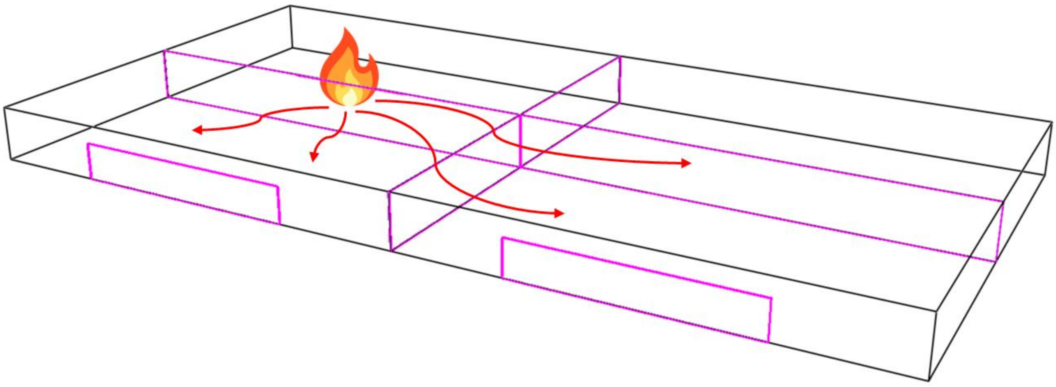
# Traveling localized fire in large compartments



*7LS1M0 Master project*
*Fire Safety Engineering (FSE)*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# List of Abbreviations

| Abbreviation | Definition |
|---|---|
| BPS | Building Physics and Services |
| CFAST | Consolidated Model of Fire and Smoke Transport |
| HRR | Heat Release Rate |
| ISO | International Organization for Standardization |
| NIPV | Nederlands Instituut Publieke Veiligheid |
| RHR | Rate of Heat Release |
| SFC | Structural Fire Compartment |
| SHEV | Smoke and Heat Exhaust Ventilation |
| $T_l$ | Lower layer temperature |
| $T_u$ | Upper layer temperature |

# 1 INTRODUCTION

Modern architectural trends have led to the preference for large open-floor plan spaces in building design. However, traditional engineering methods for structural fire safety, which assume uniform burning and homogeneous temperature conditions throughout a compartment, are challenged by these contemporary designs. Accidental fires in large, open-plan compartments have revealed a non-uniform fire behaviour, characterized by the movement of flames across floor plates, burning over limited areas at any given time. This phenomenon, known as "travelling fires", deviates from the assumptions of traditional fire models such as the standard fire curve (ISO 834) and the Eurocode 1 (EC1) parametric fire model (Nan Z. , et al., 2022).

The concept of "travelling fire" was introduced to describe fires that burn locally and spread within large compartments, as global flashover does not always occur in these spaces. This type of fire behaviour raises concerns about local heating and cooling, which can induce localized failures of key structural components. These failures can lead to structural collapses, as was observed in the World Trade Centre (WTC) fires. Additionally, the unpredictable nature of travelling fires complicates safe evacuation and increases the risk to building occupants (Nan Z. , et al., 2023).

In the realm of traveling fires, two distinct phenomena stand out: traveling compartment fires and traveling localized fires. A traveling compartment fire ignites within a structure, spreading from one enclosed space to another. These compartments, typically rooms or enclosed areas within a building, provide pathways for the fire to escalate its danger. As flames leap from compartment to compartment, they introduce fresh fuel sources, escalating the risk and potentially blocking escape routes. This type of fire poses significant hazards, particularly in densely built environments where containment becomes challenging.

On the other hand, a traveling localized fire paints a different picture. Here, the fire advances through a specific area or zone without necessarily extending its reach to neighbouring spaces. Imagine a scenario in a forest where a traveling localized fire burns through a section of trees and underbrush, its influence contained within that defined space. Despite its intensity, its impact is confined, earning it the term "localized".

Comparing a traveling localized fire with a uniformly distributed fire load over the surface sheds light on their differences. Uniformly distributed fire load refers to a scenario where combustible material is evenly spread across the surface area. In such cases, the fire may not exhibit the same characteristics as a traveling fire because the fuel is evenly distributed rather than concentrated in specific areas. This even distribution can mitigate the fire's ability to spread rapidly and extensively. In other words, in the case of a localized fire load, there's a hopeful note that it won't escalate into a traveling fire. This suggests that if the fire remains localized, it may be easier to control and contain compared to one that spreads extensively.

## 1.1 PROBLEM DESCRIPTION AND RESEARCH QUESTIONS

While extensive literature addresses traveling compartment fires in various settings, including industrial facilities, a critical gap persists in understanding and addressing the unique challenges posed by localized traveling fires within these environments. This disparity underscores the urgent need for comprehensive scientific analysis to develop methodologies tailored to these distinct fire behaviours prevalent in large compartments. Understanding and accurately modelling such non-uniform fire phenomena are imperative for ensuring the safety of both occupants and structures within large compartments. While understanding fire development is crucial, it represents only part of the overall challenge. Equally essential is the ability to predict how these fires can be effectively controlled and extinguished.

### Research Goal

The central aim of this research is to investigate the consequences of a traveling fire, both spreading and extinguishing from the axis of fire origin for building occupants and constructions. This overarching goal is supported by a set of sub-questions designed to provide clear and independent insights into various aspects of the phenomenon under study.

### Research Question

The primary research question guiding this study is:

> ***"What are the consequences when taking into account both the fire development and the extinguishing process from the axis of fire origin for both building users and constructions, exposed to a developing fire in a large compartment?"***

### Sub-Questions

1. How does the extinguishing process influence the event of flashover to a compartment fire?
   *(NIPV fire characteristics)*
2. Is it possible to prevent flashover in case of localized fire loads?
   *(NIPV fire and building characteristics)*
3. Is it possible to prevent flashover in case of a uniformly distributed fire load?
   *(NIPV fire and building characteristics)*
4. What are the consequences of a localized traveling fire for building occupants and constructions, in case of localized fire loads?
   *(NIPV fire and human characteristics)*
5. What are the consequences of a localized traveling fire for building occupants and constructions, in case of a uniformly distributed fire load?
   *(NIPV fire and human characteristics)*

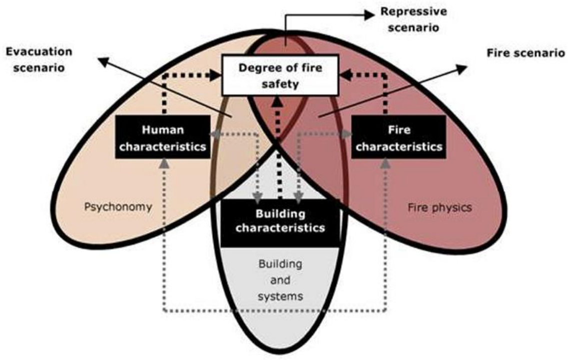


Figure 1: Summary of characteristics (Hagen & Witloks, 2014)

## 1.2 Objectives and relevance

The study aims to determine the maximum threshold values for fire characteristics, particularly focusing on fire loads, to predict the occurrence of a traveling localized fire. Additionally, it seeks to assess the thermal impacts on structures and building occupants in comparison to fires post-flashover with equivalent fire load densities.

### Scientific Relevance of the Research

The relevance of this research is underscored by its scientific significance. It addresses the evolving architectural trends towards large open-floor plan spaces and the resultant challenges for traditional engineering methods in ensuring structural fire safety within industrial settings. These challenges necessitate a scientific study to bridge the gap between architectural preferences and established safety protocols.

#### BPS Relevance of the Research

Furthermore, the research question and objectives directly contribute to the field of Building Physics and Services (BPS). Understanding the behaviour of fires in large, open-floor plan spaces is crucial for designing effective fire protection systems, such as smoke control systems and fire-resistant materials. By advancing fire safety engineering practices, this research ensures that buildings are designed to protect occupants and minimize property damage in the event of a fire.

Additionally, large, open-floor plan spaces are prevalent in various building types, particularly those used for assembly or industrial functions. Understanding how fire behaves in these spaces is essential for ensuring occupant comfort and well-being. Effective fire safety measures not only protect occupants during emergencies but also contribute to a sense of security and confidence in the built environment.

## 1.3 Scope

The scope of this research encompasses a comprehensive investigation into the consequences of considering the natural extinguishing process from the axis of fire origin for constructions and building occupants exposed to a traveling localized fire in large compartments. The study will focus on various aspects related to fire behaviour, thermal impacts, visibility, boundary conditions, building characteristics, and the effectiveness of fire protection systems.

It is important to acknowledge certain limitations within the scope of this research. The study will primarily focus on theoretical analyses and numerical simulations to investigate the behaviour of localized traveling fires. Experimental validation is limited due to practical constraints and resource considerations. Additionally, the scope of the research may not encompass all possible variations and scenarios encountered in real-world large compartments with low fire load densities.

# 2 Methodology / Research design

This chapter outlines the methodological framework utilized to address the primary research question and its associated sub-questions.

## 2.1 Literature study

A comprehensive literature review was conducted using the term "traveling (localized) fire". Despite extensive search efforts, limited relevant literature was found, which underscored the necessity of this study. The primary databases searched included academic journals and technical reports related to fire safety and modelling.

## 2.2 Simulation setup

The simulations were conducted using the Consolidated Model of Fire and Smoke Transport (CFAST) version 7 (Peacock, Reneke, & Forney, 2023). This software is employed for fire and smoke transport simulations, offering a detailed and accurate model of fire dynamics within the compartment. Microsoft Excel was also utilized for inputting and analysing data, specifically for calculating the equivalent fire duration and processing results from the CFAST simulations.

### 2.2.1 CASE STUDY

The physical context for the simulations is an industrial compartment with a production function, featuring the following characteristics:

- Dimensions: 100 meters (length) x 50 meters (width) x 6 meters (height). This large space was selected to represent typical industrial environments where traveling fires might pose significant risks.
- Overhead Doors: Two groups, each with dimensions of 25 meters (width) x 4 meters (height). The inclusion of large overhead doors simulates real-world scenarios where such doors are common and can influence fire dynamics and smoke movement.
- Compartments: To accommodate the simulation requirements of CFAST, the compartment was partitioned into four zones within the software. This segmentation mirrors the physical layout of the compartment. CFAST necessitates smaller compartments for effective simulation, allowing for a detailed analysis of fire spread and its impact on various sections of the large industrial building.

The building layout and compartmentalization are detailed in accompanying diagrams, shown in Figure 2 and 3 below.

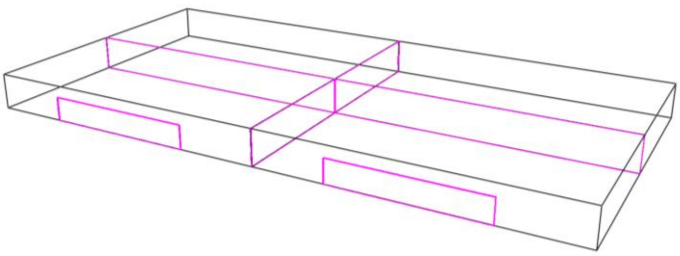

FIGURE 2: 3D LAYOUT OF THE INDUSTRIAL COMPARTMENT

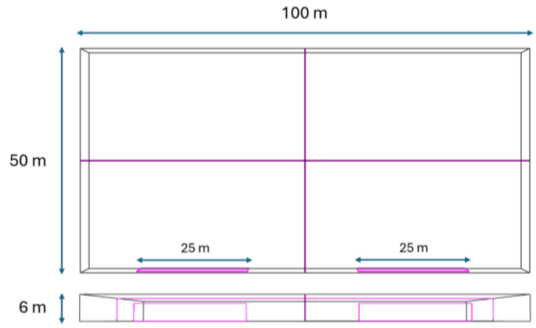


FIGURE 3: DIMENSIONS INDUSTRIAL COMPARTMENT

### 2.2.2 BASE SIMULATION SCENARIOS

To comprehensively analyse the impact of different fire load configurations, five different base scenarios were simulated using CFAST: one with a uniformly distributed fire load and four with localized fire loads. For comparison, one scenario with a uniformly distributed fire load was also simulated using Ozone.

#### *2.2.2.1 Situation 1 – Uniformly distributed fire load*

Fires typically have several stages: ignition, growth, fully developed, and decay. The expression $\left(\frac{t}{t_c}\right)^2$, also known as $t^2$, is often used in fire dynamics and represents a simplified model for the growth, pre-flashover phase of a fire. This phase is where the fire size (often measured in terms of heat release rate) increases rapidly. In this fire development model, $t$ is the time elapsed since the fire started and $t_c$ represents a characteristic time that describes how quickly the fire grows, specific to the particular

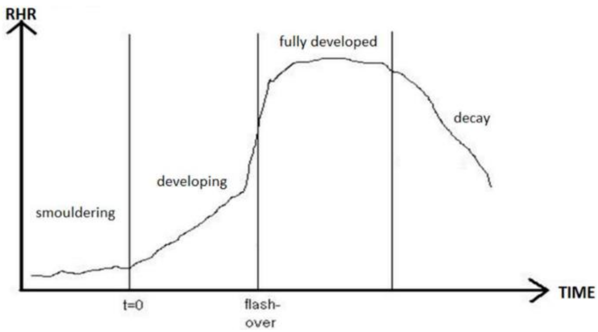


FIGURE 4: STAGES OF A FIRE
(VAN HERPEN, 2. NATURAL FIRES, 2023)

scenario or material being burned. In scenarios with a uniformly distributed fire load, the $t^2$ curve can be used to model fire development. The uniform distribution implies that the fire spread and growth will be even, leading to a predictable increase in HRR over time.

When a fire ignites, it doesn't spread uniformly in all directions. The fire starts at a specific point, which acts as the centre of expansion. From this point, heat and flames move outward. Because heat radiates in all directions from the centre, the spread forms a circular pattern if the fire load in the environment around the fire is uniform, similar to the way ripples spread out when dropping a pebble into a still pond.

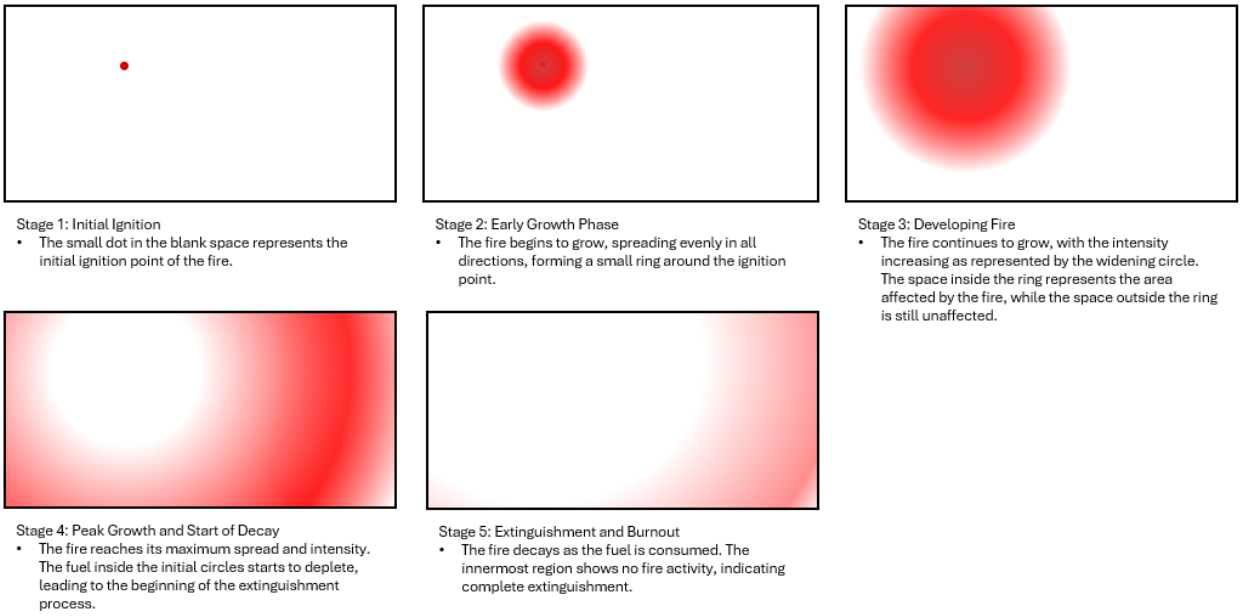


FIGURE 5: FIRE DEVELOPMENT, FROM IGNITION TO EXTINGUISHMENT (L. DOHMEN, 2024)

As the fire spreads outward, it eventually starts to diminish in intensity. Once the fuel at the core is used up, the intensity of the fire decreases. The further you move from the centre of the fire, the cooler it gets because the heat dissipates as it moves outward. This results in a decrease in the fire's intensity with distance from the centre. As the fire spreads, the available fuel in the immediate area gets consumed, leading to a reduction in flame size and heat output. As a result, the fire may begin to self-extinguish as it burns through its fuel supply. The lower the fire load density, the faster the rings follow each other in terms of development and extinguishment.

The expression $t_{burn} - \left(\frac{t}{t_c}\right)^2$ relates to fire extinguishment and is used to model the decay phase of a fire, specifically after the fire has naturally started to burn out. $t_{burn}$ represents the total burn time or the time until which the fire is expected to burn under certain conditions before being extinguished or naturally burning out. The formula subtracts the growing rate of heat release (represented by $\left(\frac{t}{t_c}\right)^2$) from the total burn time to model the decay phase, indicating a decline in the fire's intensity as it consumes available fuel.

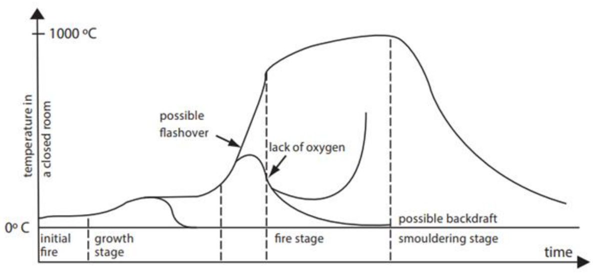


FIGURE 6: FIRE CURVE (HAGEN & WITLOKS, 2014)

## SITUATION 1.1 – CFAST

In this scenario, a uniformly distributed fire load of 300 MJ/m² was applied throughout the compartment. This represents a typical worst-case scenario in fire safety studies, where the fire load is evenly spread across the entire area. For this situation, data from the Excel sheet *"Development of Fire with a Given Fire Load in a Compartment: Uniformly Distributed Fire Load"* was transferred to CFAST to ensure accurate modelling of the fire dynamics under these conditions.

The parameters needed in this Excel Sheet *"Uniformly Distributed Fire Load"* are based on the document *"National Annex to NEN-EN 1991-1-2: Eurocode 1 - Actions on structures"*, focusing on the section *"General actions - Actions on structures exposed to fire"*. The following parameters were used, relevant to the industrial function of the compartment:

- Fire Load Density: For an industrial compartment with a production function, the fire load density is assumed to be 300 MJ/m². This value represents the energy per unit area that can be released in a fire.
- Time Constant for Fire Development: For a production function with small quantities of combustibles, the time constant for fire development is set at 600 seconds, categorized as a slow fire development rate. This reflects the slower ignition and spread of fires in environments with lower combustible material densities.
- Rate of Heat Release Density: The rate of heat release density for the industrial compartment is assumed to be 250 kW/m². This parameter indicates how quickly energy is released from the fire per unit area.
- Combustion Efficiency: The average combustion efficiency is assumed to be 0.8, meaning that 80% of the combustible material's energy is effectively released during combustion.
- Compartment Surface Area: The total surface area of the industrial compartment in the case study is 5000 m², providing a large area for fire spread and smoke movement analysis.

TABLE 1: OVERVIEW PARAMETERS UNIFORMLY DISTRIBUTED FIRE LOAD IN CFAST (NEN-EN 1991-1-2/NB, 2023)

| Parameter | Function of use / Source | Value |
|---|---|---|
| **Fire load density** | Industrial function - production | 300 MJ/m² |
| **Time constant for fire development** | Industrial function - production (small quantities) | 600 seconds (slow) |
| **Rate of Heat Release density** | Industrial function - production (small quantities) | 250 kW/m² |
| **Combustion efficiency** | Average value | 0.8 |
| **Compartment surface area** | Case study industrial compartment - production function | 5000 m² |

## SITUATION 1.2 – OZONE3

Different tools can serve various purposes based on the complexity and specific requirements of a study. For the uniformly distributed situation, Ozone (University of Liege, 2018), a simpler simulation tool, is used alongside CFAST. Ozone's simplicity is ideal for scenarios with uniform distribution, simplifying spatial fire dynamics and efficiently simulating the $t^2$ growth curve. It predicts flashover without the complex details needed in CFAST. The parameters used in Ozone are listed in Table 2 below, identical to those used in CFAST.

**Table 2: Overview parameters uniformly distributed fire load in Ozone**

| Parameter | Value |
|---|---|
| **Compartment geometry** | Rectangular floor with a flat roof, 6 x 100 x 50 m (height x length x depth) |
| **Openings in wall 2** | 2 x 25 m width x 4 meter height |
| **Parameters fire load** | Identical to those used in CFAST, listed in Table 1 above |
| **Danger of fire activation** | 1 |
| **Max fire area** | 5000 m$^2$ |
| **Fire elevation** | 0 m |
| **Fuel height** | 3 m |
| **Analysis strategy** | 2 zones (upper and lower layer) |
| **Initial temperature** | 293 K |
| **Initial pressure** | 101325 Pa |

#### 2.2.2.2 Situation 2 – 4 localized fire loads

In situation 2, four discrete fire loads were used, each with the same specific properties. This scenario simulates localized fires within the compartment, which is a common occurrence in industrial settings. The method for calculating the fire duration and maximum heat release rate is written down below.

- $Total\ fire\ load\ = 300\ MJ/m^2 * 5000\ m^2 = 1{,}500{,}000\ MJ\ (1500\ GJ)$
- $Energy\ Content\ of\ each\ fire\ load = \frac{1500\ GJ}{4\ fire\ loads} = 375\ GJ\ (375{,}000\ MJ)$
- $Density = 250\ kg/m^3\ \ (wood\ stacks)$
- $Combustion\ Value = 19\ MJ/kg$
- $Volume = \frac{375000\ MJ}{250\ kg/m^3 * 19\ MJ/kg} = 79\ m^3$
- $Height\ of\ each\ fire\ load = 3\ meters$
- $Ground\ Area\ of\ each\ fire\ load = \frac{79\ m^3}{3\ m} = 26.32\ m^2 = 5.13\ m\ x\ 5.13\ m$
- $RHR\ Density = 1\ MW/m^2 = 1000\ kW/m^2 = 1000\ kJ/s/m^2 = 1\ MJ/s/m^2$
- $Energy\ Consumption\ Rate = 1\ MJ/s/m^2 * 26.32\ m^2 = 26.32\ MJ/s$
- $Fire\ Duration = \frac{375000\ MJ}{26.32\ MJ/s} = 14250\ sec \approx 4\ uur$
- $Maximum\ Heat\ Release\ Rate\ (HRR) = 1000\ kW/m^2 * 26.32\ m^2 = 26316\ kW$

#### 2.2.2.3 Situation 3 – 8 localized fire loads

This scenario is similar to Situation 2 but involves eight discrete fire loads. The calculations use the same methodology as in Situation 2, adjusted for the increased number of fire loads. This results in different values for energy consumption rate, fire duration, and maximum HRR, as detailed in Table 3.

#### 2.2.2.4 Situation 4 – 16 localized fire loads

In this scenario, the number of fire loads is increased to sixteen. The calculations again follow the same methodology as in Situation 2, adjusted for the sixteen fire loads. The resulting values for energy consumption rate, fire duration, and maximum HRR are presented in Table 3.

#### 2.2.2.5 Situation 5 – 32 localized fire loads

The final scenario involves thirty-two fire loads, representing an extreme case of fire load distribution. The calculations use the same method as in Situation 2, adjusted for the thirty-two fire loads. This adjustment leads to different values for energy consumption rate, fire duration, and maximum HRR, as shown in Table 3.

TABLE 3: PARAMETERS FOR EVERY LOCALIZED SITUATION

| General information | | Wood stacks | | Intensity of the fire | |
|---|---|---|---|---|---|
| ***Fire load density*** | 300 MJ/m² | ***Density*** | 250 kg/m³ | ***RHR density*** | 1 MW/m² = 1 MJ/s/m² |
| ***Area room*** | 5000 m² | ***Combustion value*** | 19 MJ/kg | | 1000 kW/m² |
| ***Total fire load*** | 1,500,000 MJ (1500 GJ) | ***Height*** | 3 m | | |

TABLE 4: RESULTING PARAMETERS CALCULATIONS FOR EACH LOCALIZED FIRE LOAD

| Number of fire loads | Energy content of each fire load [MJ] | Volume [m³] | Base area [m²] | Length / width [m] | Energy consumption rate [MJ/s] | Burn duration [sec] | Maximum HRR [kW] |
|---|---|---|---|---|---|---|---|
| **4** | 375000 | 78.95 | 26.32 | 5.13 | 26.32 | 14250 | 26316 |
| **8** | 187500 | 39.47 | 13.16 | 3.63 | 13.16 | 14250 | 13158 |
| **16** | 93750 | 19.74 | 6.58 | 2.56 | 6.58 | 14250 | 6579 |
| **32** | 46875 | 9.87 | 3.29 | 1.81 | 3.29 | 14250 | 3289 |

### 2.2.3 SIMULATION PARAMETERS AND SETUP IN CFAST

Several key parameters were set for the simulations to ensure consistency and accuracy. The total duration of the simulation was set to the calculated fire duration of 14310 seconds, allowing for a comprehensive analysis of fire development and extinguishment. Detailed time-stamped records of simulation data were provided by setting the text output interval to 60 seconds. Similarly, a spreadsheet output interval of 60 seconds enabled regular data collection for further analysis.

Both indoor and outdoor temperatures were set to 20°C, representing typical ambient conditions. Compartment surfaces were analysed under two different scenarios: adiabatic and non-adiabatic. In the adiabatic scenario, it was assumed that there is no heat transfer through the surfaces, which simplifies the simulation by allowing a focus solely on the fire dynamics within the compartment without considering external heat loss or gain. In contrast, the non-adiabatic scenario takes into account heat transfer through the surfaces, providing a more realistic representation of how fire interacts with the surrounding structure. This approach acknowledges the thermal properties of the compartment's materials, such as a concrete floor, which can affect the fire's progression and intensity. The lower oxygen limit was set to 0.1, a threshold below which combustion is not sustained, which is critical for understanding fire behaviour in confined spaces.

The flow characteristics were modelled using a 2-zone approach, which in this context refers to the vertical segmentation of the space. Specifically, the compartment is divided into two distinct layers based on height: a hot upper smoke layer and a cooler lower layer. This method contrasts with models that segment the space horizontally across different floor plans or rooms. Ozone3 is a single-room two-zone model, meaning it divides one room vertically into two layers. On the other hand, CFAST is a more complex model that can handle multiple rooms or zones, effectively making it a multi-room (or multizone) model.

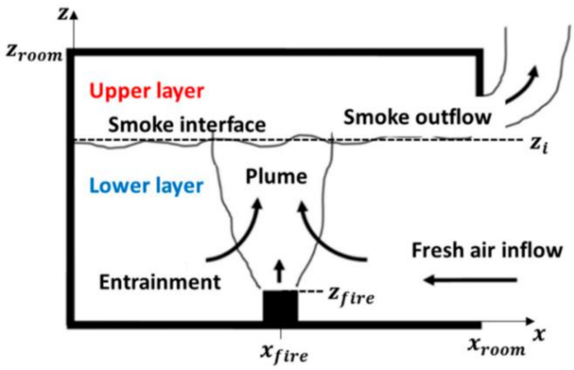


FIGURE 7: SCHEMATIC OF THE TWO-ZONE MODEL IN THE Y-PLANE (PORTERIE, ET AL., 2022)

The fire properties were defined with cellulose (chemical composition: $C_4H_6O_3$) as the fire ID, representing a common combustible material in industrial settings (van Herpen, 3. Combustion, 2023). The heat of combustion was set at 19 MJ/kg and the radiative fraction was specified as 0.35, indicating that 35% of the total energy released during combustion is emitted as thermal radiation.

The fire was positioned in the middle of zone 2, a space which has no doors or windows. If the fire starts in this part of the industrial compartment, it can quickly escalate without sufficient ventilation to dissipate heat and smoke. The lack of openings restricts the flow of fresh air into the compartment, leading to rapid fire growth and accumulation of toxic gases, simulating the worst-case scenario.

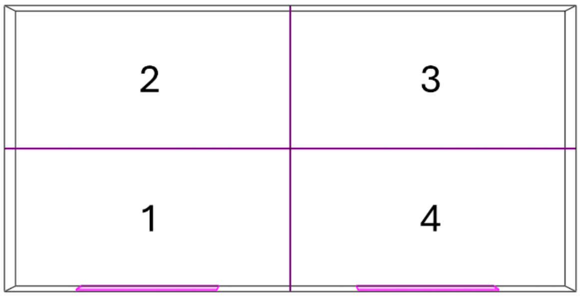


**FIGURE 8: FLOOR PLAN ZONE NUMBERING FOR INDUSTRIAL COMPARTMENT IN CFAST**

The fire height was set midway up the stack at 1.5 meters above floor level. The fire power remained constant during the 14250 seconds, simulating a sustained fire without significant growth or decay. The growth and decay phases were assumed to be very short, simplifying the analysis by focusing on the steady-state burning phase. Table 4 details the fire input parameters for situation 2 in the CFAST simulation, which involves four discrete fire loads. This configuration provides insights into the fire dynamics and the resulting impact on the compartment's environment over time. The same table is filled in for situation three, four and five, with the numbers calculated and shown in Table 3.

**TABLE 5: FIRE INPUT PARAMETERS CFAST FOR BASE SIMULATION 2**

| Time (s) | HRR (kW) | Height (m) | Area (m²) | CO Yield | Soot Yield |
|---|---|---|---|---|---|
| 0 | 0.0 | 1.50 | 26.32 | 0.0100 | 0.0250 |
| 60 | 26316.0 | 1.50 | 26.32 | 0.0100 | 0.0250 |
| 14250 | 26316.0 | 1.50 | 26.32 | 0.0100 | 0.0250 |
| 14310 | 0.0 | 0.00 | 0.00 | 0.0100 | 0.0250 |

### 2.2.4 DATA COLLECTION AND ANALYSIS

For each configuration, the following metrics were recorded to assess the impact of the fire:

- *Equivalent Fire Duration:*
  Determined using an Excel file titled *"Equivalent fire duration"*, where CFAST results for upper layer temperature (TU) and rate of heat release (RHR) are inputted to calculate the duration equivalent to a standard fire curve.
- *Temperature of the Hot Zone (upper layer):*
  The temperature in the upper layer of the compartment, which is critical for determining if flashover occurs, and for personal safety in case of evacuating underneath the hot layer.
- *Radiant Heat Flux:*
  The radiant heat flux should not exceed 15 kW/m² (van Herpen, 2. Natural fires, 2023) to prevent the fire from spreading further. This threshold is critical as higher levels of radiative heat flux can contribute to the ignition of adjacent combustibles and enhance the propagation of the fire, potentially leading to a more extensive and uncontrolled fire scenario. During evacuation, the radiation flux should be below 2.5 kW/m². The radiation flux calculations were performed using the program 'Stralingsbelasting' from InfoMil.

- *Gas temperature (lower layer):*
  The temperature in the lower layer of the compartment, which is critical for evaluating the fire's impact on occupant safety.
- *Interface Height (smoke free height):*
  The height between the hot upper layer and the cooler lower layer, providing insight into the stratification of smoke and hot gases.

#### 2.2.4.1 Flashover conditions

Flashover conditions were determined based on the following criteria:

- Radiation
  - *Upper Layer Temperature:*
    Should not exceed 500°C. This threshold is critical because at this temperature, the radiant heat flux typically reaches around 15 kW/m², indicating a high risk of flashover.
  - *Radiant Heat Flux (for localized fires):*
    Should not exceed 15 kW/m² to prevent the fire from spreading further. Both the temperature and the radiant heat flux must be monitored to assess the potential for flashover.
- Convection
  - *Upper Layer Temperature:*
    Should not exceed 300°C when the fire load is in contact with the hot upper layer.
  - *Lower Layer Temperature:*
    Should not exceed 300°C.

#### 2.2.4.2 Safe evacuation

The conditions for safe evacuation were assessed using the following criteria (van Herpen, 1a. Acceptance criteria personal safety, 2023):

- *Gas Temperature (Lower Layer):*
  - At temperatures of 45°C, individuals can be exposed infinite without experiencing any health damage. This temperature level is considered safe for evacuation purposes, as it does not pose a risk to human health.
  - At temperatures ranging from 80°C to 130°C, individuals will experience difficulty in breathing. Exposure to these temperatures should be limited to a maximum of approximately 5 minutes to avoid severe health consequences.
  - At a temperature of 150°C, the skin can suffer burns within 5 minutes of exposure. This temperature poses a significant danger to human health, and immediate evacuation is necessary to prevent serious thermal injuries.
- *Upper layer temperature:*
  - Should be below 200 degrees Celsius to ensure safe evacuation beneath the upper smoke layer, within a maximum of 5 minutes.
- *Smoke:*
  - The smoke-free height must exceed 2.5 meters to allow occupants to move freely below the smoke layer. Visibility checks are not required, because a smoke-free height of less than 2.5 meters already indicates unsafe evacuation conditions. This consideration is only relevant in mixed situations where evacuation through the smoke layer is necessary.

### 2.2.5 Mitigation strategies for flashover scenarios

After identifying scenarios prone to flashover, the analysis proceeds with two critical steps aimed at comprehensively exploring fire suppression techniques. These steps delve into practical insights and recommendations to augment fire safety measures in large compartmentalized spaces.

#### *2.2.5.1 Firefighter intervention - smothering the fire through controlled ventilation*

Upon identifying a flashover condition in any given scenario, an additional analysis is conducted to evaluate a potential mitigation strategy involving the modification of the compartment's ventilation. This step aims to assess whether controlling the ventilation can smother the fire post-evacuation, potentially preventing further escalation and reducing the need for aggressive firefighting interventions.

First, flashover conditions are identified when the upper layer temperature exceeds 500°C. It is assumed that all occupants have safely evacuated the building within 10 minutes of the fire's onset. This evacuation period is critical to ensuring human safety before implementing the subsequent fire suppression strategies. After the 10-minute evacuation window, the overhead doors are closed to significantly reduce the ventilation in the compartment, limiting the oxygen supply to the fire. The CFAST settings for this are as follows: at time 0 seconds, the fraction is 1, and at time 600 seconds, the fraction is 0.

Additionally, an analysis is performed to evaluate the impact of opening the Smoke and Heat Exhaust Ventilation System (NL: rook- en warmteafvoer systeem) after 2 minutes of fire onset. This step provides an alternative ventilation control measure to potentially reduce fire intensity. The CFAST settings for this are as follows: at time 0 seconds, the fraction is 0, and at time 120 seconds, the fraction is 1.

The revised compartment setup is then analysed using CFAST to assess the impact of reduced ventilation and the effectiveness of the roof ventilation system, as explained in Chapter 2.2.4. The results of this analysis provide crucial insights into the potential for a defensive firefighting approach. By smothering the fire through controlled ventilation or by using the SHEV system, the need for offensive firefighting may be minimized, enhancing firefighter safety.

#### *2.2.5.2 Acceptable fire load density to prevent flashover*

In addition to ventilation control, another critical aspect of fire suppression is identifying the acceptable fire load density required to prevent flashover.

Starting from the initial fire load density (300 MJ/m$^2$), the fire load density is systematically reduced in incremental steps. For each reduction, the fire dynamics are simulated using CFAST to monitor changes in key parameters such as the upper layer temperature. The simulation results are then analysed to identify the fire load density at which flashover no longer occurs. This threshold represents the acceptable fire load density required to prevent flashover in the compartment. Finally, the realism of the identified fire load density is assessed. This involves evaluating whether the determined fire load density is practical and applicable to real-world scenarios.

## 2.3 LIMITATIONS AND ASSUMPTIONS

In considering the findings of this study, it is important to acknowledge several limitations and assumptions. Firstly, the study's reliance on a specific industrial compartment layout may restrict its broader applicability to other types of buildings, as different configurations can lead to varied fire behaviours and impacts. Moreover, the simulations are based on predefined fire loads and distributions, potentially overlooking certain real-world scenarios characterized by variations in material properties, other ventilation conditions, and fire growth patterns. This limitation underscores the need for caution when extrapolating results to different contexts. Additionally, the validation of simulation outcomes was disadvantaged by a lack of comparable experimental data. While the CFAST model offers robust modelling capabilities, real-world testing and data collection are essential for verifying the accuracy of simulations. Therefore, expanding validation efforts with empirical data would enhance confidence in the model's predictive performance and its suitability for practical applications.

An important assumption underlying this study is that the fire compartment envelope remains intact, particularly in localized situations. This assumption implies that the fire's spread and effects are confined within a defined area, and that structural elements such as walls and facades are assumed not to fail, thereby preventing the fire from spreading to adjacent areas. This assumption is crucial for fire modelling and risk assessment, because it fundamentally shapes the simulation's accuracy and the design of safety measures. If the compartment envelope were to fail or if the fire were to spread beyond the assumed boundaries, the actual fire behaviour could differ significantly from the model's predictions.

# 3 RESULTS

This chapter presents the findings of the research, systematically organized into three primary sections: equivalent fire duration for both localized and uniformly distributed fire loads (Chapter 3.1), detailed graphs for localized fire loads (Chapter 3.2), and detailed graphs for the uniformly distributed fire load (Chapter 3.3). Each of the subchapters 3.2 and 3.3 delves into specific parameters, such as upper layer temperature and lower layer temperature. Chapter 3.4 explores mitigation strategies for uniformly distributed fire loads. Non-adiabatic simulations are more realistic, so the focus will be more on these results, with adiabatic simulations included only for comparison purposes. This approach explains the consistent y-axis values across comparisons, allowing for quick identification of differences. For clarity and ease of interpretation, detailed full-size graphs are included in the Appendix A1 through A4.

## 3.1 EQUIVALENT FIRE DURATIONS

The analysis included assessing the fire resistance requirements, equivalent fire duration, and time for safe evacuation for various fire loads. The required fire resistance is based on an EI 60 rating with SFC (Structural Fire Compartment) considerations. The EI 60 rating ensures that the building component can provide at least 60 minutes of fire resistance, allowing sufficient time for occupants to evacuate and for emergency services to respond. The results are shown below in Figure 9 and 10, and Table 6 and 7.

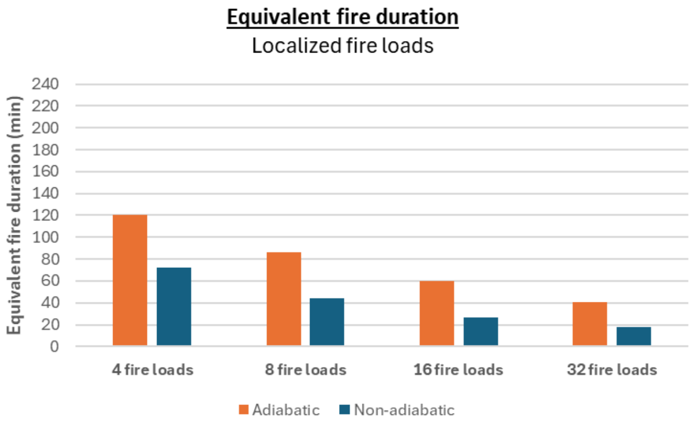


FIGURE 9: RESULTS EQUIVALENT FIRE DURATION; LOCALIZED FIRE LOADS

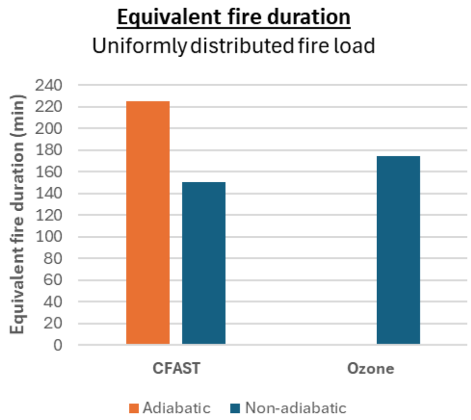


FIGURE 10: RESULTS EQUIVALENT FIRE DURATION; UNIFORMLY DISTRIBUTED FIRE LOAD

Considering both the adiabatic and non-adiabatic situations for the localized fire loads, the equivalent fire duration decreases as the number of fire loads increases. This decrease is due to the reduction in floor area allocated to each fire load, which limits the spread and intensity of each individual fire.

Comparing the results of the different environmental settings, it is evident that the adiabatic situation (representing the worst-case scenario) results in higher equivalent fire durations. This occurs because adiabatic conditions assume that no heat is lost through the boundaries of the compartment, leading to a build-up of heat and, consequently, a longer duration of elevated temperatures. In contrast, non-adiabatic conditions (more realistic situation) allow for heat loss through walls, ceilings, and other boundaries, resulting in lower overall temperatures and shorter equivalent fire durations.

The results also reveal that in two specific scenarios - when there are 4 fire loads and when the fire loads are uniformly distributed - the equivalent fire duration exceeds the required fire resistance in both adiabatic and non-adiabatic situations, shown in Tables 6 and 7 below. This indicates that in these configurations, the fire intensity and duration are sufficiently high to challenge the structural integrity beyond the designed resistance time.

TABLE 6: EQUIVALENT FIRE DURATION, LOCALIZED FIRE LOADS

| Localized fire loads | CFAST | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Adiabatic | | | | **Non-adiabatic** | | | |
| **Number of fire loads** | 4 | 8 | 16 | 32 | **4** | **8** | **16** | **32** |
| **Required fire resistance [min] (EI 60, SFC)** | 60 | 60 | 60 | 60 | **60** | **60** | **60** | **60** |
| **Equivalent fire duration [min]** | 120 | 86 | 60 | 41 | **72** | **44** | **27** | **18** |
| **Structural integrity margin [min]** | - 60 | - 26 | 0 | 19 | **- 12** | **16** | **33** | **42** |

TABLE 7: EQUIVALENT FIRE DURATION, UNIFORMLY DISTRIBUTED FIRE LOAD

| Uniformly distributed fire load | CFAST | | Ozone |
|---|---|---|---|
| | Adiabatic | **Non-adiabatic** | **Non-adiabatic** |
| **Number of fire loads** | Uniform | **Uniform** | **Uniform** |
| **Required fire resistance [min] (EI 60, SFC)** | 60 | **60** | **60** |
| **Equivalent fire duration [min]** | 227 | **150** | **174** |
| **Structural integrity margin [min]** | - 167 | **- 90** | **- 114** |

The comparison between CFAST and Ozone simulations for uniformly distributed fire loads reveals that while neither set of results is entirely favourable, the outcomes from CFAST are more advantageous than those from Ozone. Specifically, the non-adiabatic simulations in CFAST show a shorter equivalent fire duration (150 minutes) compared to Ozone (174 minutes). This disparity can be attributed to the fact that Ozone does not define an extinguishing phase, making it a less realistic and more simplistic model than CFAST, leading to a longer equivalent fire duration.

## 3.2 LOCALIZED FIRE LOADS

In this chapter, the comprehensive findings derived from the four base simulations of localized fire loads are presented, for both an adiabatic and non-adiabatic environment.

### 3.2.1 UPPER LAYER TEMPERATURE

The analysis of flashover focused on ensuring that the maximum upper layer temperature in the compartment does not exceed 500°C, a critical threshold indicating the onset of flashover. This higher threshold of 500°C, rather than 300°C, is used because the fire load is not in direct contact with the upper layer.

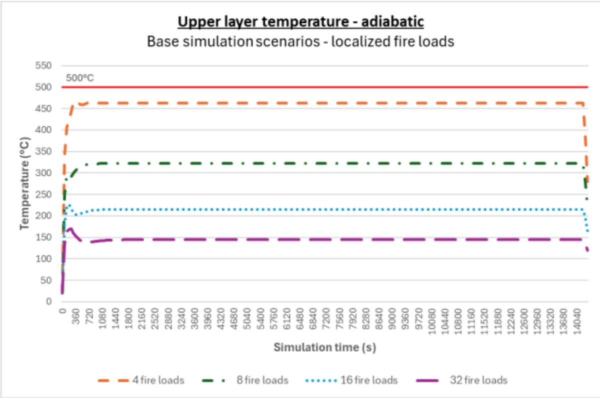


**FIGURE 11: RESULTS LOCALIZED FIRE LOADS; UPPER LAYER TEMPERATURE - ADIABATIC**

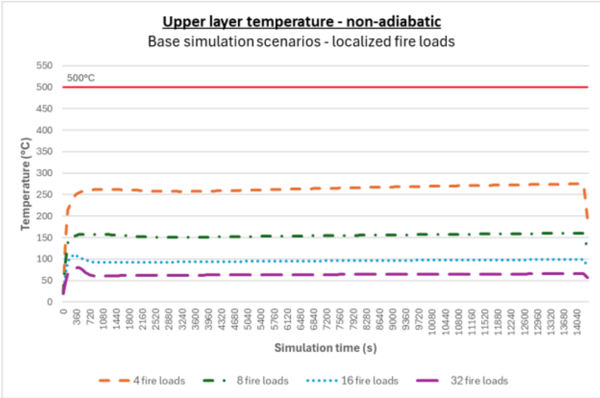


**FIGURE 12: RESULTS LOCALIZED FIRE LOADS; UPPER LAYER TEMPERATURE - NON-ADIABATIC**

The findings, as illustrated in Figures 11 and 12 and summarized in Table 8, indicate that in all scenarios involving localized fire loads, whether in adiabatic or non-adiabatic conditions, the maximum upper layer temperature remains below the 500°C threshold. This result implies that the conditions studied did not reach the temperature where flashover would occur, suggesting that the risk of flashover is effectively managed within these scenarios. The fire loads remained confined to their point of origin, reinforcing the notion that localized fires do not escalate into larger fires and are contained within the initial area.

**TABLE 8: MAXIMUM UPPER LAYER TEMPERATURE FOR VARIOUS AMOUNTS OF LOCALIZED FIRE LOADS**

| Maximum upper layer temperature | 4 fire loads | 8 fire loads | 16 fire loads | 32 fire loads |
|---|---|---|---|---|
| **Adiabatic environment** | 463°C | 322°C | 215°C | 145°C |
| Moment of maximum temperature | 12 minutes | 13 minutes | 3 minutes | 4 minutes |
| **Non-adiabatic environment** | 261°C | 157°C | 109°C | 78°C |
| Moment of maximum temperature | 14 minutes | 8 minutes | 5 minutes | 7 minutes |

### 3.2.2 RADIANT HEAT FLUX

The analysis of radiant heat flux from the fire scenarios aimed to ensure it remains below the critical threshold of 15 kW/m², crucial for preventing fire spread. Calculations were performed using the 'Stralingsbelasting' program from InfoMil, which prioritizes factors such as the dimensions of individual fire loads (width, depth, height) and the smallest spacing between them, regardless of whether the scenario is adiabatic or non-adiabatic (see the screenshots in Appendix A4). The results detailing heat radiation levels at assessment points ranging from 1 to 5 meters in height are summarized in Table 9.

**TABLE 9: RESULTS RADIANT HEAT FLUX TO OTHER FIRE LOADS FROM THE FLAME OF THE LOCALIZED FIRE**

| Heat radiation level | 4 fire loads | 8 fire loads | 16 fire loads | 32 fire loads |
|---|---|---|---|---|
| **Assessment point 5 m high** | 1.14 kW/m² | 1.23 kW/m² | 3.18 kW/m² | 3.99 kW/m² |
| **Assessment point 4 m high** | 1.14 kW/m² | 1.24 kW/m² | 3.27 kW/m² | 4.21 kW/m² |
| **Assessment point 3 m high** | 1.14 kW/m² | 1.24 kW/m² | 3.28 kW/m² | 4.26 kW/m² |
| **Assessment point 2 m high** | 1.13 kW/m² | 1.22 kW/m² | 3.19 kW/m² | 4.13 kW/m² |
| **Assessment point 1 m high** | 1.11 kW/m² | 1.20 kW/m² | 3.02 kW/m² | 3.82 kW/m² |

Based on the results, it is clear that the heat radiation levels consistently remain well below the critical threshold of 15 kW/m² across all assessment points and fire load scenarios. For the smallest fire load of 4 fire loads, the maximum recorded heat radiation level is 1.14 kW/m². As the fire load increases to 8 fire loads, there is a slight rise in the maximum heat radiation level to 1.24 kW/m², which remains comfortably within safe limits. At higher fire loads of 16 and 32 fire loads, the heat radiation levels increase more noticeably. For 16 fire loads, the maximum level reaches 3.28 kW/m², while for 32 fire loads, it peaks at 4.26 kW/m². Even under these conditions with increased fire loads, the radiant heat flux levels remain significantly below the 15 kW/m² threshold considered critical for fire spread. These findings underscore that, under the simulated conditions, the radiant heat flux is insufficient to generate a traveling fire, keeping the fire localized and posing minimal risk of spreading beyond its point of origin.

For safe evacuation, radiation levels should not exceed the recommended threshold of 2.5 kW/m². To ensure accurate assessment of evacuation safety, new calculations were performed focusing specifically on assessment points at 1, 2, and 3 meters height, representing typical walking levels for occupants. Additionally, the analysis considered distances of 5, 10 and 20 meters between the fire load and the evacuation path to capture various scenarios. This approach ensures a consistent basis for comparison across all four scenarios, helping to provide a more accurate evaluation of evacuation safety.

TABLE 10: RESULTS RADIANT HEAT FLUX TO WALKING OCCUPANTS FROM THE FLAME OF THE LOCALIZED FIRE

| Heat radiation level [kW/m²] | 4 fire loads | | | 8 fire loads | | | 16 fire loads | | | 32 fire loads | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance between fire load and occupants | 5 m | 10 m | 20 m | 5 m | 10 m | 20 m | 5 m | 10 m | 20 m | 5 m | 10 m | 20 m |
| Assessment point 3 m high | 20.74 | 6.74 | 1.78 | 15.48 | 4.77 | 1.24 | 11.07 | 3.28 | 0.84 | 8.6 | 2.61 | 0.63 |
| Assessment point 2 m high | 19.74 | 6.52 | 1.76 | 14.77 | 4.62 | 1.22 | 10.63 | 3.19 | 0.83 | 8.3 | 2.57 | 0.62 |
| Assessment point 1 m high | 17.53 | 6.13 | 1.72 | 13.13 | 4.36 | 1.20 | 9.47 | 3.02 | 0.81 | 7.41 | 2.52 | 0.61 |

Table 10 shows that all scenarios exceed the threshold of 2.5 kW/m² at a closer distance (5 meters) to the fire load, as well as at a distance of 10 meters. However, at a distance of 20 meters, the values fall below the threshold. Despite these stringent conditions, it is important to consider that the actual risk to occupants is mitigated by several factors: evacuation routes are designed to be positioned away from the primary fire load sources, reducing direct exposure to intense radiation. Moreover, the time required for the fire to reach these elevated radiation levels generally allows occupants to evacuate safely before reaching hazardous flux levels.

### 3.2.3 LOWER LAYER TEMPERATURE

The analysis of maximum lower layer temperatures aimed to evaluate potential safety and health risks to individuals during fire scenarios. Temperature thresholds used in this assessment are based on human tolerance to heat exposure, with a maximum of 130°C not exceeding 5 minutes, as discussed in Chapter 2.2.4.2, 'Safe evacuation'. Additionally, the lower layer temperature should not exceed 300°C to prevent flashover due to convection, which significantly increases the risk of fire spread.

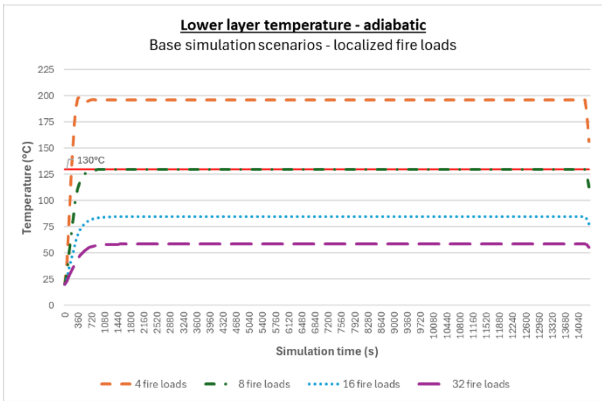


FIGURE 13: RESULTS LOCALIZED FIRE LOADS; LOWER LAYER TEMPERATURE - ADIABATIC

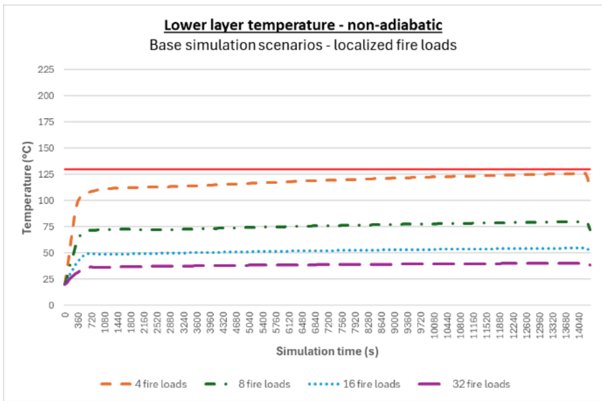


FIGURE 14: RESULTS LOCALIZED FIRE LOADS; LOWER LAYER TEMPERATURE - NON-ADIABATIC

Figure 13, Figure 14, and Table 11 present the lower layer temperatures after 10 minutes (the critical timeframe required for safe evacuation) for various localized fire load configurations. In both adiabatic and non-adiabatic environments, the lower layer temperatures remain below the threshold of 130°C for scenarios involving 8, 16 and 32 fire loads. However, with 4 fire loads in the adiabatic environment, the lower layer temperature exceeds this threshold, reaching 194°C. Since the non-adiabatic situation more accurately reflects real-life conditions, with a lower layer temperature of 107°C, all scenarios meet the requirements by staying below 130°C. Additionally, there is no concern for flashover due to convection, as temperatures stay well below the critical threshold of 300°C in all scenarios.

TABLE 11: LOWER LAYER TEMPERATURE AFTER 10 MINUTES FOR VARIOUS AMOUNTS OF LOCALIZED FIRE LOADS

| Lower layer temperature | 4 fire loads | 8 fire loads | 16 fire loads | 32 fire loads |
|---|---|---|---|---|
| Adiabatic environment | 194°C | 127°C | 79°C | 54°C |
| Non-adiabatic environment | 107°C | 71°C | 49°C | 36°C |

### 3.2.4 SMOKE FREE HEIGHT

Assessing the smoke-free height is critical to ensuring occupant safety during fire incidents, as it provides sufficient clearance for unobstructed movement below the smoke layer. A smoke-free height of at least 2.5 meters is deemed necessary to facilitate unhindered evacuation routes. Figure 15 and 16 present the results for both adiabatic and non-adiabatic environments, showing that the smoke-free height remains above 2.5 meters for all four scenarios involving 4, 8, 16 and 32 localized fire loads.

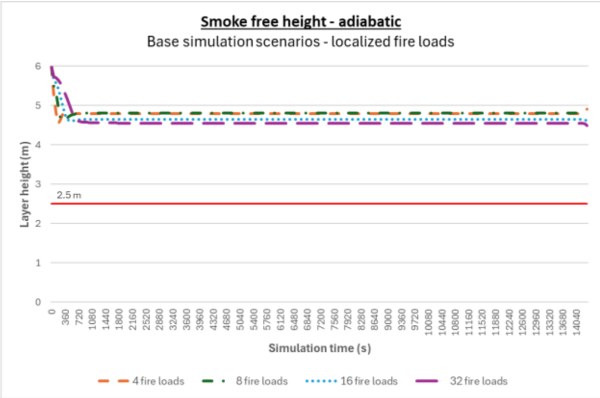


FIGURE 15: RESULTS LOCALIZED FIRE LOADS; SMOKE FREE HEIGHT - ADIABATIC

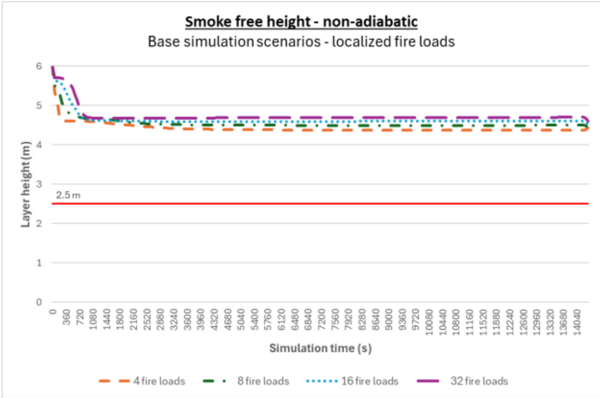


FIGURE 16: RESULTS LOCALIZED FIRE LOADS; SMOKE FREE HEIGHT - NON-ADIABATIC

## 3.3 UNIFORMLY DISTRIBUTED FIRE LOAD

In this chapter, the comprehensive findings derived from the two base simulations of the uniformly distributed fire load (300 MJ/m²), conducted using CFAST and Ozone, are presented.

### 3.3.1 UPPER LAYER TEMPERATURE

The analysis of flashover focused on ensuring that the maximum upper layer temperature in the compartment does not exceed 500°C, a critical threshold indicating the onset of flashover.

The findings in Figure 17 and Table 12 show that in every uniformly distributed scenario, flashover occurs, leading to the fire spreading progressively throughout the compartment. In Ozone, the maximum temperature is lower than with the simulation in CFAST, but the time to reach flashover is shorter. Flashover occurs in Ozone after approximately 2 hours, whereas in CFAST it occurs after approximately 4 hours.

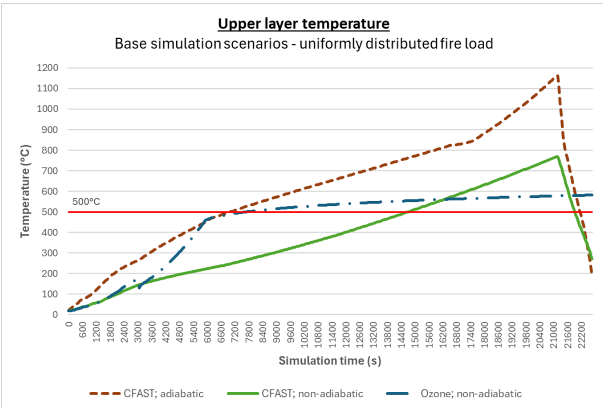


FIGURE 17: RESULTS UNIFORMLY DISTRIBUTED FIRE LOAD; UPPER LAYER TEMPERATURE

TABLE 12: MAXIMUM UPPER LAYER TEMPERATURE FOR UNIFORMLY DISTRIBUTED FIRE LOADS

| **Maximum upper layer temperature** | CFAST | | Ozone |
|---|---|---|---|
| | Adiabatic | Non-adiabatic | Non-adiabatic |
| **Uniformly distributed fire load** | 1153°C | 766°C | 581°C |
| Moment of maximum temperature | 352 minutes (≈ 6 hours) | 353 minutes (≈ 6 hours) | 378 minutes (> 6 hours) |
| **Moment of flashover (500°C)** | 117 minutes (≈ 2 hours) | 245 minutes (≈ 4 hours) | 128 minutes (≈ 2 hours) |

### 3.3.2 Lower layer temperature

Figure 18 and Table 13 show that in both adiabatic and non-adiabatic environments within CFAST, temperatures surpass 130°C, indicating a moment of unsafe conditions. This occurs after an extended period, with the adiabatic environment reaching this temperature after 1 hour and the non-adiabatic environment taking nearly 3 hours.

Similarly, in the simulation conducted in Ozone, temperatures also exceed 130°C, occurring after approximately 1.5 hours. In all three simulations, this provides more than enough time to safely evacuate the building.

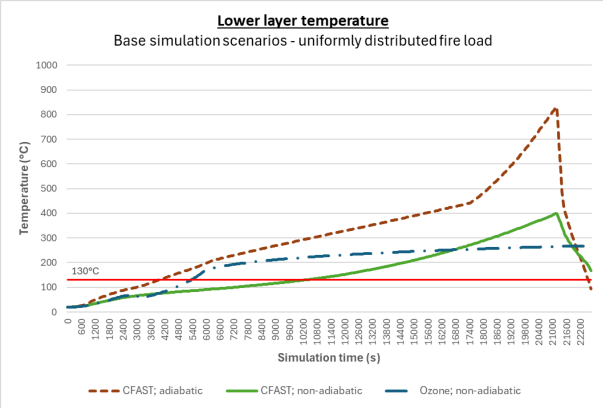


Figure 18: Results uniformly distributed fire load; lower layer temperature

Table 13: Maximum lower layer temperature for uniformly distributed fire loads

| **Maximum lower layer temperature** | **CFAST** | | **Ozone** |
|---|---|---|---|
| | Adiabatic | Non-adiabatic | Non-adiabatic |
| **Uniformly distributed fire load** | 831°C | 399°C | 268°C |
| Moment of maximum temperature | 353 minutes (≈ 6 hours) | 353 minutes (≈ 6 hours) | 378 minutes (> 6 hours) |
| **Moment of unsafe conditions (130°C)** | 66 minutes (≈ 1 hour) | 172 minutes (≈ 3 hours) | 89 minutes (≈ 1.5 hour) |

### 3.3.3 Smoke free height

A smoke-free height of at least 2.5 meters is essential for ensuring unobstructed evacuation routes. Figure 19 illustrates that in all three simulations, the smoke-free height drops below 2.5 meters. In the adiabatic simulation within CFAST, this occurs after just 5 minutes. The non-adiabatic simulation in CFAST, which reflects more realistic conditions, shows the smoke-free height falling below 2.5 meters only after 108 minutes (nearly 2 hours). The Ozone simulation falls in between, with the smoke-free height dropping below 2.5 meters after 51 minutes (almost 1 hour).

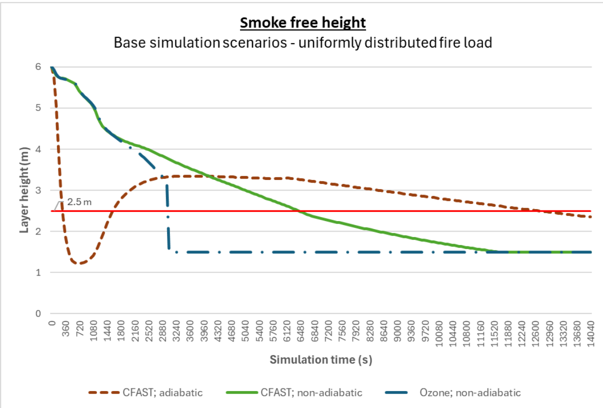


Figure 19: Results uniformly distributed fire load; smoke free height

## 3.4 Mitigation strategies

The results chapter on mitigation strategies explores critical interventions aimed at enhancing fire safety in large compartmentalized spaces prone to flashover. After identifying scenarios vulnerable to flashover, the analysis focuses on two essential approaches to effectively mitigate fire hazards. The uniformly distributed fire load scenario, which results in flashover, underscores the urgency and importance of these mitigation strategies. This chapter focuses exclusively on the uniformly distributed fire load results from CFAST, not from Ozone.

## 3.4.1 Smothering the fire through controlled ventilation

This first sub-chapter examines the strategy of controlled ventilation as a means to suppress fires post-evacuation. This method involves modifying compartment ventilation to restrict oxygen supply, thereby potentially halting fire escalation. The study evaluates scenarios where ventilation adjustments, such as closing overhead doors after 10 minutes and activating Smoke and Heat Exhaust Ventilation Systems (SHEVS) after 2 minutes, are used to effectively smother fires.

### *3.4.1.1 Upper layer temperature*

The results from the adiabatic environment simulations indicate unrealistic outcomes, with temperatures reaching levels that are not feasible in real-world scenarios. Consequently, the graph representing these results is truncated at 2000°C, ignoring any data exceeding this temperature threshold. In contrast, more realistic and practical results are depicted in Figure 21, which illustrates the temperature behaviour in a non-adiabatic environment. This non-adiabatic scenario provides a more accurate representation of conditions likely to be encountered in actual fire events, making it a crucial reference for evaluating fire safety measures.

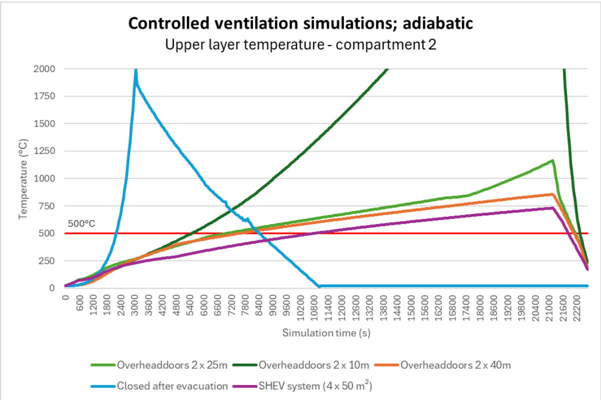


**FIGURE 20: RESULTS CONTROLLED VENTILATION; UPPER LAYER TEMPERATURE - ADIABATIC**

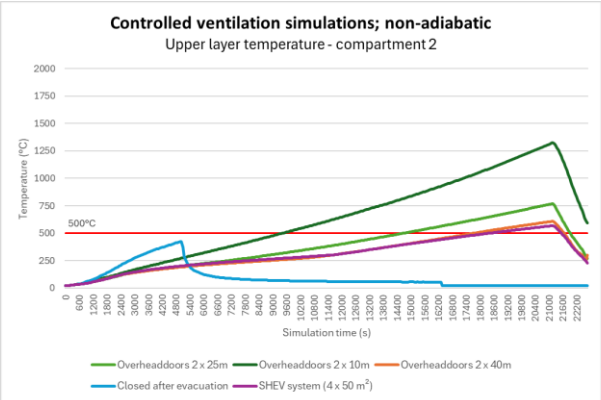


**FIGURE 21: RESULTS CONTROLLED VENTILATION; UPPER LAYER TEMPERATURE - NON-ADIABATIC**

The results from the non-adiabatic simulations indicate that smaller overhead doors (2 x 10 meters) lead to higher upper layer temperatures. When the overhead doors are increased to 2 x 40 meters, the temperature drops to 608°C, compared to 766°C in the uniformly distributed base simulation. Similarly, using a Smoke and Heat Exhaust Ventilation (SHEV) system results in a maximum upper layer temperature of 568°C, which nearly prevents flashover.

Closing the overhead doors significantly reduces the ventilation in the compartment, which in turn limits the oxygen supply to the fire. This action smothers the fire, causing it to burn less intensely and reducing the overall temperature within the compartment. By controlling the oxygen flow, the fire's growth is stunted, leading to lower upper layer temperatures. Therefore, the best solution is closing the overhead doors of 2 x 25 meters after 10 minutes (post-evacuation), which leads to a maximum upper layer temperature of 426°C, effectively preventing flashover.

These findings suggest that by optimizing ventilation strategies, such as enlarging overhead doors or utilizing SHEV systems, and implementing timely closures of overhead doors, the risk of flashover can be significantly reduced or prevented. Consequently, the need for offensive firefighting interventions may be minimized, enhancing firefighter safety. By lowering temperatures and controlling fire spread through these mitigation strategies, the immediate danger to firefighters is reduced, allowing for safer and more controlled firefighting operations.

#### *3.4.1.2 Lower layer temperature*

Additionally, the lower layer temperatures have been analysed for the controlled ventilation simulations, with only the non-adiabatic simulations providing realistic results. These simulations demonstrate that in every ventilation scenario, the temperature exceeds the maximum threshold of 130°C. Specifically, in the scenario where the overhead doors close post-evacuation, this temperature threshold is exceeded after 30 minutes. By this time, the overhead doors have already been closed (after 10 minutes), ensuring that all occupants have safely exited the building.

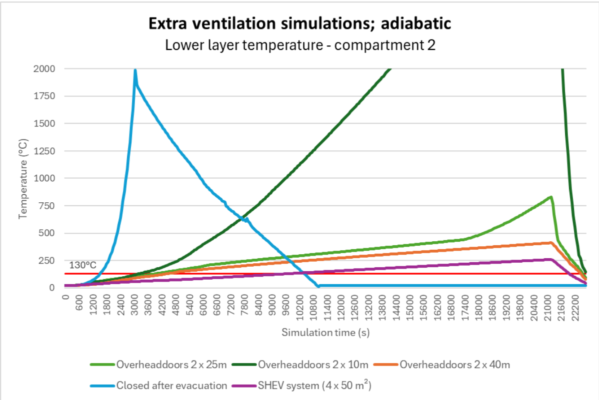


FIGURE 22: RESULTS CONTROLLED VENTILATION; LOWER LAYER TEMPERATURE - ADIABATIC

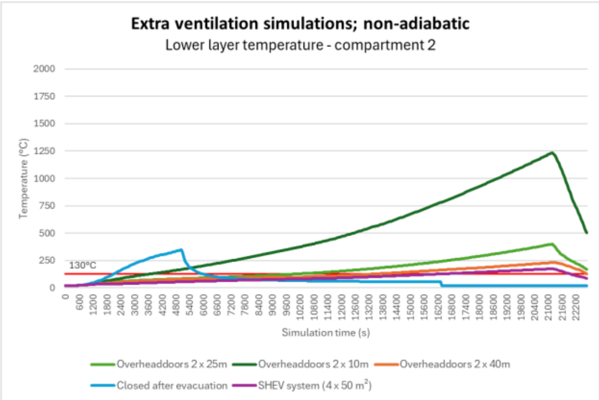


FIGURE 23: RESULTS CONTROLLED VENTILATION; LOWER LAYER TEMPERATURE - NON-ADIABATIC

### 3.4.2 ACCEPTABLE FIRE LOAD DENSITY

This sub-chapter investigates the concept of acceptable fire load density to prevent flashover. By systematically reducing fire load densities and simulating fire dynamics using CFAST, the study determines the threshold at which flashover ceases to occur.

#### *3.4.2.1 Upper layer temperature*

The results from reducing the fire load density reveal significant differences between adiabatic and non-adiabatic simulations. The adiabatic simulations (Figure 24) indicate that the acceptable fire load density to prevent flashover must be 80 MJ/m², which is equivalent to 4.21 kg/m². This fire load density is comparable to that of a low-hazard environment, such as an office space with minimal combustibles.

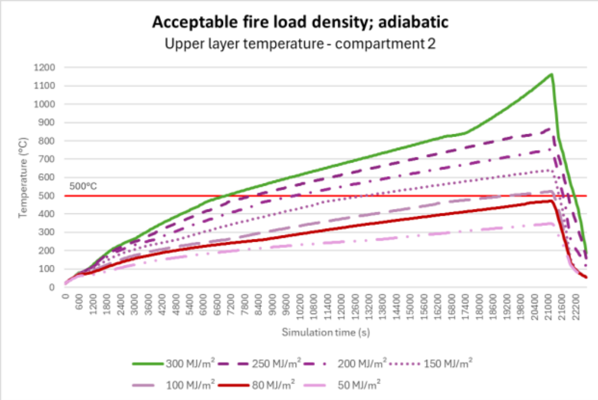


**FIGURE 24: RESULTS ACCEPTABLE FIRE LOAD DENSITY; UPPER LAYER TEMPERATURE - ADIABATIC**


**FIGURE 25: RESULTS ACCEPTABLE FIRE LOAD DENSITY; UPPER LAYER TEMPERATURE - NON-ADIABATIC**

In contrast, the non-adiabatic simulations (Figure 25), which provide more realistic results, show that the acceptable fire load density is 200 MJ/m². This value, equivalent to approximately 10.53 kg/m², aligns more closely with environments such as metalworking facilities or spaces with a higher concentration of combustible materials, where higher fire load densities are typical. These findings underscore the importance of considering realistic fire load densities in fire safety planning to ensure adequate protection and prevention measures are in place.

#### *3.4.2.2 Lower layer temperature*

The results regarding lower layer temperatures indicate that even in scenarios where flashover is successfully prevented, the temperature threshold of 130°C is still exceeded. However, this temperature rise occurs after more than 3 hours, providing sufficient time for safe evacuation. This extended timeframe ensures that all occupants can evacuate the building well before the lower layer temperature reaches dangerous levels, thereby maintaining occupant safety despite the prolonged fire exposure.

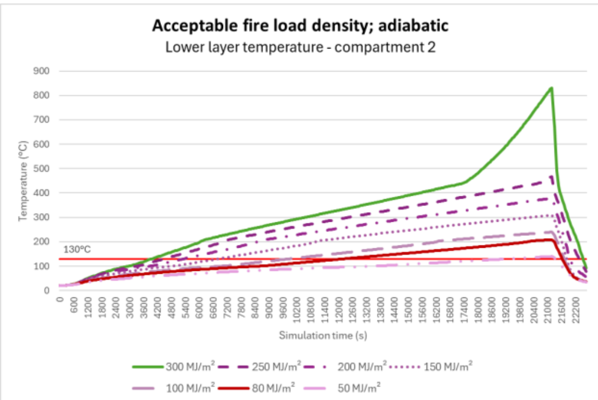


**FIGURE 26: RESULTS ACCEPTABLE FIRE LOAD DENSITY; LOWER LAYER TEMPERATURE - ADIABATIC**

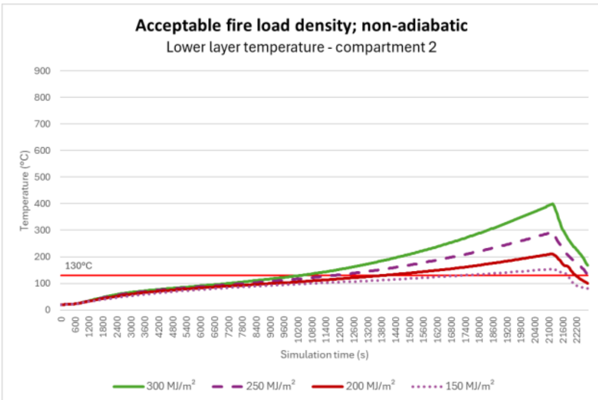


**FIGURE 27: RESULTS ACCEPTABLE FIRE LOAD DENSITY; LOWER LAYER TEMPERATURE - NON-ADIABATIC**

# 4 DISCUSSION

This chapter combines the findings on the effects of localized fire loads and the uniformly distributed fire load on building structures and occupants. It also evaluates the impact of mitigation strategies, including controlled ventilation and reduced fire load density, in preventing and managing flashover scenarios. Each sub-question is addressed and results are interpreted within the study's objectives and limitations.

## 4.1 INFLUENCE EXTINGUISHING PROCESS

*Influence of the extinguishing process on the event of flashover to a compartment fire*

The extinguishing process plays a crucial role in influencing the event of flashover in a compartment by reducing the heat release rate (HRR) and controlling the upper layer temperature within the compartment, thereby delaying or preventing the onset of flashover. By interrupting the fire growth curve, the extinguishing process prevents the fire from reaching its fully developed stage, which is necessary for flashover. This interruption is crucial in both localized and uniformly distributed fire loads, as demonstrated by the differences in equivalent fire duration and flashover times between models with and without extinguishing phases.

The CFAST model shows a shorter equivalent fire duration (150 minutes) compared to the Ozone model (174 minutes). This is primarily because Ozone does not include an extinguishing phase, making it a less realistic and more simplistic model. Consequently, the absence of an extinguishing phase in Ozone results in a prolonged fire duration. For uniformly distributed fire loads, flashover occurs in both CFAST and Ozone models, but the timing and temperatures vary. In the CFAST model (non-adiabatic), flashover occurs after approximately 4 hours, whereas in the Ozone model, it occurs sooner, after approximately 2 hours. The delayed flashover in the CFAST model indicates more effective management of heat release and temperature control, attributable to the inclusion of the extinguishing process in the model.

Extinguishing efforts (Chapter 3.4 Mitigation strategies) minimize radiant heat transfer and thermal feedback to unignited fuels, which are key mechanisms in the spread of fire and the occurrence of flashover. This reduction in radiant heat helps keep the compartment temperature below the flashover threshold, ensuring safer conditions and effective fire control.

## 4.2 PREVENTING FLASHOVER

*Possibility to prevent flashover in case of localized fire loads and a uniformly distributed fire load*

### 4.2.1 LOCALIZED FIRE LOADS

Based on the results of Chapter 3.2.1 '*Localized fire loads – upper layer temperature*', it is possible to prevent both flashover and traveling fires in the case of localized fire loads. The analysis focused on keeping the maximum upper layer temperature in the compartment below the critical threshold of 500°C, which signifies the onset of flashover. The simulation results indicate that in all scenarios involving localized fire loads, both in adiabatic and non-adiabatic conditions, the maximum upper layer temperature remained below the 500°C threshold. This demonstrates that the temperatures did not reach levels that would lead to flashover.

In addition to temperature control, the analysis of radiant heat flux (Chapter 3.2.2) further supports the prevention of flashover. The critical threshold for radiant heat flux is 15 kW/m², which is crucial for preventing fire spread. Results from the 'Stralingsbelasting' program showed that the heat radiation levels at various heights remained well below this threshold. Even at the highest fire loads, the radiant heat flux levels were significantly below the 15 kW/m² threshold. This indicates that the risk of fire spread due to radiant heat is minimal, contributing to safer conditions within the compartment.

### 4.2.2 Uniformly distributed fire load

Preventing flashover in cases with uniformly distributed fire loads presents significant challenges. The simulation results from both the CFAST and Ozone models show that flashover occurs under these conditions. The maximum upper layer temperatures recorded were considerably high and surpass the critical flashover threshold of 500°C, making flashover inevitable in these scenarios. The time to reach flashover varied between the models. In the CFAST simulation, flashover occurred approximately 4 hours (245 minutes) after the start, whereas in the Ozone simulation, it happened after approximately 2 hours (128 minutes).

#### Mitigation strategies

Effective mitigation strategies can play a crucial role in improving fire safety. One such strategy is controlled ventilation. Implementing measures like closing overhead doors and using Smoke and Heat Exhaust Ventilation Systems (SHEVS) can significantly reduce upper layer temperatures. For instance, closing overhead doors of 2 x 25 meters after 10 minutes resulted in a maximum temperature of 426°C in non-adiabatic conditions, which effectively prevented flashover.

Consequently, the need for offensive firefighting interventions may be minimized, enhancing firefighter safety. By significantly reducing the fire's oxygen supply and smothering the flames after closing the doors, the overall compartment temperature is lowered, and the fire's intensity is diminished. This strategy reduces the immediate danger to firefighters, allowing for safer and more controlled firefighting operations without exposing them to the severe heat and structural risks associated with intense fires.

Another important strategy is determining the acceptable fire load density to prevent flashover. Adiabatic simulations indicate that a fire load density of 80 MJ/m², typical of spaces with minimal combustibles such as offices or retail stores, is sufficient to prevent flashover. In contrast, more realistic non-adiabatic simulations suggest that flashover prevention is achievable at a higher fire load density of 200 MJ/m². This higher threshold is appropriate for environments with significant amounts of combustible materials, such as warehouses or industrial settings that handle paper products or textiles.

## 4.3 Consequences for building occupants and constructions

*Consequences of a localized traveling fire for building occupants and constructions, in case of localized fire loads and a uniformly distributed fire load*

### 4.3.1 Localized fire loads

In the context of localized fire loads, the analysis demonstrates that the impact on both building occupants and construction is minimal.

The results indicate that the upper layer temperatures in all scenarios involving localized fire loads remain below the critical threshold of 500°C, which is necessary for flashover. Whether in adiabatic or non-adiabatic environments, the temperatures never reached levels where flashover would occur. Even at higher fire loads, the temperatures remained well below the 500°C threshold. This suggests that flashover is effectively managed under these conditions, indicating that the risk of flashover is low.

Radiant heat flux levels, which are essential for preventing fire spread, also remained substantially below the critical 15 kW/m² threshold in all scenarios. Even with the highest fire load distribution of 32, the maximum heat radiation level recorded was only 4.26 kW/m². This is far below the critical threshold, suggesting that the risk of fire spread due to radiant heat is minimal.

When evaluating evacuation safety, it is noted that heat radiation levels exceed the recommended 2.5 kW/m² threshold at closer distances (5 and 10 meters) from the fire load, potentially posing a hazard to occupants. However, at a distance of 20 meters from the fire load, the radiation levels fall below the 2.5 kW/m² threshold for safe evacuation. This indicates a reduced risk for occupants during evacuation. Despite the high radiation levels near the fire, the risk is mitigated by two key factors: evacuation routes are designed to avoid intense radiation sources, and there is typically sufficient time for occupants to evacuate before reaching hazardous radiation levels. Therefore, while localized fires with localized fire loads can generate high radiation levels close to the fire, the design of evacuation routes and the time available for evacuation contribute to a safer evacuation process.

Additionally, localized fire loads generally exert less thermal stress on construction elements compared to traveling fires. Because these fires are confined to a specific area, the overall thermal load on structural components is lower, which often means that extensive fire resistance is not required for most construction elements. However, construction elements situated near the fire axis, where the fire intensity is greatest, may still experience significant thermal exposure and might require enhanced fire resistance to ensure structural safety.

Regarding lower layer temperatures, which impact the safety and health of individuals, all scenarios met safety thresholds. In non-adiabatic environments, lower layer temperatures stayed below the 130°C limit deemed safe for evacuation. This ensures that the temperature conditions are safe for occupants to evacuate. Finally, the smoke-free height, which ensures clear evacuation routes, consistently remained above the 2.5 meters requirement in all scenarios. This height ensures that occupants have sufficient clearance to move without obstruction during a fire.

### 4.3.2 Uniformly distributed fire load

The impact on building occupants and structures in the event of a uniformly distributed fire load is both significant and complex.

The analysis of equivalent fire durations indicates that uniformly distributed fire loads, whether considered in adiabatic or non-adiabatic conditions, lead to fire durations that exceed the required EI 60 fire resistance rating. This means that the fire intensity and duration in these scenarios challenge the structural integrity beyond the designed resistance time. In practical terms, this implies that the building's structural elements may be subjected to conditions that exceed their fire resistance capabilities, which could compromise the safety of the structure if the fire persists.

The simulations for uniformly distributed fire loads show that flashover occurs in every scenario. In particular, the non-adiabatic CFAST simulation indicates that flashover happens after approximately 2 hours. During these simulations, temperatures significantly surpass the critical 500°C threshold for flashover, with maximum temperatures reaching up to 766°C in the non-adiabatic CFAST scenario.

These elevated temperatures underscore a severe flashover risk, which can lead to uncontrollable fire conditions, posing substantial dangers to building occupants and necessitating prompt and effective fire suppression measures. In a natural fire concept, suppression by the fire service is not included. However, in the case of a traveling fire, preventing flashover through successful intervention, as outlined in section 4.2.2 – Mitigation Strategies, could greatly improve the chances of a positive outcome.

The lower layer temperatures also present a concern. In all scenarios, the temperatures exceed 130°C, which is considered unsafe for prolonged exposure. In the CFAST simulations, this threshold is surpassed after nearly 3 hours in non-adiabatic conditions. These temperatures, while providing enough time for evacuation, still pose a serious risk to occupants' safety. The smoke-free height, which is crucial for ensuring clear evacuation routes, drops below the recommended 2.5 meters in all simulations. In the non-adiabatic CFAST simulation, it falls below the threshold after nearly 2 hours. This reduction in smoke-free height indicates that, although there may be time for evacuation, the presence of smoke and its accumulation can significantly hinder movement and evacuation efforts.

# 5 CONCLUSION

In addressing the primary research question, "*What are the consequences when taking into account the natural extinguishing process from the axis of fire origin for both building users and constructions, exposed to a developing fire in a large compartment?*", several key findings have emerged. Table 14 shows all the simulation results in one overview.

### EXTINGUISHING PHASE

The extinguishing process plays a crucial role in preventing flashover by reducing the heat release rate, controlling temperatures, and interrupting fire growth. Simulations using CFAST and Ozone models have demonstrated the significant impact of incorporating extinguishing phases in accurately predicting and managing flashover risks. In natural fire scenarios in Ozone, the extinguishing process starting from the axis of the fire origin is typically not considered, with a linear decrease in fire power assumed once 70% of the fire load has burned. However, research shows that accounting for the extinguishing process from the fire origin axis provides notable advantages, particularly in uniformly distributed fire loads, where this phase offers a thermal load advantage. This adjustment effectively reduces the risk of flashover and subsequent fire spread compared to standard natural fire modelling.

### CONSTRUCTION SAFETY

Localized fire loads generally pose minimal risk to constructions. In scenarios with localized fires, flashover is effectively prevented and radiant heat levels remain manageable, typically results in localized fires without flashover or traveling fire. However, it is important to note that flashover can occur with higher fire load densities and that construction elements near the fire axis, where intensity is greatest, may still require enhanced fire protection to ensure structural integrity. On the other hand, uniformly distributed fire loads almost always lead to flashover, except in cases of very low fire load density. These scenarios result in high upper layer temperatures, which pose significant challenges to the structural integrity of buildings. Although flashover cannot be entirely prevented under simulated conditions, its risk can be significantly mitigated through strategic fire management measures. Implementing controlled ventilation is critical for reducing the probability of flashover and enhancing overall construction safety.

### Personal safety

When it comes to personal safety, localized fire loads typically result in conditions that minimize risk to occupants. With effective prevention of flashover and manageable radiant heat levels, the environment remains safer for evacuation. The lower layer temperatures are safe, and the smoke-free heights allow for sufficient clearance during evacuation processes. In these scenarios, occupants can exit the building without significant danger. Conversely, uniformly distributed fire loads present a greater threat to personal safety, as they almost invariably lead to flashover unless fire load density is very low. This can create high upper layer temperatures and reduced smoke-free heights, complicating evacuation and potentially endangering occupants. Although there is usually enough time for evacuation, the elevated temperatures and smoke risks underscore the importance of implementing effective fire safety measures.

### Conservatism of a uniformly distributed fire load scenario

It is important to note that a uniformly distributed fire load scenario 300 MJ/m² represents a conservative approach. This scenario assumes a widespread and even distribution of combustible materials, which may not always reflect real-world conditions where fire loads are often more localized. As such, while this conservative approach ensures a thorough evaluation of worst-case scenarios, it may overestimate the risk in typical settings.

### Intervention by fire service

Fire service intervention is crucial for managing fires. The likelihood of successful indoor suppression is highest when the fire is still in the pre-flashover stage, as the fire remains more controllable. In these cases, direct suppression efforts can effectively limit the fire's spread. However, when offensive suppression is too dangerous or not feasible, reducing ventilation and smothering the fire becomes a viable alternative. This approach is particularly useful in the situations were a fire gets to the traveling or post-flashover phase, where limiting the oxygen supply can significantly decrease fire intensity.

The results from mitigation strategies emphasize the importance of early intervention to manage fire risks in large, compartmentalized spaces. Optimizing ventilation control, such as closing overhead doors post-evacuation and employing Smoke and Heat Exhaust Ventilation Systems (SHEVS), can significantly lower upper layer temperatures, preventing flashover and reducing the need for aggressive firefighting efforts. By controlling fire intensity and spread, these strategies not only enhance occupant safety but also reduce risks to firefighters.

### Future Directions

The conclusions drawn from this study are specific to the case study and scenarios investigated. To advance fire safety strategies, future research should expand empirical validation across various industrial and architectural contexts. It is essential to further explore the interactions between ventilation strategies, material properties, and fire load distributions to enhance the predictive accuracy of fire safety engineering models and improve overall building resilience to fire hazards.

Particularly relevant is the investigation of mitigation strategies, such as identifying the lowest effective fire load density. It is crucial to recognize that the minimum fire load density required for maintaining safety may vary depending on the specific case study and scenario. Additionally, while equivalent burning time serves as a general test for structures, it is not necessary to convert steel constructions into equivalent burning times, as they can be directly compared to critical steel temperatures. This method is appropriate for steel structures, often used in industrial halls. In contrast, concrete structures, due to their composite nature, require a more complex analysis (European Commission et al., 2017).

TABLE 14: OVERVIEW TABLE WITH ALL THE RESULTS FROM THE SIMULATIONS IN CFAST

| Localized fire loads | | | | |
|---|---|---|---|---|
| ***Criterium*** | ***Requirement*** | ***Results*** | ***Adiabatic **** | ***Non-adiabatic*** |
| Upper layer temperature | < 500°C | 4 fire loads | 463°C | 261°C |
| | | 8 fire loads | 322°C | 157°C |
| | | 16 fire loads | 215°C | 109°C |
| | | 32 fire loads | 145°C | 78°C |
| Maximum radiant heat flux | < 15 kW/m² | 4 fire loads | 1.14 kW/m² | |
| | | 8 fire loads | 1.24 kW/m² | |
| | | 16 fire loads | 3.28 kW/m² | |
| | | 32 fire loads | 4.26 kW/m² | |
| Lower layer temperature (after 10 minutes) | < 130°C | 4 fire loads | 194°C | 107°C |
| | | 8 fire loads | 127°C | 71°C |
| | | 16 fire loads | 79°C | 49°C |
| | | 32 fire loads | 54°C | 36°C |
| Smoke free height | > 2.5 meters | 4 fire loads | > 2.5 meters | > 2.5 meters |
| | | 8 fire loads | > 2.5 meters | > 2.5 meters |
| | | 16 fire loads | > 2.5 meters | > 2.5 meters |
| | | 32 fire loads | > 2.5 meters | > 2.5 meters |
| **Uniformly distributed fire load** | | | | |
| ***Criterium*** | ***Requirement*** | ***Results*** | ***Adiabatic **** | ***Non-adiabatic*** |
| Upper layer temperature | < 500°C | Uniformly distributed fire load | 1153°C | 766°C |
| Lower layer temperature | < 130°C | Uniformly distributed fire load | 831°C | 399°C |
| Smoke free height | > 2.5 meters | Uniformly distributed fire load | < 2.5 meters | < 2.5 meters |
| **Mitigation strategies – controlled ventilation** | | | | |
| ***Criterium*** | ***Requirement*** | ***Results*** | ***Adiabatic **** | ***Non-adiabatic*** |
| Upper layer temperature | < 500°C | Overhead doors 2x25 m | 1153°C | 766°C |
| | | Overhead doors 2x10 m | > 2000°C | 1325°C |
| | | Overhead doors 2x40 m | 855°C | 608°C |
| | | Closed after evacuation | > 2000°C | 426°C |
| | | SHEV system | 730°C | 568°C |
| Lower layer temperature | < 130°C | Overhead doors 2x25 m | 831°C | 399°C |
| | | Overhead doors 2x10 m | > 2000°C | 1233°C |
| | | Overhead doors 2x40 m | 410°C | 231°C |
| | | Closed after evacuation | > 2000°C | 347°C |
| | | SHEV system | 258°C | 174°C |
| **Mitigation strategies – acceptable fire load density** | | | | |
| ***Criterium*** | | | ***Adiabatic **** | ***Non-adiabatic*** |
| Acceptable fire load uniformly distributed fire load [MJ/m²] | | | 80 MJ/m² | 200 MJ/m² |

* *Temperatures in adiabatic conditions are not realistic, especially when considering mitigation strategies*

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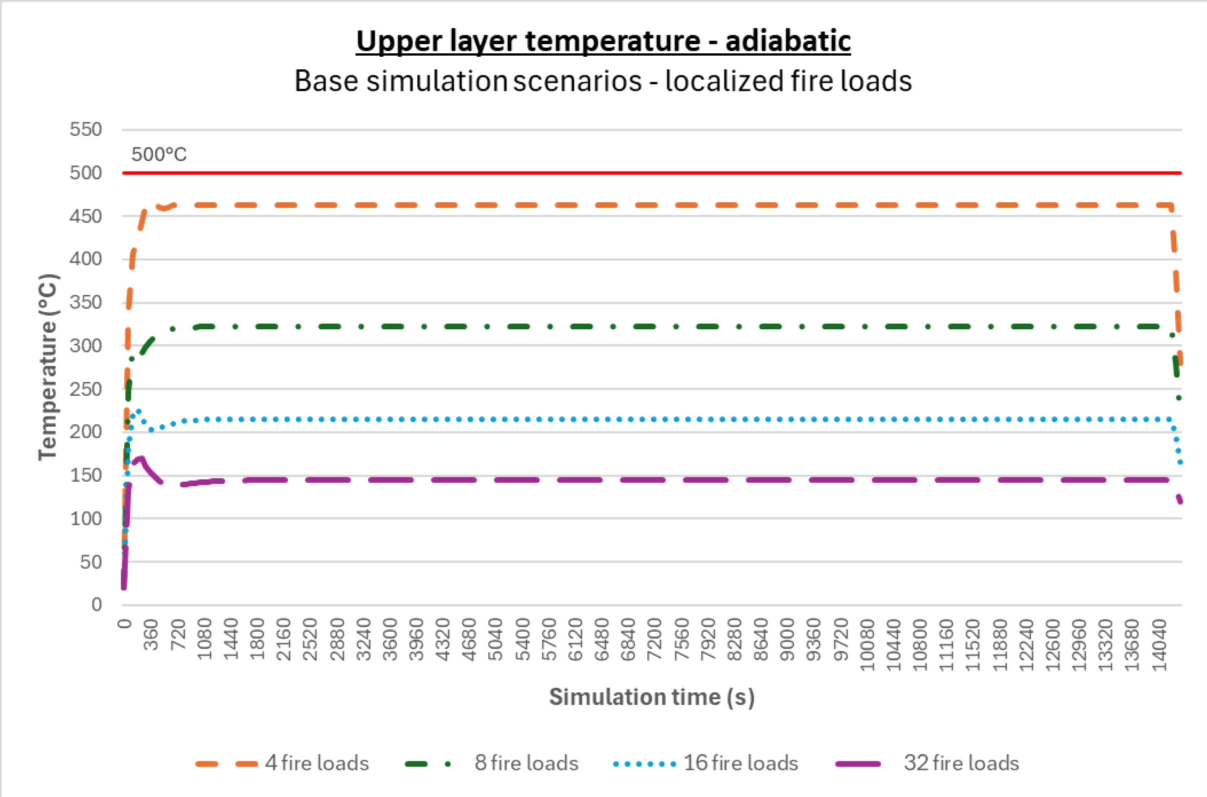
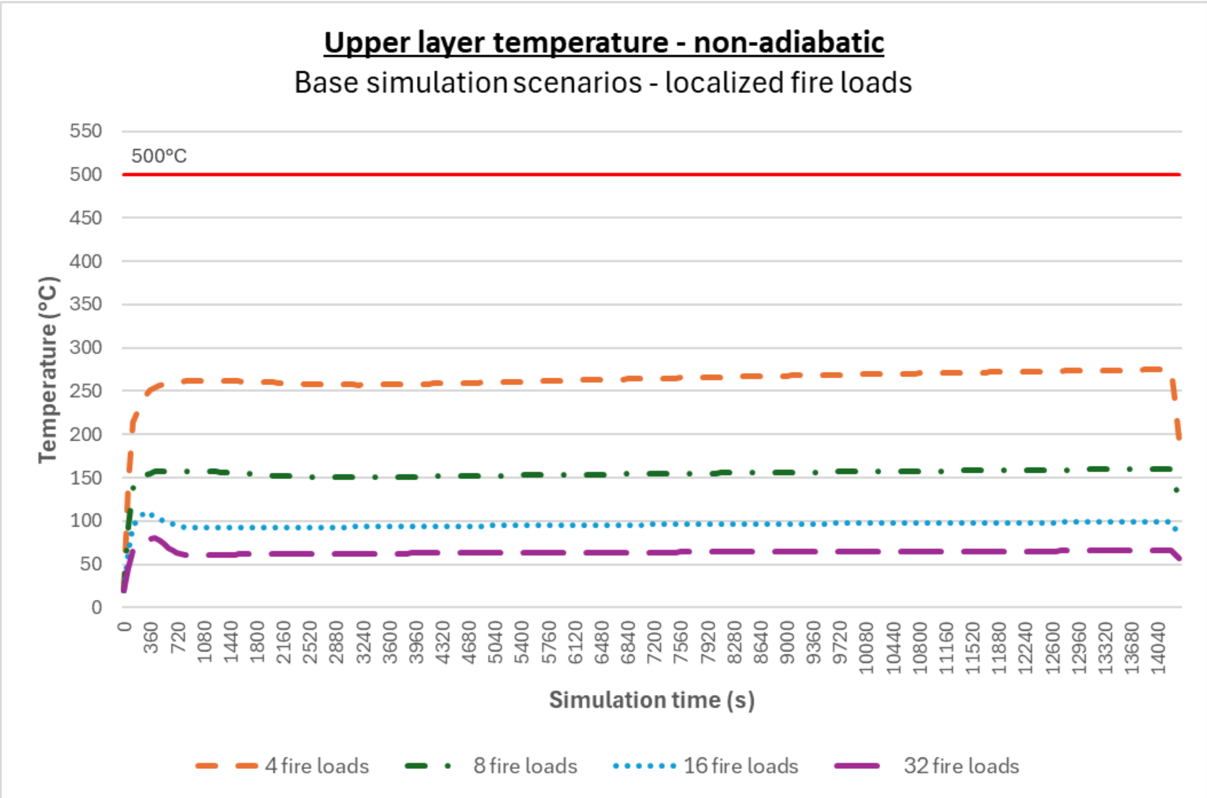
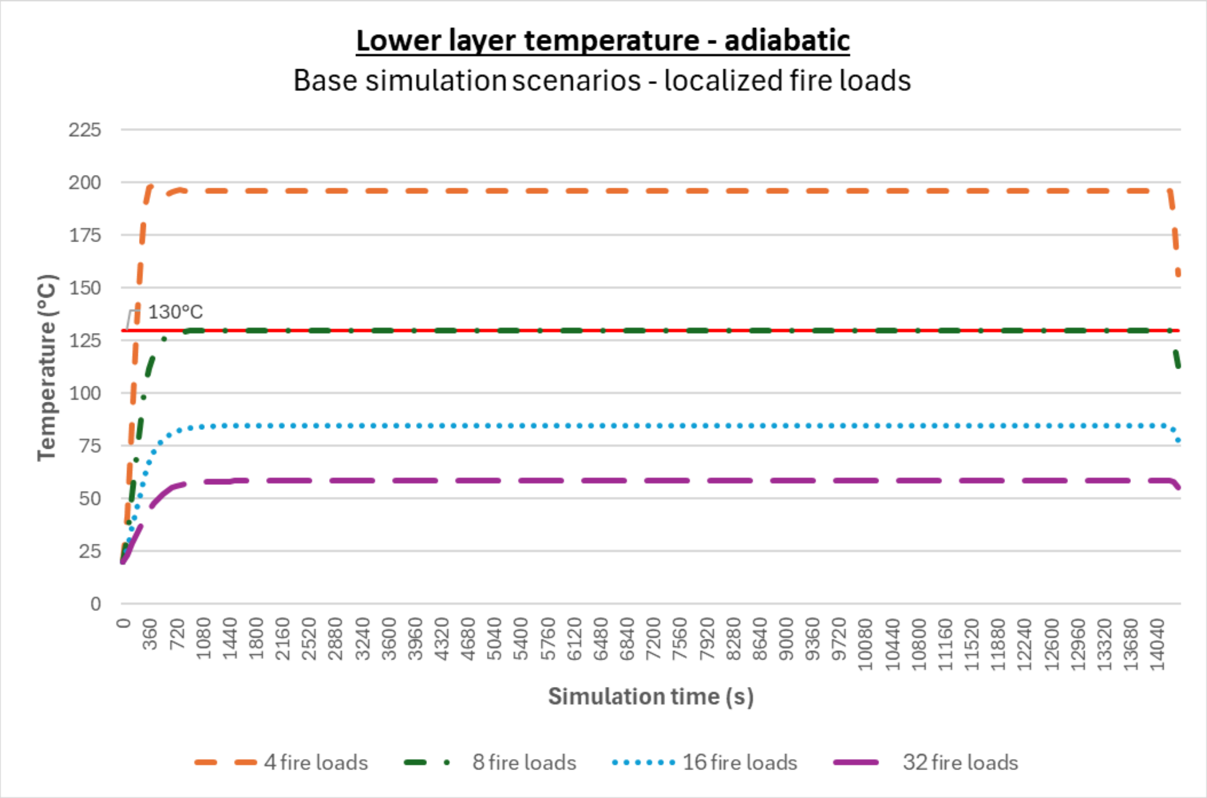
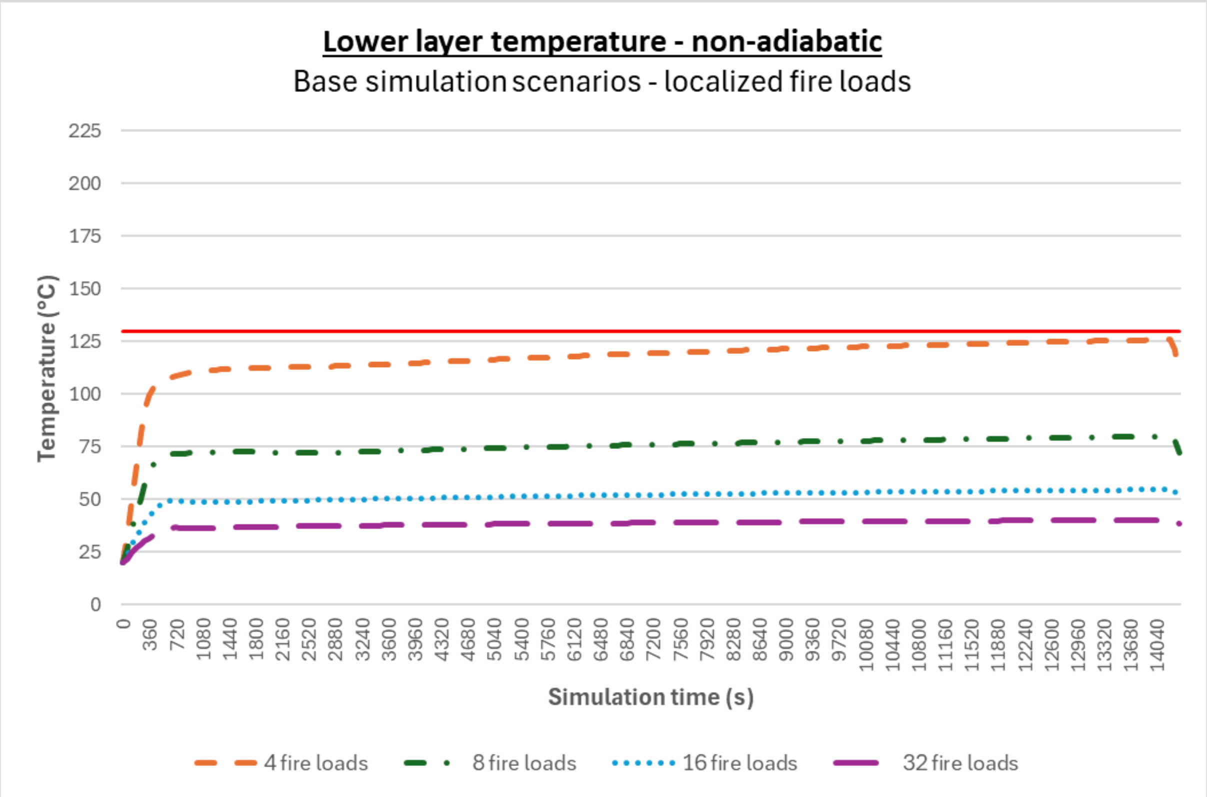
# Appendix

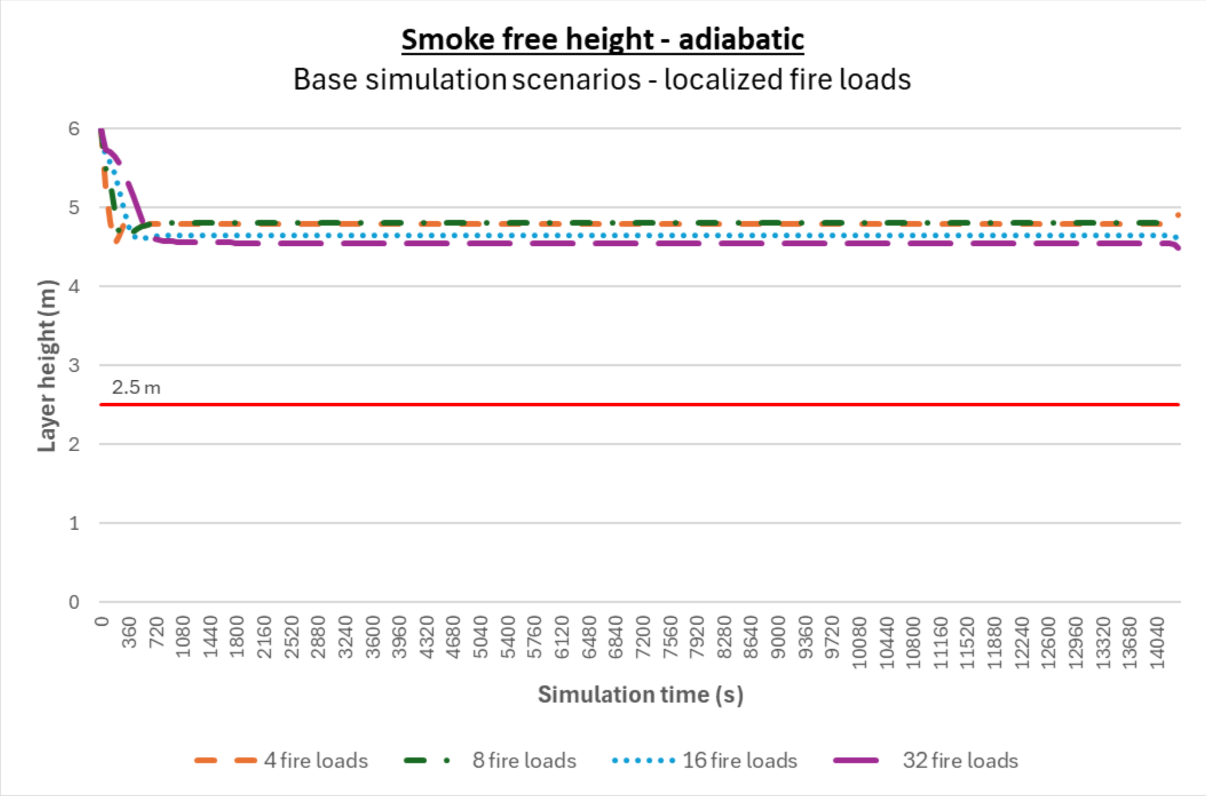
## A1. Figures base simulation scenarios

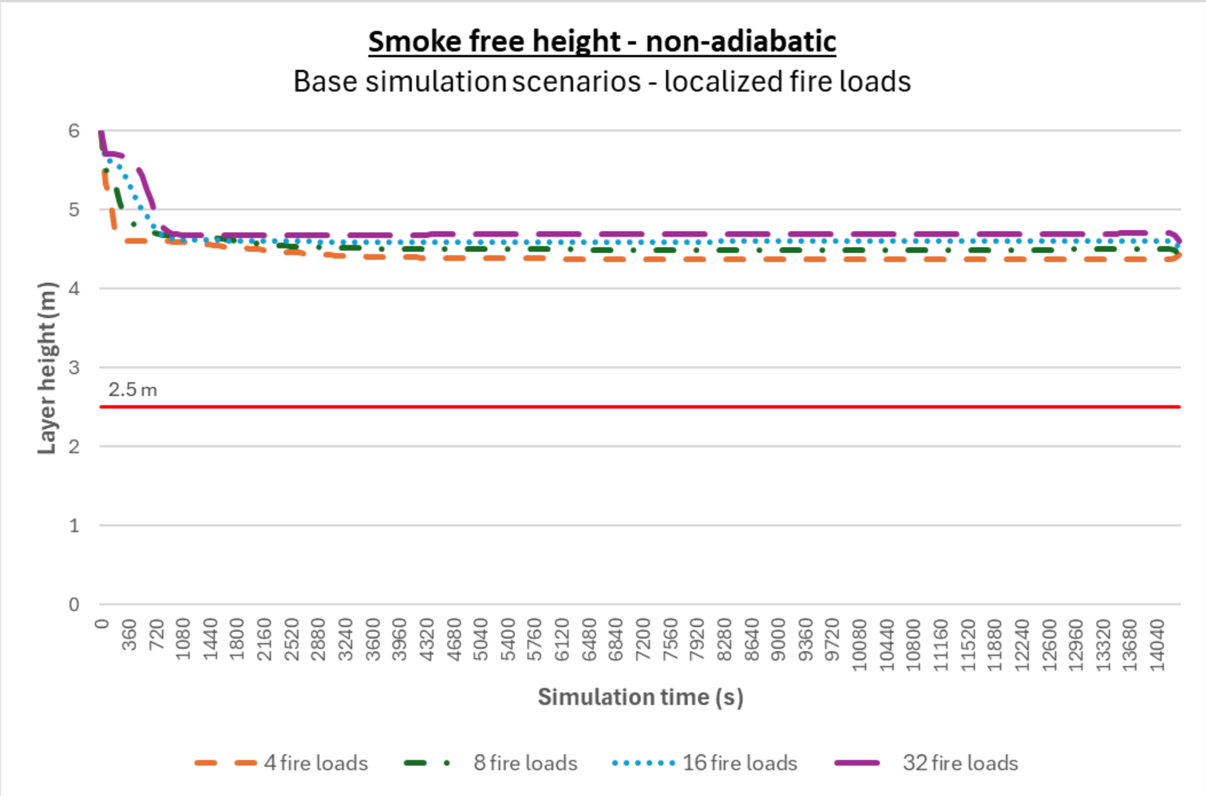


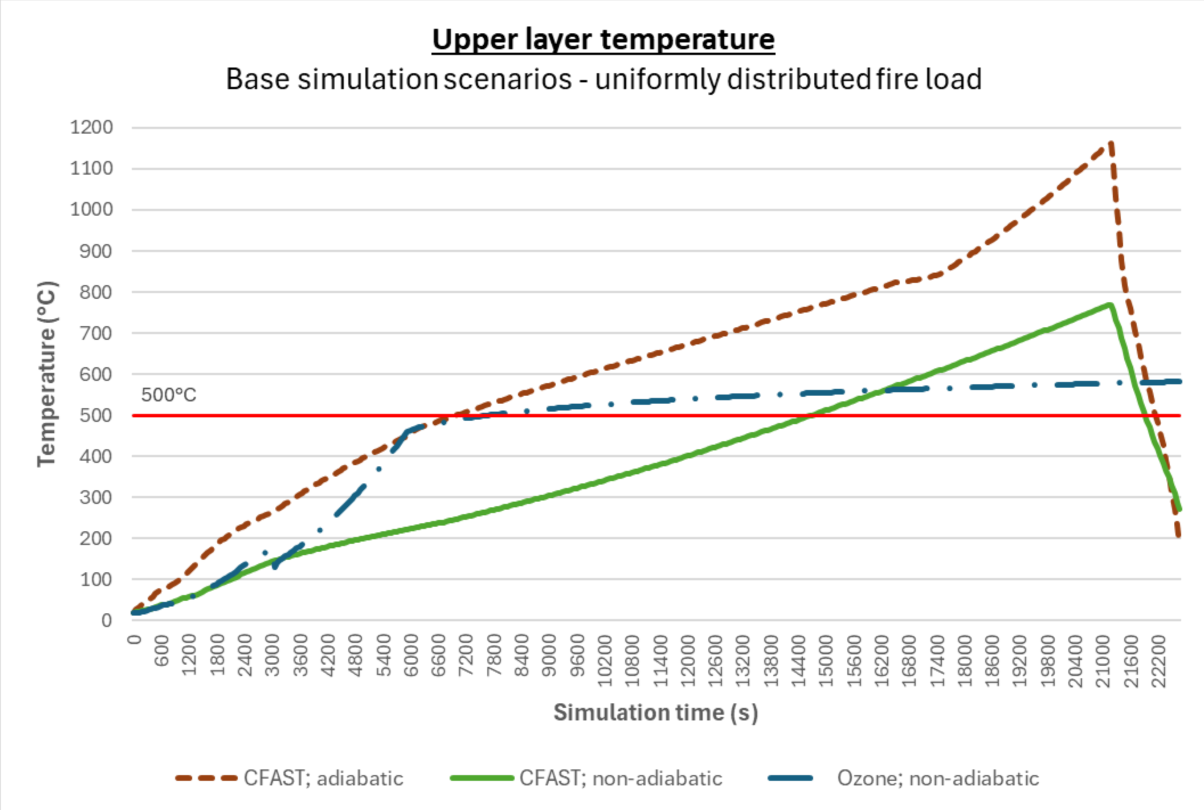



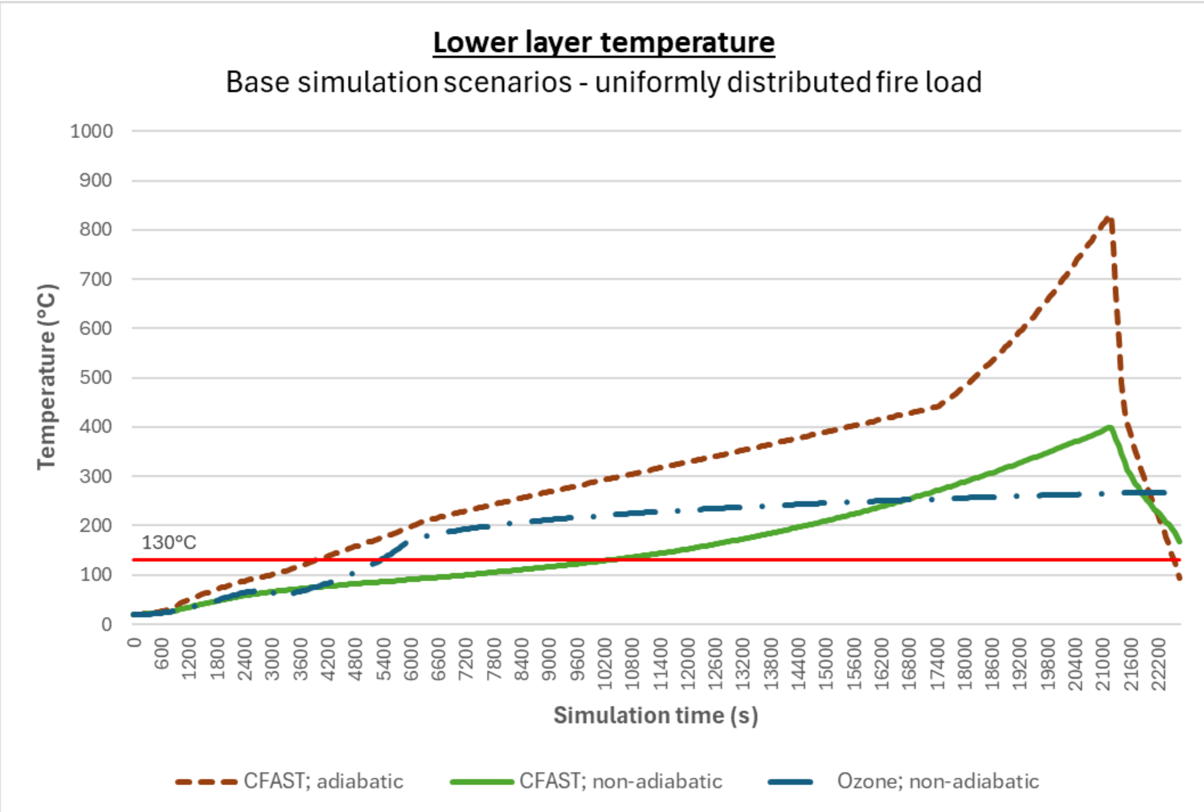

Lower layer temperature - adiabatic
Base simulation scenarios - localized fire loads
Temperature (°C)
225
200
175
150
125
100
75
50
25
0
130°C
0 360 720 1080 1440 1800 2160 2520 2880 3240 3600 3960 4320 4680 5040 5400 5760 6120 6480 6840 7200 7560 7920 8280 8640 9000 9360 9720 10080 10440 10800 11160 11520 11880 12240 12600 12960 13320 13680 14040
Simulation time (s)
4 fire loads
8 fire loads
16 fire loads
32 fire loads

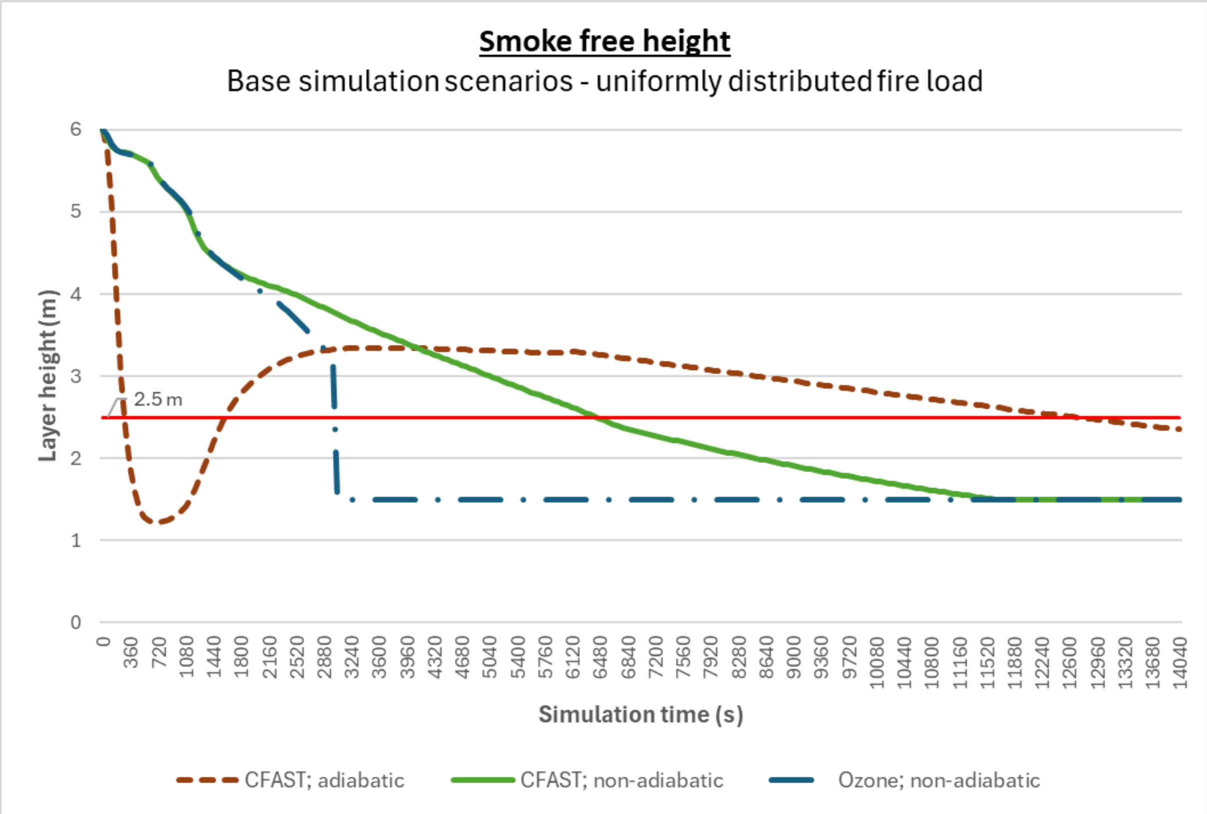

Lower layer temperature - non-adiabatic
Base simulation scenarios - localized fire loads
Temperature (°C)
225
200
175
150
125
100
75
50
25
0
0 360 720 1080 1440 1800 2160 2520 2880 3240 3600 3960 4320 4680 5040 5400 5760 6120 6480 6840 7200 7560 7920 8280 8640 9000 9360 9720 10080 10440 10800 11160 11520 11880 12240 12600 12960 13320 13680 14040
Simulation time (s)
4 fire loads
8 fire loads
16 fire loads
32 fire loads

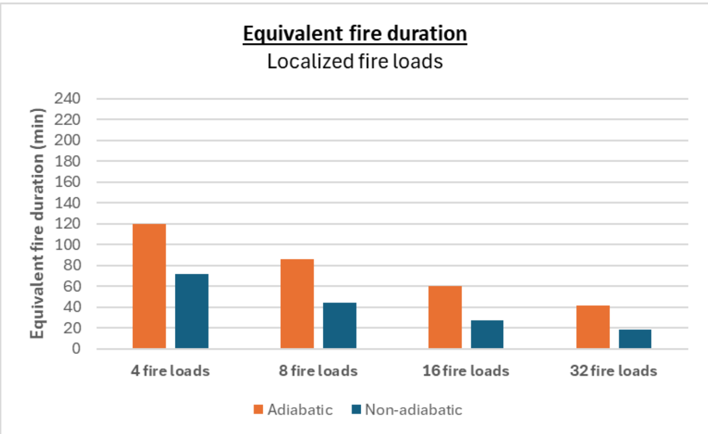

Smoke free height - adiabatic
Base simulation scenarios - localized fire loads
Layer height (m)
2.5 m
Simulation time (s)
4 fire loads
8 fire loads
16 fire loads
32 fire loads

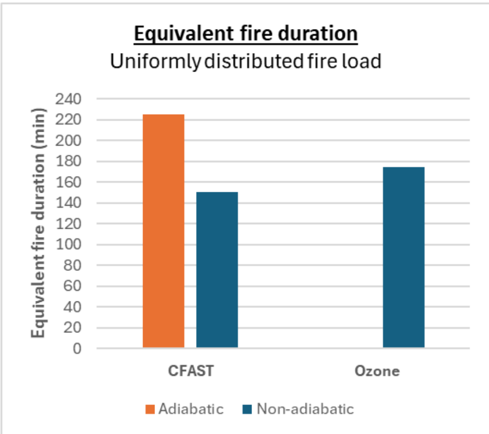

Smoke free height - non-adiabatic
Base simulation scenarios - localized fire loads
Layer height (m)
2.5 m
Simulation time (s)
4 fire loads
8 fire loads
16 fire loads
32 fire loads


Upper layer temperature
Base simulation scenarios - uniformly distributed fire load
Temperature (°C)
500°C
Simulation time (s)
CFAST; adiabatic
CFAST; non-adiabatic
Ozone; non-adiabatic

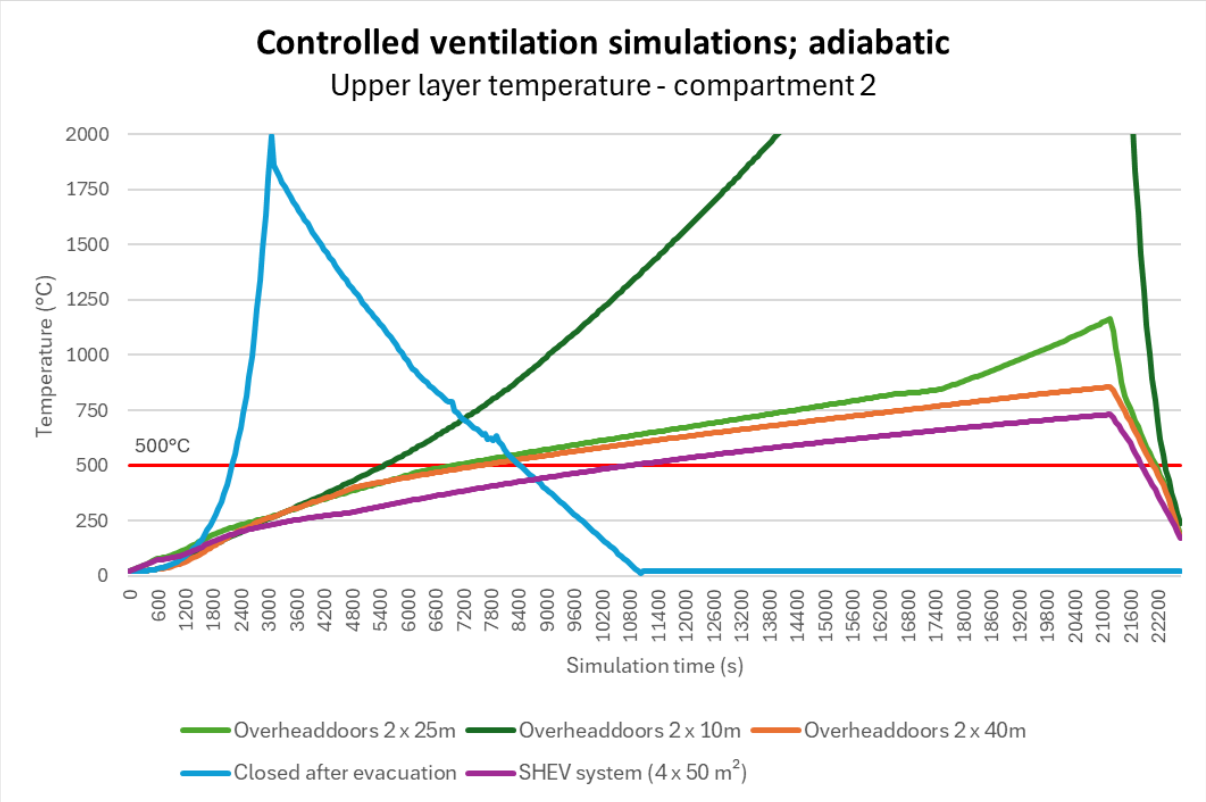

Lower layer temperature
Base simulation scenarios - uniformly distributed fire load
Temperature (°C)
130°C
Simulation time (s)
CFAST; adiabatic
CFAST; non-adiabatic
Ozone; non-adiabatic

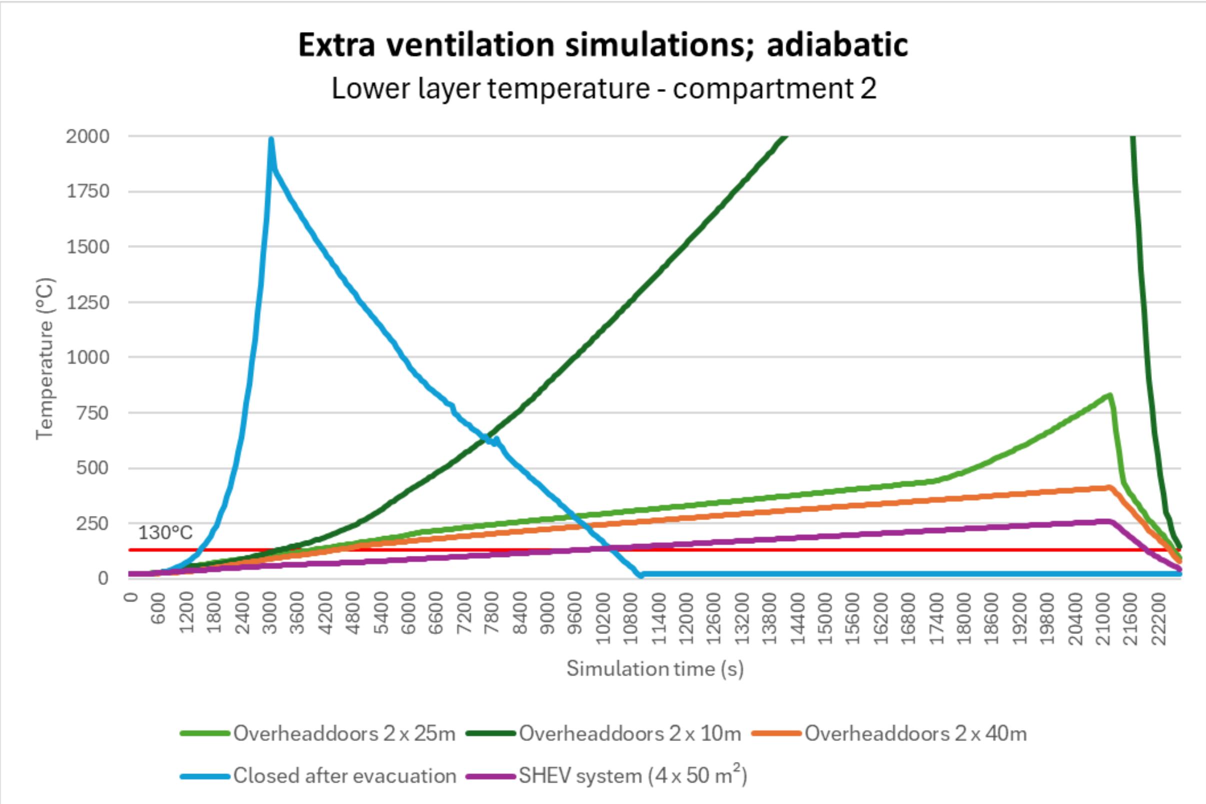

Smoke free height
Base simulation scenarios - uniformly distributed fire load
Layer height (m)
2.5 m
Simulation time (s)
CFAST; adiabatic
CFAST; non-adiabatic
Ozone; non-adiabatic

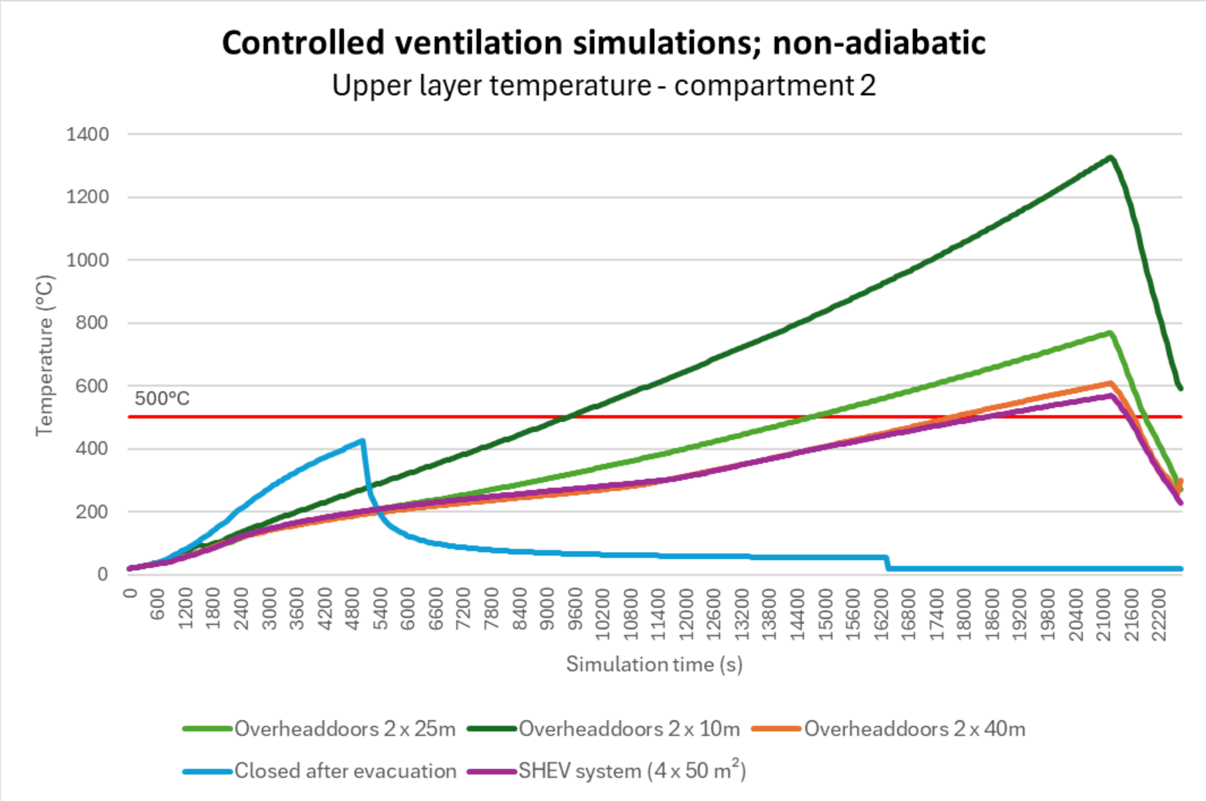

Equivalent fire duration
Localized fire loads
Equivalent fire duration (min)
4 fire loads
8 fire loads
16 fire loads
32 fire loads
Adiabatic
Non-adiabatic

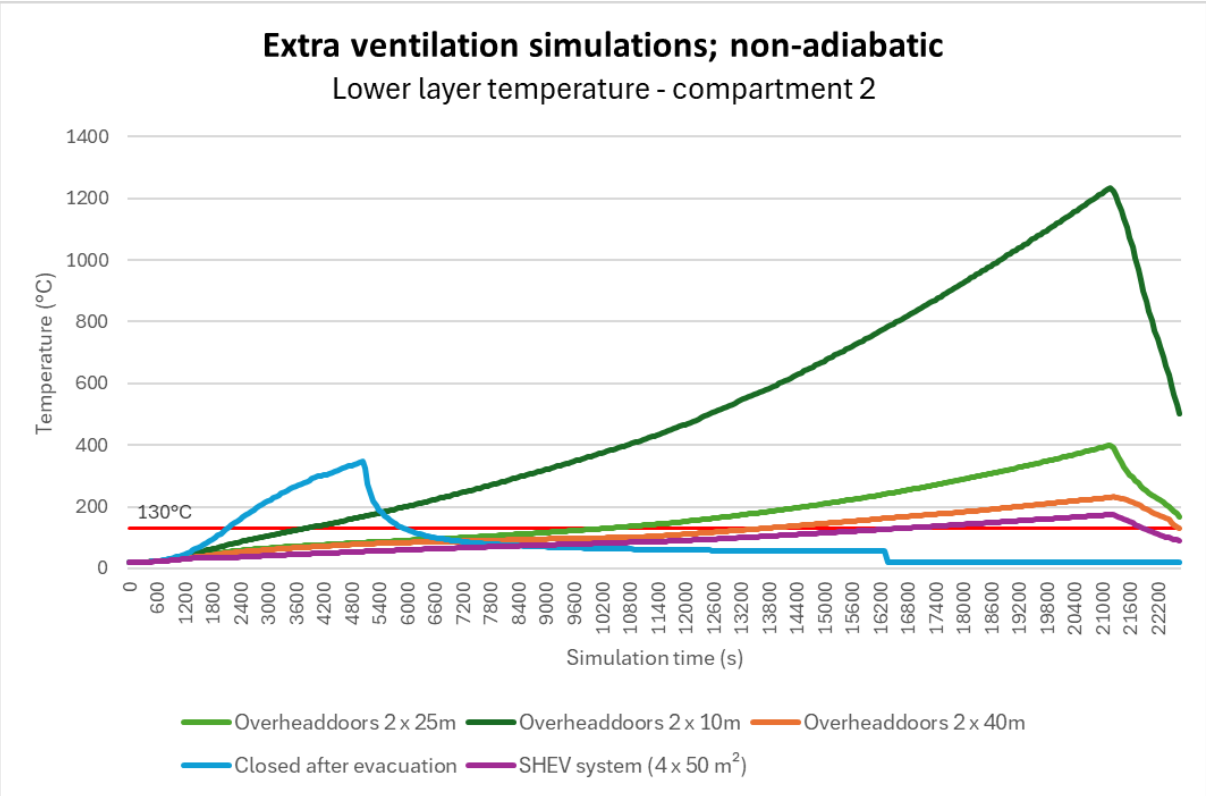

Equivalent fire duration
Uniformly distributed fire load
Equivalent fire duration (min)
CFAST
Ozone
Adiabatic
Non-adiabatic

## A2. Figures controlled ventilation simulation scenarios

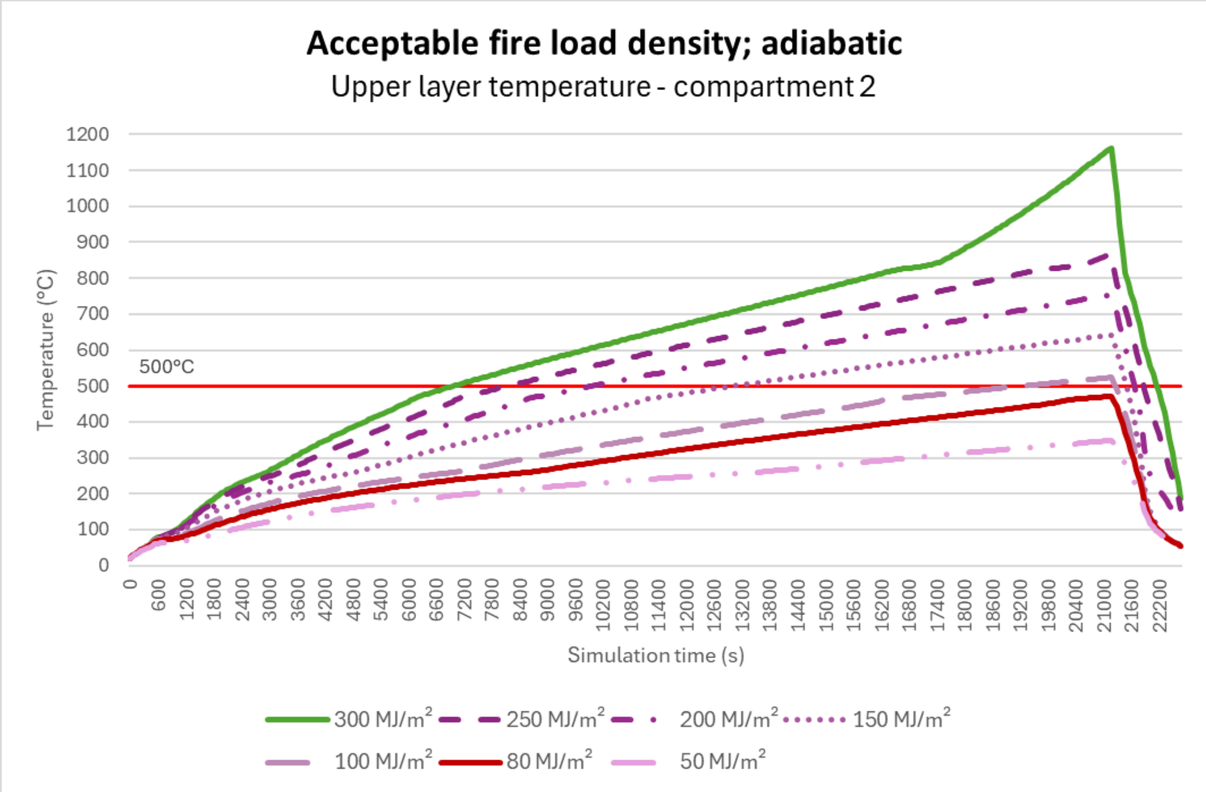


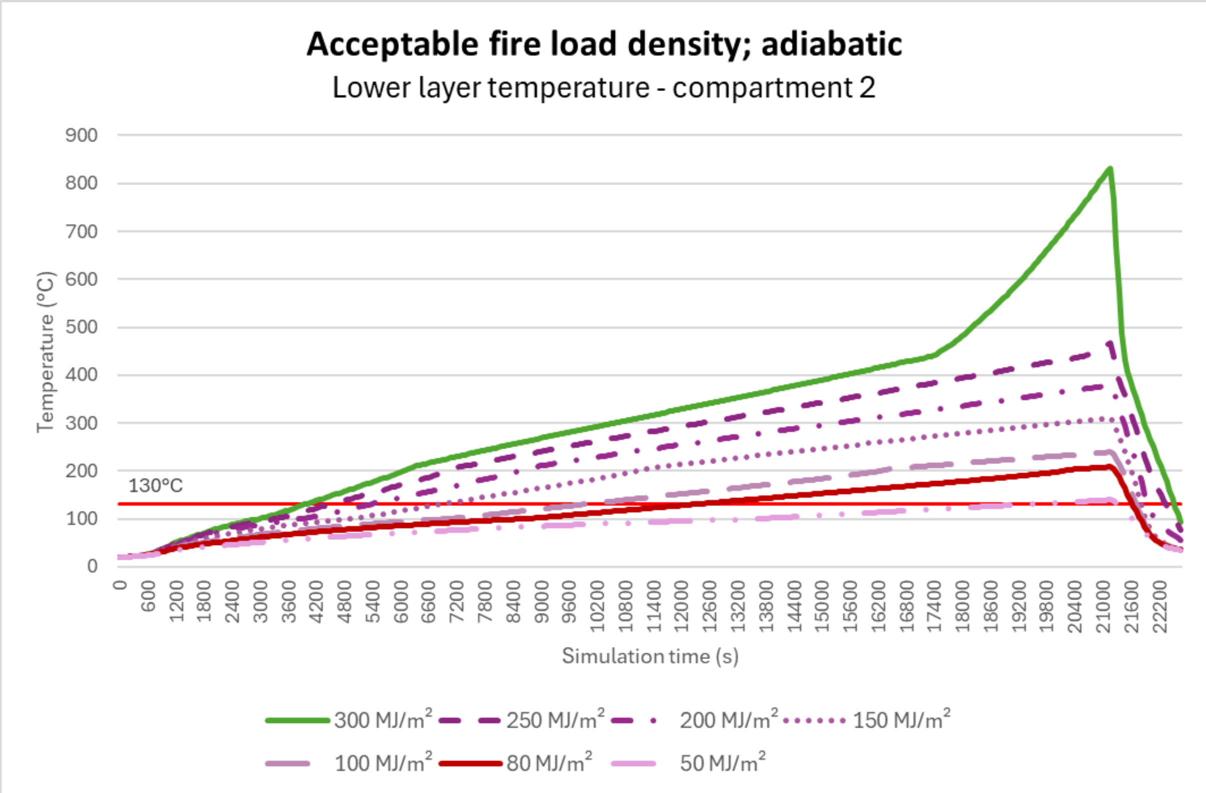



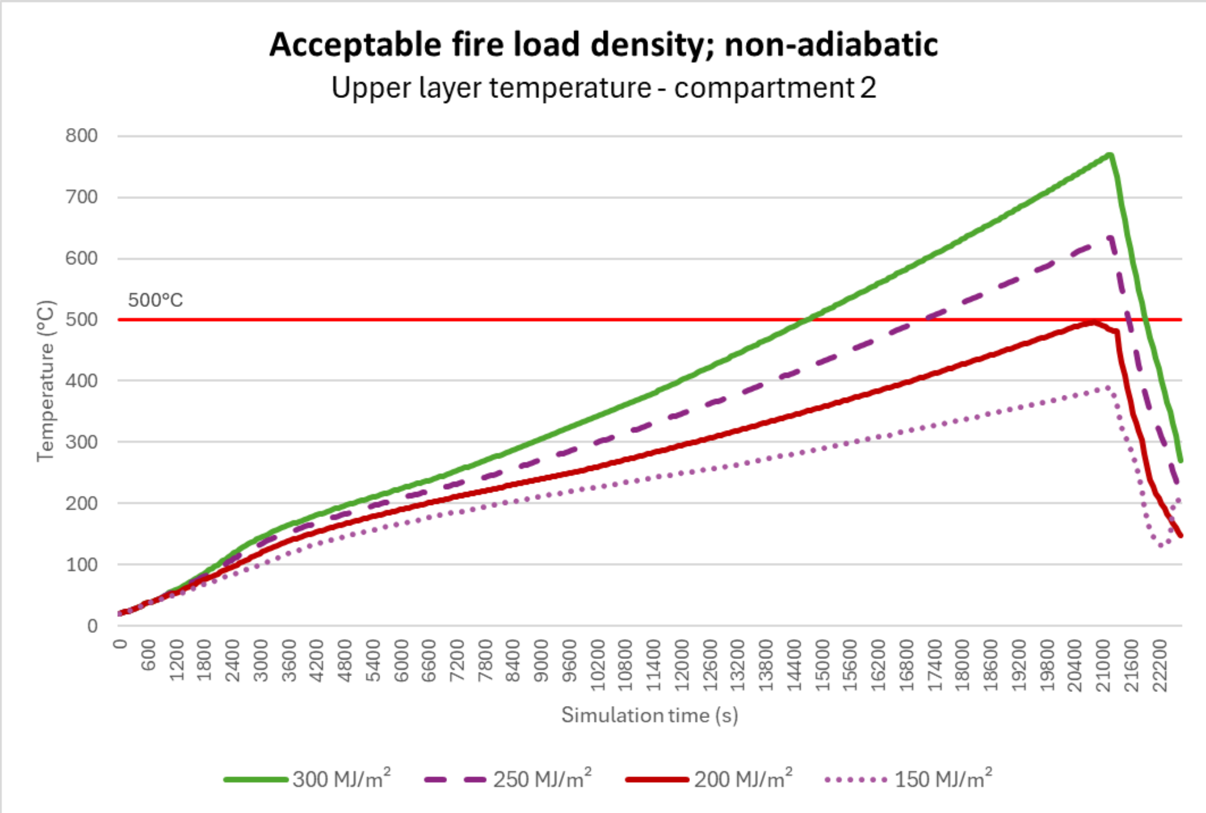

Controlled ventilation simulations; non-adiabatic
Upper layer temperature - compartment 2
Temperature (°C)
500°C
Simulation time (s)
Overheaddoors 2 x 25m
Overheaddoors 2 x 10m
Overheaddoors 2 x 40m
Closed after evacuation
SHEV system (4 x 50 m²)


Extra ventilation simulations; non-adiabatic
Lower layer temperature - compartment 2
Temperature (°C)
130°C
Simulation time (s)
Overheaddoors 2 x 25m
Overheaddoors 2 x 10m
Overheaddoors 2 x 40m
Closed after evacuation
SHEV system (4 x 50 m²)

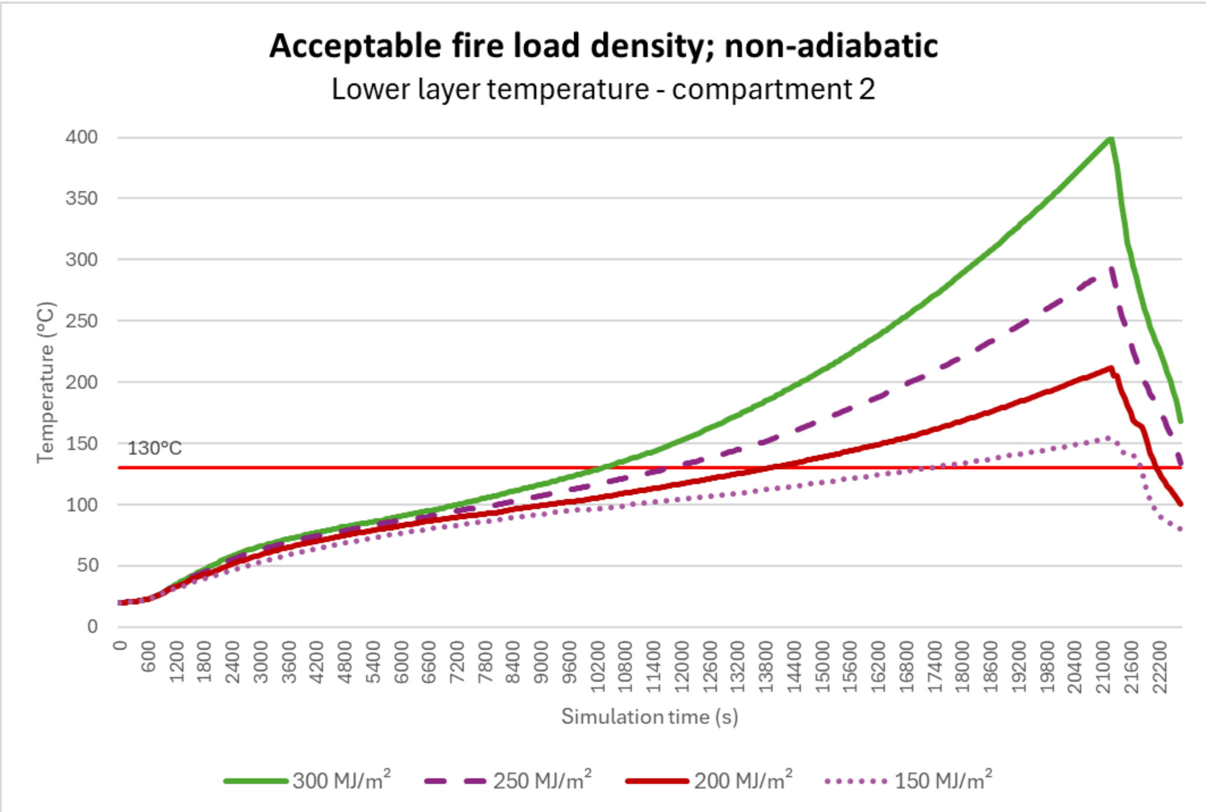
## A3. Figures acceptable fire load density simulation scenarios





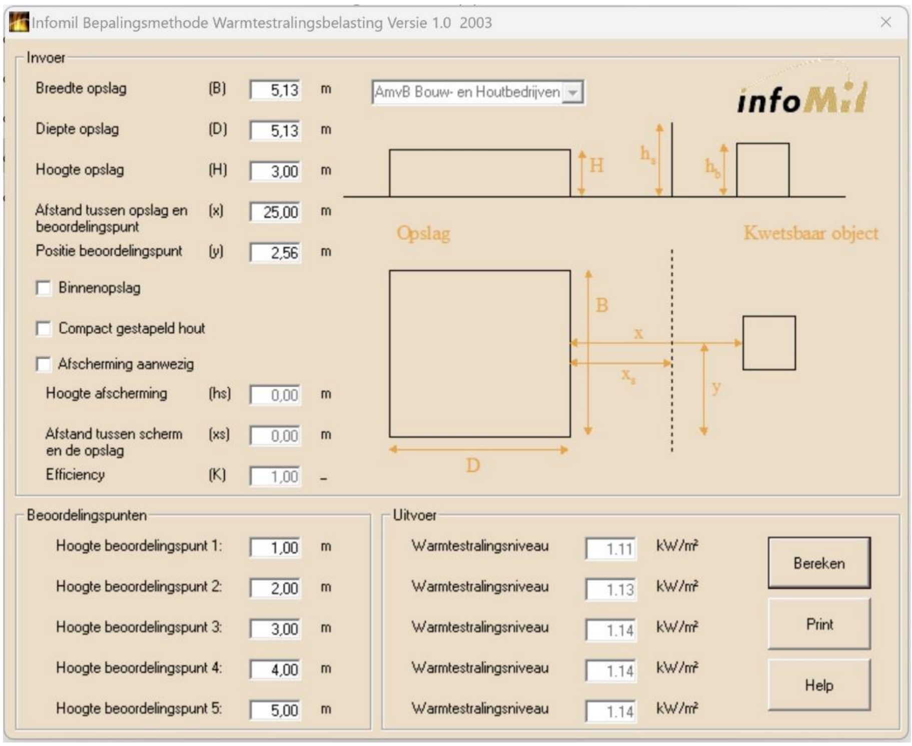
Acceptable fire load density; non-adiabatic
Upper layer temperature - compartment 2
800
700
600
500°C
500
400
300
200
100
0
Temperature (°C)
0
600
1200
1800
2400
3000
3600
4200
4800
5400
6000
6600
7200
7800
8400
9000
9600
10200
10800
11400
12000
12600
13200
13800
14400
15000
15600
16200
16800
17400
18000
18600
19200
19800
20400
21000
21600
22200
Simulation time (s)
300 MJ/m2
250 MJ/m2
200 MJ/m2
150 MJ/m2

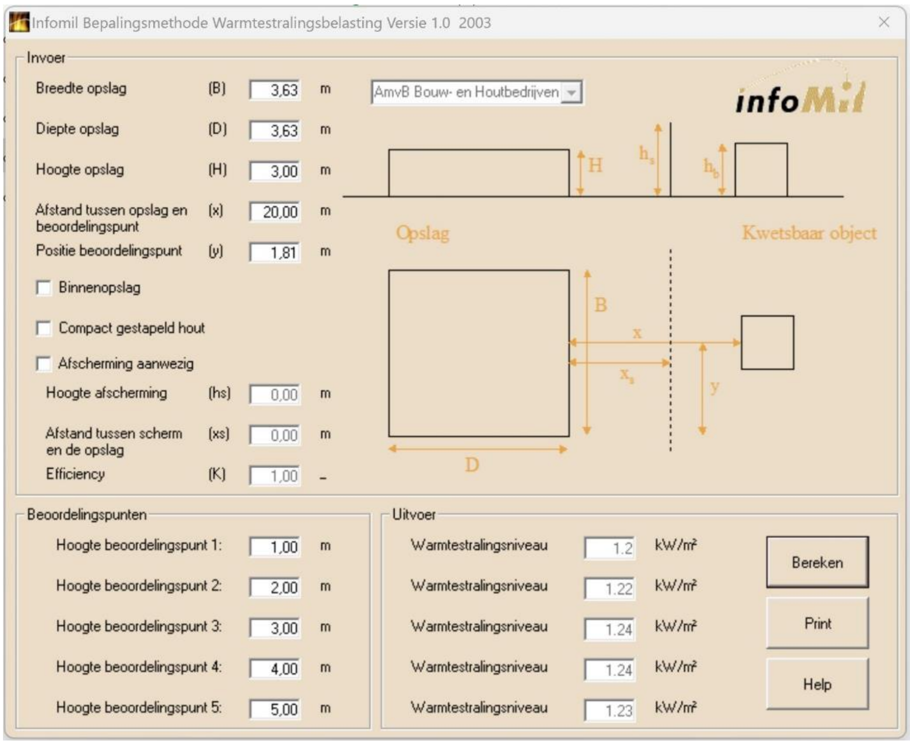
Acceptable fire load density; non-adiabatic
Lower layer temperature - compartment 2
400
350
300
250
200
150
130°C
100
50
0
Temperature (°C)
0
600
1200
1800
2400
3000
3600
4200
4800
5400
6000
6600
7200
7800
8400
9000
9600
10200
10800
11400
12000
12600
13200
13800
14400
15000
15600
16200
16800
17400
18000
18600
19200
19800
20400
21000
21600
22200
Simulation time (s)
300 MJ/m2
250 MJ/m2
200 MJ/m2
150 MJ/m2

# A4. Results 'Stralingsbelasting' program from InfoMil

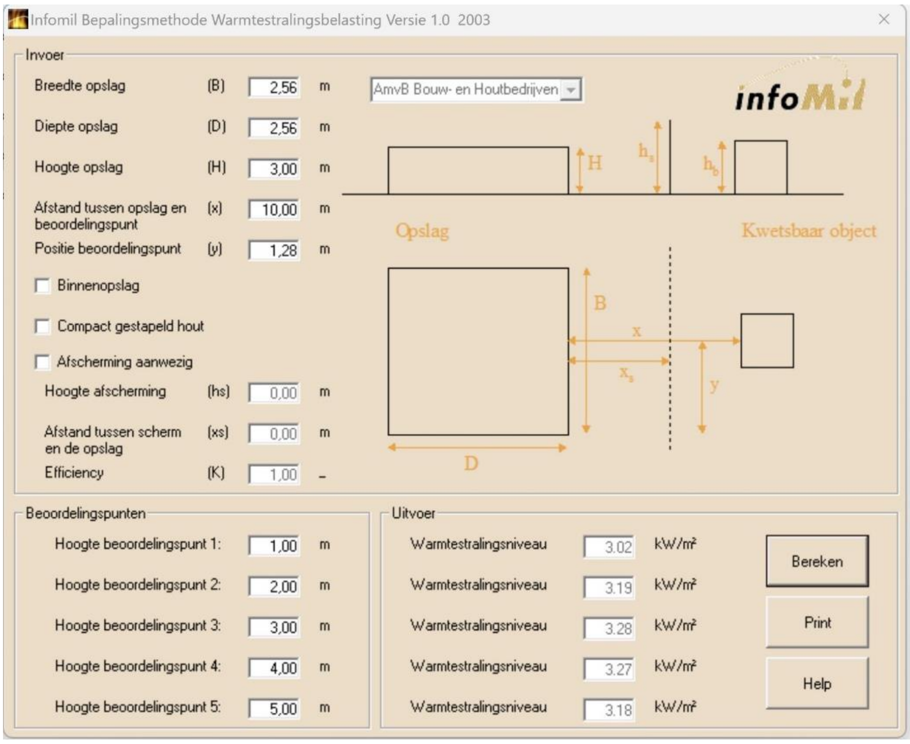
## *4 fire loads*



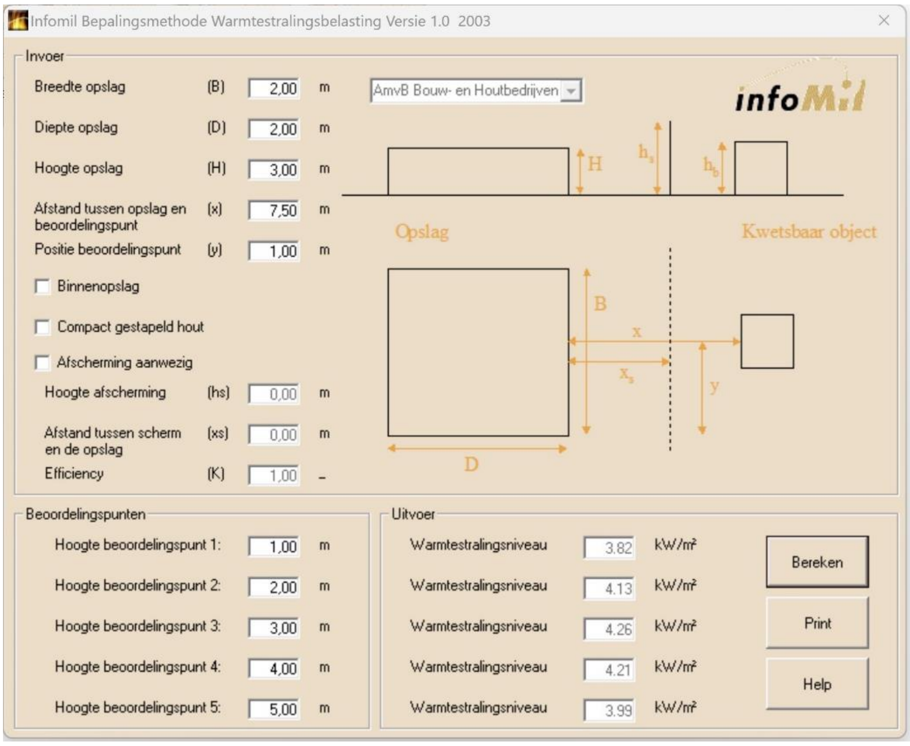

## *8 fire loads*



### *16 fire loads*




### *32 fire loads*



## A5. Base input file CFAST – uniformly distributed 300 MJ/m$^2$

!! Scenario Configuration

&TIME SIMULATION = 22680 PRINT = 60 SMOKEVIEW = 15 SPREADSHEET = 60 /

&INIT PRESSURE = 101325 RELATIVE_HUMIDITY = 50 INTERIOR_TEMPERATURE = 20 EXTERIOR_TEMPERATURE = 20 /

&MISC LOWER_OXYGEN_LIMIT = 0.1 /

!! Material Properties

&MATL ID = 'NM 1' MATERIAL = 'Adiabat_seperation',

CONDUCTIVITY = 0.01 DENSITY = 10 SPECIFIC_HEAT = 10, THICKNESS = 0.05 EMISSIVITY = 0.9 /

&MATL ID = 'NM 2' MATERIAL = 'Concrete',

CONDUCTIVITY = 2 DENSITY = 2300 SPECIFIC_HEAT = 0.9, THICKNESS = 0.2 EMISSIVITY = 0.9 /

!! Compartments

&COMP ID = 'Comp 1'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 2'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 3'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 4'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 0, 0 GRID = 50, 50, 50 /

!! Wall Vents

&VENT TYPE = 'WALL' ID = 'Open 1-2' COMP_IDS = 'Comp 1', 'Comp 2', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'REAR' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 2-3' COMP_IDS = 'Comp 2', 'Comp 3', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 3-4' COMP_IDS = 'Comp 3', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'FRONT' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 1-4' COMP_IDS = 'Comp 1', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 1' COMP_IDS = 'Comp 1' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT' OFFSET = 12 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 2' COMP_IDS = 'Comp 4' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT' OFFSET = 12 /

!! Fires

&FIRE ID = 'New Fire 1' COMP_ID = 'Comp 2', FIRE_ID = 'Cellulose' LOCATION = 25, 12.5 /

&CHEM ID = 'Cellulose' CARBON = 4 CHLORINE = 0 HYDROGEN = 6 NITROGEN = 0 OXYGEN = 3 HEAT_OF_COMBUSTION = 19000 RADIATIVE_FRACTION = 0.35 /

&TABL ID = 'Cellulose' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' , 'TRACE_YIELD' /

```
&TABL ID = 'Cellulose', DATA = 0, 0, 1.5, 0.01, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 378, 397, 1.5, 1.59, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 756, 1588, 1.5, 6.35, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 1512, 6080, 1.5, 24.32, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 2268, 11120, 1.5, 44.48, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 3024, 16160, 1.5, 64.64, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 3780, 21200, 1.5, 84.8, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 4536, 26240, 1.5, 104.96, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 5292, 31280, 1.5, 125.12, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 6048, 36320, 1.5, 145.28, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 6804, 41360, 1.5, 165.44, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 7560, 46400, 1.5, 185.6, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 8316, 51440, 1.5, 205.76, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 9072, 56480, 1.5, 225.92, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 9828, 61520, 1.5, 246.08, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 10584, 66560, 1.5, 266.24, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 11340, 71600, 1.5, 286.4, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 12096, 76640, 1.5, 306.56, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 12852, 81680, 1.5, 326.72, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 13608, 86720, 1.5, 346.88, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 14364, 91760, 1.5, 367.04, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 15120, 96800, 1.5, 387.2, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 15876, 101840, 1.5, 407.36, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 16632, 106880, 1.5, 427.52, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 17388, 111920, 1.5, 447.68, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 18144, 116960, 1.5, 467.84, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 18900, 122000, 1.5, 488, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 19656, 127040, 1.5, 508.16, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 20412, 132080, 1.5, 528.32, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 21168, 137120, 1.5, 548.48, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 21924, 56988, 1.5, 227.95, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 22680, 0, 1.5, 0.09, 0.01, 0.025, 0, 0, 0 /
```

## A6. BASE INPUT FILE CFAST – 4 LOCALIZED FIRE LOADS

!! Scenario Configuration

&TIME SIMULATION = 14310 PRINT = 60 SMOKEVIEW = 15 SPREADSHEET = 60 /

&INIT PRESSURE = 101325 RELATIVE_HUMIDITY = 50 INTERIOR_TEMPERATURE = 20 EXTERIOR_TEMPERATURE = 20 /

&MISC LOWER_OXYGEN_LIMIT = 0.1 /

!! Material Properties

&MATL ID = 'NM 1' MATERIAL = 'Adiabat_seperation',

CONDUCTIVITY = 0.01 DENSITY = 10 SPECIFIC_HEAT = 10, THICKNESS = 0.05 EMISSIVITY = 0.9 /

&MATL ID = 'NM 2' MATERIAL = 'Concrete',

CONDUCTIVITY = 2 DENSITY = 2300 SPECIFIC_HEAT = 0.9, THICKNESS = 0.2 EMISSIVITY = 0.9 /

!! Compartments

&COMP ID = 'Comp 1'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 2'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 3'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 4'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 0, 0 GRID = 50, 50, 50 /

!! Wall Vents

&VENT TYPE = 'WALL' ID = 'Open 1-2' COMP_IDS = 'Comp 1', 'Comp 2', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'REAR'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 2-3' COMP_IDS = 'Comp 2', 'Comp 3', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 3-4' COMP_IDS = 'Comp 3', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'FRONT'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 1-4' COMP_IDS = 'Comp 1', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 1' COMP_IDS = 'Comp 1' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT'  OFFSET = 12 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 2' COMP_IDS = 'Comp 4' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT'  OFFSET = 12 /

!! Fires

&FIRE ID = 'New Fire 1'  COMP_ID = 'Comp 2', FIRE_ID = 'Cellulose'  LOCATION = 25, 12.5 /

&CHEM ID = 'Cellulose' CARBON = 4 CHLORINE = 0 HYDROGEN = 6 NITROGEN = 0 OXYGEN = 3 HEAT_OF_COMBUSTION = 19000 RADIATIVE_FRACTION = 0.35 /

&TABL ID = 'Cellulose' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' , 'TRACE_YIELD'  /

&TABL ID = 'Cellulose', DATA = 0, 0, 1.5, 26.32, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 60, 26316, 1.5, 26.32, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 14250, 26316, 1.5, 26.32, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 14310, 0, 0, 0.0001, 0.01, 0.025, 0, 0, 0 /

&TAIL /

## A7. Base input file CFAST – 8 localized fire loads

!! Scenario Configuration

&TIME SIMULATION = 14310 PRINT = 60 SMOKEVIEW = 15 SPREADSHEET = 60 /

&INIT PRESSURE = 101325 RELATIVE_HUMIDITY = 50 INTERIOR_TEMPERATURE = 20 EXTERIOR_TEMPERATURE = 20 /

&MISC LOWER_OXYGEN_LIMIT = 0.1 /

!! Material Properties

&MATL ID = 'NM 1' MATERIAL = 'Adiabat_separation',

CONDUCTIVITY = 0.01 DENSITY = 10 SPECIFIC_HEAT = 10, THICKNESS = 0.05 EMISSIVITY = 0.9 /

&MATL ID = 'NM 2' MATERIAL = 'Concrete',

CONDUCTIVITY = 2 DENSITY = 2300 SPECIFIC_HEAT = 0.9, THICKNESS = 0.2 EMISSIVITY = 0.9 /

!! Compartments

&COMP ID = 'Comp 1'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 2'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 3'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 4'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 0, 0 GRID = 50, 50, 50 /

!! Wall Vents

&VENT TYPE = 'WALL' ID = 'Open 1-2' COMP_IDS = 'Comp 1', 'Comp 2', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'REAR'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 2-3' COMP_IDS = 'Comp 2', 'Comp 3', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 3-4' COMP_IDS = 'Comp 3', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'FRONT'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 1-4' COMP_IDS = 'Comp 1', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT'  OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 1' COMP_IDS = 'Comp 1' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT'  OFFSET = 12 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 2' COMP_IDS = 'Comp 4' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT'  OFFSET = 12 /

!! Fires

&FIRE ID = 'New Fire 1'  COMP_ID = 'Comp 2', FIRE_ID = 'Cellulose'  LOCATION = 25, 12.5 /

&CHEM ID = 'Cellulose' CARBON = 4 CHLORINE = 0 HYDROGEN = 6 NITROGEN = 0 OXYGEN = 3 HEAT_OF_COMBUSTION = 19000 RADIATIVE_FRACTION = 0.35 /

&TABL ID = 'Cellulose' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' , 'TRACE_YIELD'  /

&TABL ID = 'Cellulose', DATA = 0, 0, 1.5, 13.16, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 60, 13158, 1.5, 13.16, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 14250, 13158, 1.5, 13.16, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 14310, 0, 0, 0.0001, 0.01, 0.025, 0, 0, 0 /

&TAIL /

## A8. Base input file CFAST – 16 localized fire loads

!! Scenario Configuration

&TIME SIMULATION = 14310 PRINT = 60 SMOKEVIEW = 15 SPREADSHEET = 60 /

&INIT PRESSURE = 101325 RELATIVE_HUMIDITY = 50 INTERIOR_TEMPERATURE = 20 EXTERIOR_TEMPERATURE = 20 /

&MISC  LOWER_OXYGEN_LIMIT = 0.1 /

!! Material Properties

&MATL ID = 'NM 1' MATERIAL = 'Adiabat_separation',

CONDUCTIVITY = 0.01 DENSITY = 10 SPECIFIC_HEAT = 10, THICKNESS = 0.05 EMISSIVITY = 0.9 /

&MATL ID = 'NM 2' MATERIAL = 'Concrete',

CONDUCTIVITY = 2 DENSITY = 2300 SPECIFIC_HEAT = 0.9, THICKNESS = 0.2 EMISSIVITY = 0.9 /

!! Compartments

&COMP ID = 'Comp 1'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 2'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 3'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 4'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 0, 0 GRID = 50, 50, 50 /

```
!! Wall Vents

&VENT TYPE = 'WALL' ID = 'Open 1-2' COMP_IDS = 'Comp 1', 'Comp 2', BOTTOM = 0 HEIGHT = 6, WIDTH = 50
    FACE = 'REAR'  OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'Open 2-3' COMP_IDS = 'Comp 2', 'Comp 3', BOTTOM = 0 HEIGHT = 6, WIDTH = 25
    FACE = 'RIGHT'  OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'Open 3-4' COMP_IDS = 'Comp 3', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 50
    FACE = 'FRONT'  OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'Open 1-4' COMP_IDS = 'Comp 1', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 25
    FACE = 'RIGHT'  OFFSET = 0 /
&VENT TYPE = 'WALL' ID = 'Overheaddoor 1' COMP_IDS = 'Comp 1' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25
    FACE = 'FRONT'  OFFSET = 12 /
&VENT TYPE = 'WALL' ID = 'Overheaddoor 2' COMP_IDS = 'Comp 4' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25
    FACE = 'FRONT'  OFFSET = 12 /

!! Fires
&FIRE ID = 'New Fire 1'  COMP_ID = 'Comp 2', FIRE_ID = 'Cellulose'  LOCATION = 25, 12.5 /
&CHEM ID = 'Cellulose' CARBON = 4 CHLORINE = 0 HYDROGEN = 6 NITROGEN = 0 OXYGEN = 3 HEAT_OF_COMBUSTION = 19000 RADIATIVE_FRACTION = 0.35 /
&TABL ID = 'Cellulose' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' , 'TRACE_YIELD'  /
&TABL ID = 'Cellulose', DATA = 0, 0, 1.5, 6.58, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 60, 6579, 1.5, 6.58, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 14250, 6579, 1.5, 6.58, 0.01, 0.025, 0, 0, 0 /
&TABL ID = 'Cellulose', DATA = 14310, 0, 0, 0.0001, 0.01, 0.025, 0, 0, 0 /

&TAIL /
```

## A9. BASE INPUT FILE CFAST – 32 LOCALIZED FIRE LOADS

!! Scenario Configuration

&TIME SIMULATION = 14310 PRINT = 60 SMOKEVIEW = 15 SPREADSHEET = 60 /

&INIT PRESSURE = 101325 RELATIVE_HUMIDITY = 50 INTERIOR_TEMPERATURE = 20 EXTERIOR_TEMPERATURE = 20 /

&MISC LOWER_OXYGEN_LIMIT = 0.1 /

!! Material Properties

&MATL ID = 'NM 1' MATERIAL = 'Adiabat_separation',

CONDUCTIVITY = 0.01 DENSITY = 10 SPECIFIC_HEAT = 10, THICKNESS = 0.05 EMISSIVITY = 0.9 /

&MATL ID = 'NM 2' MATERIAL = 'Concrete',

CONDUCTIVITY = 2 DENSITY = 2300 SPECIFIC_HEAT = 0.9, THICKNESS = 0.2 EMISSIVITY = 0.9 /

!! Compartments

&COMP ID = 'Comp 1'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 0, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 2'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 0, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 3'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 25, 0 GRID = 50, 50, 50 /

&COMP ID = 'Comp 4'

DEPTH = 25 HEIGHT = 6 WIDTH = 50

CEILING_MATL_ID = 'NM 1' CEILING_THICKNESS = 0.01 WALL_MATL_ID = 'NM 1' WALL_THICKNESS = 0.01 FLOOR_MATL_ID = 'NM 2' FLOOR_THICKNESS = 0.2

ORIGIN = 50, 0, 0 GRID = 50, 50, 50 /

!! Wall Vents

&VENT TYPE = 'WALL' ID = 'Open 1-2' COMP_IDS = 'Comp 1', 'Comp 2', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'REAR' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 2-3' COMP_IDS = 'Comp 2', 'Comp 3', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 3-4' COMP_IDS = 'Comp 3', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 50

FACE = 'FRONT' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Open 1-4' COMP_IDS = 'Comp 1', 'Comp 4', BOTTOM = 0 HEIGHT = 6, WIDTH = 25

FACE = 'RIGHT' OFFSET = 0 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 1' COMP_IDS = 'Comp 1' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT' OFFSET = 12 /

&VENT TYPE = 'WALL' ID = 'Overheaddoor 2' COMP_IDS = 'Comp 4' 'OUTSIDE' , BOTTOM = 0 HEIGHT = 4, WIDTH = 25

FACE = 'FRONT' OFFSET = 12 /

!! Fires

&FIRE ID = 'New Fire 1' COMP_ID = 'Comp 2', FIRE_ID = 'Cellulose' LOCATION = 25, 12.5 /

&CHEM ID = 'Cellulose' CARBON = 4 CHLORINE = 0 HYDROGEN = 6 NITROGEN = 0 OXYGEN = 3 HEAT_OF_COMBUSTION = 19000 RADIATIVE_FRACTION = 0.35 /

&TABL ID = 'Cellulose' LABELS = 'TIME', 'HRR' , 'HEIGHT' , 'AREA' , 'CO_YIELD' , 'SOOT_YIELD' , 'HCN_YIELD' , 'HCL_YIELD' , 'TRACE_YIELD' /

&TABL ID = 'Cellulose', DATA = 0, 0, 1.5, 3.29, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 60, 3289, 1.5, 3.29, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 14250, 3289, 1.5, 3.29, 0.01, 0.025, 0, 0, 0 /

&TABL ID = 'Cellulose', DATA = 14310, 0, 0, 0.0001, 0.01, 0.025, 0, 0, 0 /

&TAIL /

# A10. Spreadsheet traveling fire base scenario – 300 MJ/m$^2$

**_ONTWIKKELING VAN BRAND_**
**_bij gegeven vuurbelasting in een compartiment_**

| | |
|---|---|
| Project: | ***Masterproject Fire Safety*** |
| Variant: | ***Uniform verdeelde vuurbelasting*** |
| Werknummer: | ***300 MJ/m2*** |
| Initialen: | ***LDO*** |
| Scenario: | ***Brandscenario 1*** |

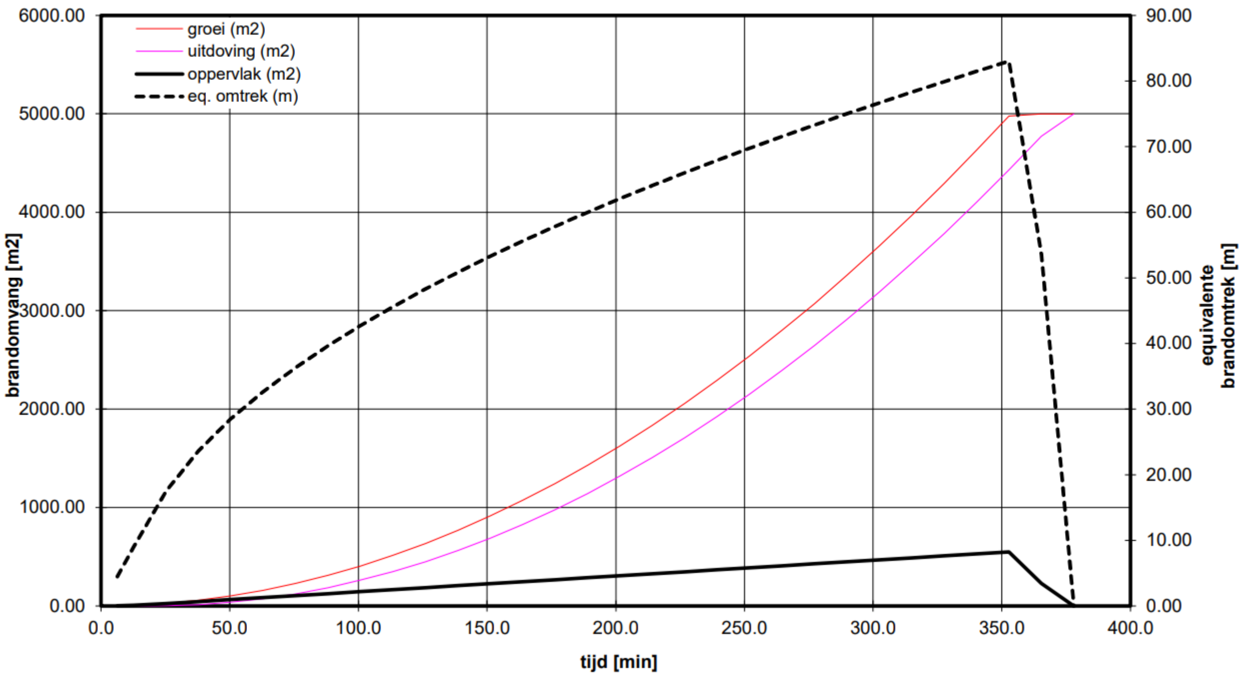
Uitgangspunten

| | | |
|---|---|---|
| referentievermogen | *250* | kW/m$^2$ |
| tijdconstante | *600* | s |
| gemiddelde vuurbelasting | *300* | MJ/m$^2$ |
| verbrandingsefficientie | *0.8* | [0..1] |
| compartimentsoppervlakte | *5000* | m$^2$ |
| eindtijd | *378* | min |

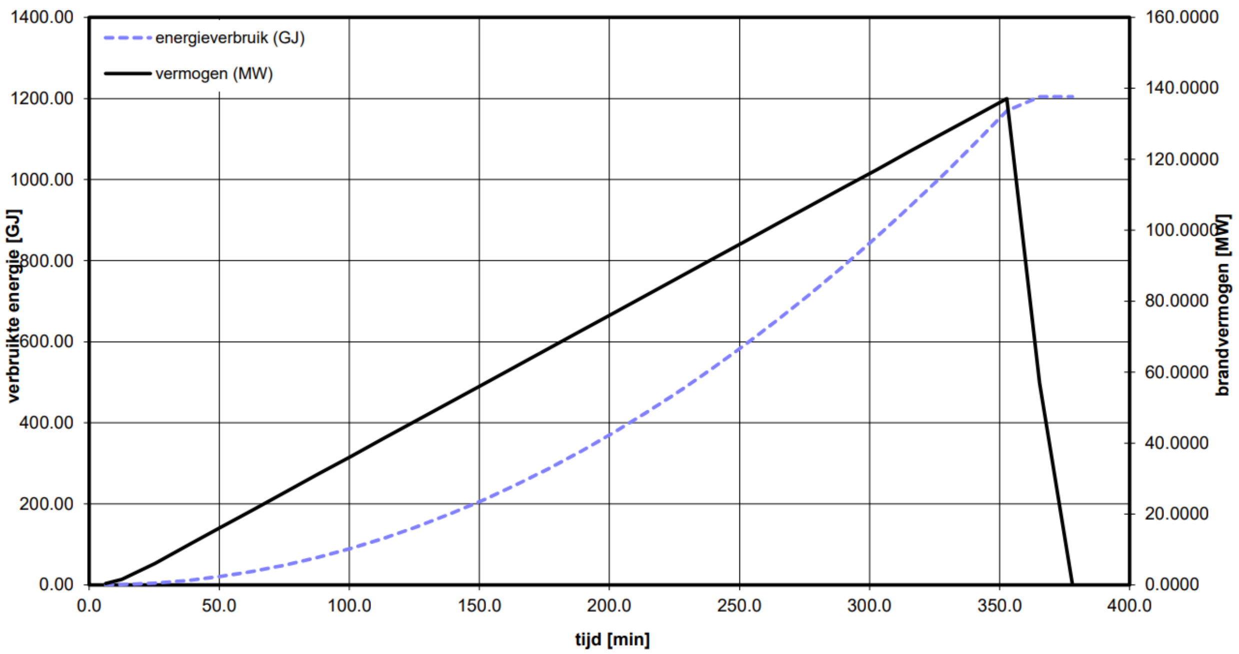
Brandontwikkeling

| | tijd (min) | groei (m2) | uitdoving (m2) | oppervlak (m2) | omtrek (m) | vermogen (MW) | vermogen (kW) | energieverbruik (GJ) | Height (m) |
|---|---|---|---|---|---|---|---|---|---|
| 378 | 6.3 | 1.59 | 0.00 | 1.59 | 4.47 | 0.3969 | 397 | 0.12 | 1.5 |
| 756 | 12.6 | 6.35 | 0.00 | 6.35 | 8.93 | 1.5876 | 1588 | 0.60 | 1.5 |
| 1512 | 25.2 | 25.40 | 1.08 | 24.32 | 17.48 | 6.0800 | 6080 | 4.28 | 1.5 |
| 2268 | 37.8 | 57.15 | 12.67 | 44.48 | 23.64 | 11.1200 | 11120 | 11.00 | 1.5 |
| 3024 | 50.4 | 101.61 | 36.97 | 64.64 | 28.50 | 16.1600 | 16160 | 20.78 | 1.5 |
| 3780 | 63.0 | 158.76 | 73.96 | 84.80 | 32.64 | 21.2000 | 21200 | 33.60 | 1.5 |
| 4536 | 75.6 | 228.61 | 123.65 | 104.96 | 36.32 | 26.2400 | 26240 | 49.47 | 1.5 |
| 5292 | 88.2 | 311.17 | 186.05 | 125.12 | 39.65 | 31.2800 | 31280 | 68.39 | 1.5 |
| 6048 | 100.8 | 406.43 | 261.15 | 145.28 | 42.73 | 36.3200 | 36320 | 90.35 | 1.5 |
| 6804 | 113.4 | 514.38 | 348.94 | 165.44 | 45.60 | 41.3600 | 41360 | 115.37 | 1.5 |
| 7560 | 126.0 | 635.04 | 449.44 | 185.60 | 48.29 | 46.4000 | 46400 | 143.43 | 1.5 |
| 8316 | 138.6 | 768.40 | 562.64 | 205.76 | 50.85 | 51.4400 | 51440 | 174.54 | 1.5 |
| 9072 | 151.2 | 914.46 | 688.54 | 225.92 | 53.28 | 56.4800 | 56480 | 208.70 | 1.5 |
| 9828 | 163.8 | 1073.22 | 827.14 | 246.08 | 55.61 | 61.5200 | 61520 | 245.91 | 1.5 |
| 10584 | 176.4 | 1244.68 | 978.44 | 266.24 | 57.84 | 66.5600 | 66560 | 286.16 | 1.5 |
| 11340 | 189.0 | 1428.84 | 1142.44 | 286.40 | 59.99 | 71.6000 | 71600 | 329.47 | 1.5 |
| 12096 | 201.6 | 1625.70 | 1319.14 | 306.56 | 62.07 | 76.6400 | 76640 | 375.82 | 1.5 |
| 12852 | 214.2 | 1835.27 | 1508.55 | 326.72 | 64.08 | 81.6800 | 81680 | 425.22 | 1.5 |
| 13608 | 226.8 | 2057.53 | 1710.65 | 346.88 | 66.02 | 86.7200 | 86720 | 477.67 | 1.5 |
| 14364 | 239.4 | 2292.49 | 1925.45 | 367.04 | 67.91 | 91.7600 | 91760 | 533.16 | 1.5 |
| 15120 | 252.0 | 2540.16 | 2152.96 | 387.20 | 69.75 | 96.8000 | 96800 | 591.71 | 1.5 |
| 15876 | 264.6 | 2800.53 | 2393.17 | 407.36 | 71.55 | 101.8400 | 101840 | 653.30 | 1.5 |
| 16632 | 277.2 | 3073.59 | 2646.07 | 427.52 | 73.30 | 106.8800 | 106880 | 717.94 | 1.5 |
| 17388 | 289.8 | 3359.36 | 2911.68 | 447.68 | 75.00 | 111.9200 | 111920 | 785.63 | 1.5 |
| 18144 | 302.4 | 3657.83 | 3189.99 | 467.84 | 76.67 | 116.9600 | 116960 | 856.37 | 1.5 |
| 18900 | 315.0 | 3969.00 | 3481.00 | 488.00 | 78.31 | 122.0000 | 122000 | 930.15 | 1.5 |
| 19656 | 327.6 | 4292.87 | 3784.71 | 508.16 | 79.91 | 127.0400 | 127040 | 1006.99 | 1.5 |
| 20412 | 340.2 | 4629.44 | 4101.12 | 528.32 | 81.48 | 132.0800 | 132080 | 1086.87 | 1.5 |
| 21168 | 352.8 | 4978.71 | 4430.23 | 548.48 | 83.02 | 137.1200 | 137120 | 1169.80 | 1.5 |
| 21924 | 365.4 | 5000.00 | 4772.05 | 227.95 | 53.52 | 56.9884 | 56988 | 1204.27 | 1.5 |
| 22680 | 378.0 | 5000.00 | 5000.00 | 0.00 | 0.00 | 0.0000 | 0 | 1204.27 | 1.5 |
| | | | | | | *verbruikte vuurlast:* | | 63382 kg vurenhout | |

**Brandontwikkeling**
**geometrisch verloop**




**Brandontwikkeling**
**energetisch verloop**



## A11. Output Ozone

Area of the floor of the compartment [m2] 5000.00

Height of the compartment [m] 6.00

Initial temperature [K] 293.00

Initial pressure [Pa] 101325.00

Combustion Heat of fuel [J/kg] 14000000.

Maximum timestep used by the solver [s] 60.00

Timestep to print the results [s] 60.00

Time of the end of the calculation [s] 22680.00

**********************************************

Type of the ceiling [] 0

Area of the ceiling [m2] 5000.00

Number of elements in the ceiling [] 7

Length/material of element n° 1, [m]/[], 0.01/ 1

Length/material of element n° 2, [m]/[], 0.01/ 1

Length/material of element n° 3, [m]/[], 0.01/ 1

Length/material of element n° 4, [m]/[], 0.01/ 1

Length/material of element n° 5, [m]/[], 0.01/ 1

Length/material of element n° 6, [m]/[], 0.01/ 1

Length/material of element n° 7, [m]/[], 0.01/ 1

Area of the floor [m2] 5000.00

Number of elements in the ceiling [] 7

Length/material of element n° 1, [m]/[], 0.03/ 2

Length/material of element n° 2, [m]/[], 0.03/ 2

Length/material of element n° 3, [m]/[], 0.03/ 2

Length/material of element n° 4, [m]/[], 0.03/ 2

Length/material of element n° 5, [m]/[], 0.03/ 2

Length/material of element n° 6, [m]/[], 0.03/ 2

Length/material of element n° 7, [m]/[], 0.03/ 2

Length of the wall n° 1 [m2] 50.00

Number of elements in this wall [] 7

Length/material of element n° 1, [m]/[], 0.01/ 1

Length/material of element n° 2, [m]/[], 0.01/ 1

Length/material of element n° 3, [m]/[], 0.01/ 1

Length/material of element n° 4, [m]/[], 0.01/ 1

Length/material of element n° 5, [m]/[], 0.01/ 1

Length/material of element n° 6, [m]/[], 0.01/ 1

Length/material of element n° 7, [m]/[], 0.01/ 1

Length of the wall n° 2 [m2] 100.00

Number of elements in this wall [] 7

Length/material of element n° 1, [m]/[], 0.01/ 1

Length/material of element n° 2, [m]/[], 0.01/ 1

Length/material of element n° 3, [m]/[], 0.01/ 1

Length/material of element n° 4, [m]/[], 0.01/ 1

Length/material of element n° 5, [m]/[], 0.01/ 1

Length/material of element n° 6, [m]/[], 0.01/ 1

Length/material of element n° 7, [m]/[], 0.01/ 1

Length of the wall n° 3 [m2] 50.00

Number of elements in this wall [] 7

Length/material of element n° 1, [m]/[], 0.01/ 1

Length/material of element n° 2, [m]/[], 0.01/ 1

Length/material of element n° 3, [m]/[], 0.01/ 1

Length/material of element n° 4, [m]/[], 0.01/ 1

Length/material of element n° 5, [m]/[], 0.01/ 1

Length/material of element n° 6, [m]/[], 0.01/ 1

Length/material of element n° 7, [m]/[], 0.01/ 1

Length of the wall n° 4 [m2] 100.00

Number of elements in this wall [] 7

Length/material of element n° 1, [m]/[], 0.01/ 1

Length/material of element n° 2, [m]/[], 0.01/ 1

Length/material of element n° 3, [m]/[], 0.01/ 1

Length/material of element n° 4, [m]/[], 0.01/ 1

Length/material of element n° 5, [m]/[], 0.01/ 1

Length/material of element n° 6, [m]/[], 0.01/ 1

Length/material of element n° 7, [m]/[], 0.01/ 1

*********************************************

Number of materials for partitions [] 2

Material N° 1

Density [kg/m3] 10.00

Conductivity [W/(mK)] 0.00

Specific heat [J/(kgK)] 10.00

Relative emisivity, inside surface [] 0.90

Relative emisivity, outside surface [] 0.90

Convection coef., inside surf. [W/(m2K)] 25.00

Convection coef., outside surf. [W/(m2K)] 9.00

Material N° 2

Density [kg/m3] 2300.00

Conductivity [W/(mK)] 0.00

Specific heat [J/(kgK)] 0.90

Relative emisivity, inside surface [] 0.90

Relative emisivity, outside surface [] 0.90

Convection coef., inside surf. [W/(m2K)] 25.00

Convection coef., outside surf. [W/(m2K)] 9.00

*********************************************

Number of openings [] 2

Opening N° 1

Heigth of the sill of the opening [m] 0.00

Heigth of the soffit of the opening [m] 4.00

Width of the opening [m] 25.00

Contraction coef. (Bernoulli) [] 0.70

Opening N° 2

Heigth of the sill of the opening [m] 0.00

Heigth of the soffit of the opening [m] 4.00

Width of the opening [m] 25.00

Contraction coef. (Bernoulli) [] 0.70

*********************************************

The pyrolisis rate is defined by a t2 curve, a plateau

and a linear decrease. The 4 parameters are:

rmfmax,tplateau,tendplateau,tendfire,rfireareamax,RHRf

66.6354 18326. 18326. 23562. 5000. 250000.

*********************************************

The number of forced vent is 0

*********************************************

The number of horizontal vent group is 0

*********************************************

The maximum fire area (5000.00m²) is greater than 25% of the floor area (5000.00m²). The fire load is uniformly distributed.

*********************************************

## A12. Spreadsheets equivalent fire duration

*Equivalent fire duration – uniformly distributed fire load (CFAST)*

*Adiabatic*

Equivalent%20fire%20duration%2

*Non-adiabatic*

Equivalent%20fire%20duration%2

*Equivalent fire duration – uniformly distributed fire load (Ozone)*

*Non-adiabatic*

Equivalent%20fire%20duration%2

*Equivalent fire duration – 4 localized fire loads (CFAST)*

*Adiabatic*

Equivalent%20fire%20duration%2

*Non-adiabatic*

Equivalent%20fire%20duration%2

*Equivalent fire duration – 8 localized fire loads (CFAST)*

*Adiabatic*

Equivalent%20fire%20duration%2

*Non-adiabatic*

Equivalent%20fire%20duration%2

*Equivalent fire duration – 16 localized fire loads (CFAST)*

*Adiabatic*

Equivalent%20fire%20duration%2

*Non-adiabatic*

Equivalent%20fire%20duration%2

*Equivalent fire duration – 32 localized fire loads (CFAST)*

*Adiabatic*

Equivalent%20fire%20duration%2

*Non-adiabatic*

Equivalent%20fire%20duration%2