growth rate of the fire, whether medium or ultra-fast, is distinctly reflected in the heat release rate graphs. Notably, values are higher and achieved more rapidly in the ultra-fast growth cases.

5.1.1 Fire curtains

Regarding the use of smoke curtains, a comparison between cases 1 and 2 with cases 3 and 4, where the early activation of the ESFR system occurs 15 minutes after the fire origin, demonstrates that the absence of curtains results in lower maximum temperatures reached in all the sprinklers. This discrepancy arises from the dispersion of hot gases in the former scenario versus smoke accumulation in the latter, causing temperature to rise until SCTEH activation, then normalizing and approaching values akin to the other scenario.

Furthermore, the application of curtains in scenarios with delayed SCTEH activation can pose challenges to the system, as smoke overflows into adjacent reservoirs. One potential advantage of curtains is that smoke exposure to the rest of the warehouse is minimized, albeit in a thinner layer.

This prompts us to question the actual utility of using these curtains and perhaps consider exploring new scenarios to fine-tune this response further.

5.1.2 Sprinklers

It is evident that, firstly, in medium growth scenarios compared to ultra-fast growth, a significantly higher number of sprinklers are required to control the fire. This demand comes from the higher temperatures attained in the latter case, as reflected by the results. Similarly, scenarios with and without curtains exhibit analogous trends; instances with smoke reservoirs experience elevated temperatures in this region, triggering the activation of more sprinklers.

In the case of an automatic activation after detection and a 60 seconds delay, both fire types necessitate fewer sprinklers, accompanied by lower temperatures. This trend is particularly pronounced in medium fire growth scenarios, where the outcomes closely resemble those without curtains.

Lastly, the highest temperatures are reached in scenarios using a 180°C thermal detector, a temperature that is not achieved due to the substantial ceiling height, the impact of sprinklers, and consequently, preventing the SCTEH systems' activation.

5.2 Final insights

In conclusion, the activation of SCTEH systems in tall logistic warehouse scenarios with ESFR sprinkler systems is crucial. The results suggest that manual activation, historically proposed, may not be the most effective solution. Similarly, individual activation of extruders via high-temperature thermal sensors does not appear to yield improved outcomes. Therefore, the evidence points towards automatic activation after flow detection or sprinkler activation with a 60-second delay as the more effective approach. This finding underscores the potential of automated responses in optimizing fire safety outcomes in these complex settings.

ANEX A. Alignment with the SDG

This project aligns with several of the United Nations' Sustainable Development Goals (SDGs) (United Nations). Specifically, it aligns with:

SDG 3: Good Health and Well-being (Figure 47): Ensuring the safety and health of people on the work environment of warehouse facilities by studying the interaction between ESFR and smoke vents and assessing their effectiveness in controlling fires to reduce damages and risks.



Figure 47. SDG 3

SDG 9: Industry, Innovation and Infrastructure (Figure 48): Using advanced technologies such as CFD simulations to provide more reliable results, in this way the project contributes to the development of innovative solutions for fire protection in industrial warehouses and other large compartments.



Figure 48. SDG 9

SDG 11: Sustainable Cities and Communities (Figure 49): The main goal of this project is to reduce fire propagations and help to create the best configuration of current tools to control fire produce specially in warehouses which leads to smokes and contamination, and therefore the project contributes to ensuring the safety and well-being of people, and the environment both in industrial and urban areas.



Figure 49. SDG 11

SDG 13: Climate Action (Figure 50): By assessing the effectiveness of fire protection systems in industrial warehouses, the project contributes to reducing the risk of fire-related emissions and greenhouse gases, which will help mitigate climate change.



Figure 50. SDG 13

ANEX B. Characterization of the products released in the combustion reaction

Considering that the industrial warehouse is a large and adequately ventilated space, the use of the mixture fraction combustion model is proposed, which is the most suitable for this type of fire engineering studies.

It is suggested to employ the presence of polyurethane foam GM37 to characterize combustion, which is commonly used as a conservative value in warehouses without defined products.

Parameter	Polyurethane Foam GM37
Formulation	$\text{CH}_{1,2}\text{O}_{0,2}\text{N}_{0,08}$
Heat of Combustion	28.000 kJ/kg
CO Production	0,024 kg/kg
Soot Production	0,113 kg/kg

Table 21. Physicochemical data of the polyurethane foam.

The data has been obtained from Table A.39 of the SFPE Handbook of Fire Protection Engineering (5th edition) (SFPE, 2016).

ANEX C. FM Datasheet 2-0

This FM Global property loss prevention data sheet outlines suggestions for setting up automatic sprinkler systems, which include both the automatic sprinklers themselves and the components that support them above ground. The document offers guidance on various aspects, including the components involved in a sprinkler system, how to secure and support these components, the speed at which sprinklers react to a fire, how the sprinkler discharge is distributed within a fire-affected area, the documentation needed for an FM Global plan review, and the information necessary for an FM Global acceptance test.

In this section, the key aspects for this project are succinctly covered, with a particular focus on the diagrams (Figure 51) that provide a concise overview and clear guidance to facilitate its implementation.

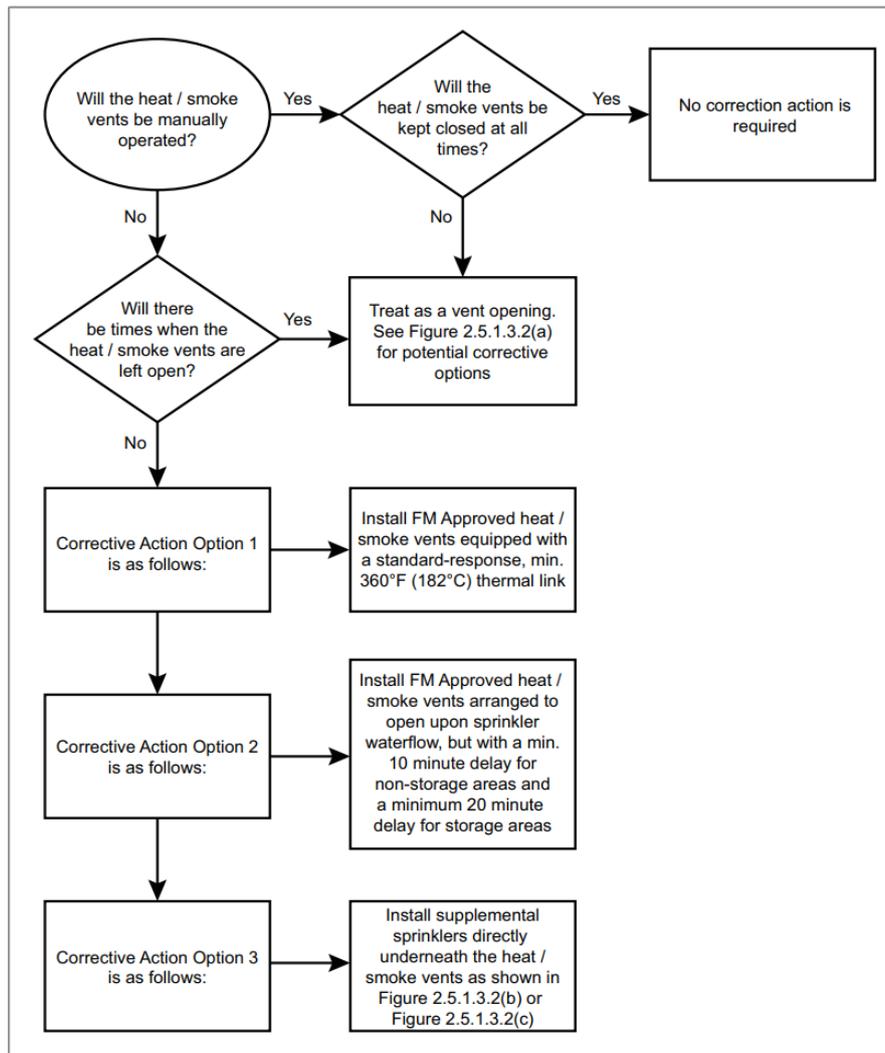


Figure 51. Flowchart for potential recommendations when vents or smoke vents must be installed (FM Global, 2021)

Bibliografía

Alternatives in Engineering, Inc. 2020. aifire. [Online] 11 17, 2020. <https://aifire.com/common-fire-risks-hazards-warehouse-distribution-center/#:~:text=In%20the%20NFPA%20study%2C%20from,for%2038%25%20of%20civilian%20injuries.https://aifire.com/common-fire-risks-hazards-warehouse-distribution-center/#:~:text=In%20the%20N>.

BOE. 2014. REGLAMENTO DE SEGURIDAD CONTRA INCENDIOS EN LOS ESTABLECIMIENTOS INDUSTRIALES. [Online] 12 17, 2014. [Cited: 02 10, 2023.] <https://www.boe.es/buscar/act.php?id=BOE-A-2004-21216>.

Campbell, Richard. 2022. National Fire Protection Association. [Online] July 2022. <https://www.nfpa.org/>.

COLT. 2004. esi.info. [Online] 2004. https://cms.esi.info/Media/documents/Colt_singlestorey_ML.pdf.

cottes. 2020. cottesgroup. [Online] 10 27, 2020. <https://www.cottesgroup.com/blog/exutorios-eficiencia-energetica>.

Cuerpo de Bomberos de la Comunidad de Madrid. 2021. Comunidad de Madrid. [Online] 2021. <https://www.comunidad.madrid/>.

Day-Impex Ltd. day-impex.co.uk. [Online] <https://www.day-impex.co.uk/fire/>.

Dirección General de Emergencias y Protección civil. 2021. Portal web del Ayuntamiento de Madrid. [Online] Septiembre 23, 2021. madrid.es.

—. 202. Portal web del Ayuntamiento de Madrid. [Online] 202. madrid.es.

ESFR Sprinklers: A Strong Line of Defense in Storage Applications. **Quick Response Fire Supply. 2022.** 406, 2022, QRFS.

firewize. firewize.com. [Online] <https://firewize.com/learn>.

FM Global. 2021. 2-0 INSTALLATION GUIDELINES FOR AUTOMATIC SPRINKLERS. [Online] 10 2021. <https://www.fmglobal.com/research-and-resources/fm-global-data-sheets>.

MINISTERIO DE INDUSTRIA, COMERCIO Y TURISMO. 2022. [Online] Septiembre 15, 2022. <file:///Users/gusterrerfos/Documents/TFM/Bibliografi%CC%81a/Texto%20del%20Proyecto%20de%20Real%20Decreto.pdf>.

NFPA. 2021. NFPA 1. [Online] 2021. <https://link.nfpa.org/free-access/publications/1/2021>.

-
- . **2022.** NFPA 10. [Online] 2022. <https://link.nfpa.org/free-access/publications/10/2022>.
 - . **2022.** NFPA 13. [Online] 2022. <https://link.nfpa.org/free-access/publications/13/2022>.
 - . **2021.** NFPA 204. [Online] 2021. <https://link.nfpa.org/free-access/publications/204/2021>.
 - . **2021.** NFPA 92. [Online] 2021. <https://link.nfpa.org/free-access/publications/92/2021>.

Normalización Española. 2017. UNE 23 585:2017. [Online] 11 22, 2017. [Cited: 02 10, 2023.] <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0059303>.

—. **2021.** UNE-EN 12845:2016. [Online] Enero 2021. <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0059303>.

—. **2017.** UNE-EN ISO 16733-1. [Online] 2017. <https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0059484>.

SFPE. 2016. *SFPE Handbook of Fire Protection Engineering*. s.l. : Springer, 2016.

TRGET FIRE PROTECTION. target-fire.co.uk. [Online] <https://www.target-fire.co.uk/resource-centre/different-types-fires-start/>.

Unespa. 2020-2021. unespa.es. [Online] 2020-2021. <https://www.unespa.es/main-files/uploads/2022/02/Fuego-Los-incendios-asegurados-2020-2021-FINAL.pdf>.

United Nations. Sustainable Development Goals. [Online] Naciones Unidas. <https://sdgs.un.org/es/goals>.

