STUDY REPORT

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Effective Passive Roof Venting using Roof Panels in the Event of a Fire

Part 1: Preliminary Modelling Results

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Preface

This report was prepared as a result of a preliminary modelling investigation of material characteristics, general designs and test methods for passive roof venting during a fire event to determine appropriate standard test methods, performance criteria and any other design requirements for recommendations for achieving effective fire venting.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for regulatory authorities, researchers, manufacturers, fire engineers and designers.

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Reference

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Abstract

This report comprises Part 1 of a three-part series on aspects investigating passive buoyancy-driven roof fire vents in large floor area single storey buildings.

The objective of this report is to present and discuss the preliminary modelling performed to investigate required general material properties and building design for fire venting using roofing panels that are assumed to form openings when exposed to hot combustion gases. Recommendations based on the analysis of this investigation are presented.

The scope of this report is limited to researching the appropriateness of buoyancy-driven fire venting relying on the passive failure and subsequent dislodgement of plastic materials to create the opening of the roof vent within the limitations of the modelling approaches applied. Assessment of specific materials and proprietary systems was outside the scope of this project, since roof construction method, specific engineering additives to the base material and geometry (e.g. thickness) contribute to the fire venting performance of the sheeting.

Performance criteria for roof venting is defined for this research as at the time first fire suppression activities begin (which is assumed to be 1,000 s) the conditions within the building are:

- a maximum incident radiation of 4.5 kW/m² at 1.5 m above the floor,
- a minimum height to the bottom of the smoke layer of 2.0 m (visibility of 20 m), and
- a maximum gas temperature of 573 K.

A field modelling approach, using the software package FDS, was used to compare scenarios of:

1. no venting and no smoke reservoirs,
2. fire venting via passive roofing panels with no smoke reservoirs,
3. fire venting via passive roofing panels with smoke reservoirs, and
4. fire venting via a thermally activated dedicated vent system with smoke reservoirs.

This approach was used to assess the influence of venting parameters, including vent location, effective activation temperatures, effective response time indices (RTIs), design fire peak heat release rate (HRR), wind speed, compartment height, etc., on compartment conditions when using potential passive roofing panel venting.

From the analysis presented here alone a definitive answer cannot be ascertained for the potential use of plastic panels for passive fire venting. Results from the experimental investigation of the plastic panels are necessary before a definitive conclusion can be drawn. However several important aspects are highlighted in the results of this study. Some of the more important results include:

1. It is imperative that the intent of ‘effective fire venting’ is defined by the regulator.
2. Buoyancy-driven vents have a high sensitivity to ambient wind conditions. This is expected in particular for winds that are not parallel to the ground.
3. Location of the panels is important. The larger the area of potential venting closer to the seat of the fire, the earlier openings form for venting and subsequently the earlier the venting effects on the conditions within the compartment.
4. The effective RTI and effective activation temperature values would need to be estimated from testing for each material and building design. Underestimating these values would provide model results that overestimate the fire venting effectiveness in the design.
5. Smoke baffles play an important role in limiting the spread of hot gases across the ceiling of the compartment and aiding passive venting of hot gases and smoke.
6. Quasi-steady-state conditions were observed to form within the vented compartment for the scenarios considered. Therefore finding a combination of appropriate materials and appropriate location of passive venting panels for a compartment design may be able to achieve the performance criteria, discussed in Section 3.2, or other selected values for a defined range of design fires and the ambient conditions.

These results are important aspects of design of passive buoyancy-driven roof venting and should be considered in both design and assessment stages.

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Abbreviations

Amd.	Amendment
max.	maximum
constr.	construction
compart.	compartment

Acronyms

C/AS1	Fire Safety Compliance Documents (C Clauses), Acceptable Solution
FHC	Fire Hazard Category
FLED	Fire Load Effective Design
HRR	Heat Release Rate
NZ	New Zealand
NZBC	New Zealand Building Code
NZFS	New Zealand Fire Service
RTI	Response Time Index
US	United States (of America)

Nomenclature

A	horizontal cross-sectional area of the enclosure (m²)
A_i	total area of all inlets (m²)
A_{inlet}	inlet area (m²)
A_{vent}	vent area (m²)
A_v	measured throat area of ventilators for the reservoir being considered (m²)
$A_v C_v$	aerodynamic free area of natural ventilation (m²)
C_d	coefficient of discharge (~0.6)
C_i	entry coefficient for inlets (dimensionless)
C_P	specific heat of ambient air (1.004 kJ/kg.K)
C_v	coefficient of discharge (dimensionless)
C_w	to wind pressure coefficient,
d_b	depth of smoke beneath ventilator (m)
d_{plume}	plume diameter in meters
d_{smoke}	thickness of the smoke layer (m)
F_C	Froude number (dimensionless)
g	acceleration due to gravity (m/s²)
H	height of the ceiling above the base of the fire (m)
K_d	plume diameter constant (recommended values are 0.5 for plume contact with walls and 0.25 for beam detection of the plume)
$\dot{m}_{plume}$	mass flow rate in the plume (kg/s)
$\dot{m}_{vent}$	mass flow rate through the vent (kg/s)
$\dot{M}$	mass flow rate of smoke to be extracted (kg/s)

P refers to pressure (Pa)

P_w wind pressure (Pa),

$\dot{Q}$ total heat release rate for steady fires (kW)

$\dot{Q}_c$ convective portion of heat release rate (kW)

R specific gas constant for dry air (287.05 J/kg.K)

$S_{\min}$ minimum edge to edge separation distance between adjacent vents (m)

t time (s)

t_g growth time (s.m$^{-4/5}$)

t_s time to fill the smoke layer to a certain depth (which is based on the estimate of the volumetric smoke production rate, as discussed in Section 5.7)

T temperature (K)

T_o ambient temperature (293 K)

T_{plume} average temperature of the plume (K)

T_s average smoke layer temperature (K)

U_z to the wind speed at height z (m/s)

$\dot{V}_{smoke}$ smoke volume flow rate (m³/s)

$\dot{V}_{\max}$ maximum volumetric flow rate without plugholing (m³/s)

$\dot{V}_{vent}$ volumetric flow rate of one exhaust inlet (m³/s)

y height of the clear layer (m)

z clear height above the base of the fire (m)

ρ_o ambient air density (1.2 kg/m³)

ρ_{air} density of air (kg/m³)

θ_c temperature rise of smoke layer above ambient (ºC)

χ_s heat loss fraction from smoke to the enclosure

γ exhaust location factor (1 when centre of vent is located more than twice the vent diameter from a wall, or 0.5 when centred closer)

1. INTRODUCTION

This report comprises one part of a series on aspects investigating passive buoyancy-driven roof fire vents in large floor area single storey buildings.

In large area single storey buildings, "…although a fire may involve only a relatively small area of the floor, the smoke and hot gases will quickly fill the building and experience has shown that the fire can be completely concealed before the arrival of the fire brigade." (Thomas et al 1963) Fire-fighting is then difficult and dangerous, since the fire must be located within the building and the smoke and heat conditions may be sufficiently severe to limit the fire brigade to conducting an external fire attack. External attacks are ineffective as fire hose streams rarely reach the seat of the fire to extinguish it and this only results in more water damage and potential for contaminated run-off. The temperature of the hot smoke layer trapped beneath the roof may also be sufficiently high to cause softening or failure of unprotected roof construction or ignite flammable roof materials.

A passive fire venting system relying on buoyancy of the hot fire products to provide the driving force for removal of the hot gases has advantages: simplicity, effectiveness in a wide range of fire conditions and independence from any available power supply that may be disrupted during a fire. For example, the rate of removal of hot gases is largely dependent upon the depth and temperature of smoke. Therefore if a fire grows larger than the assumed design point used to calculate the venting, then a larger depth and higher temperature of gases would lead to an increased flow rate through the vent (i.e. venting of the hot products would still occur, but the desired level of 'effectiveness' may not be achieved). Thus a passive fire venting system has an element of self-compensation (Morgan and Gardner 1990). However, as with all 'reliable' and "effective" systems, the reliability and effectiveness must be determined through demonstration of design.

1.1 Motivation

The motivation for this series of reports includes:

- The New Zealand Building Act (2004) does not require building owners to consider owner property protection and consequently most industrial buildings have been constructed in the expectation that insurers will cover the fire loss.
- Fires in large industrial buildings can be very difficult for the fire service to control and extinguish. To assist fire service operations, the Building Code Compliance Document C/AS1 (2001, with Amendments up to October 2005) places a limit on the maximum compartment floor area in unsprinklered buildings (typically 1500 m^2). This is designed to limit the total fire load in a firecell to less than 2 million MJ.
- No subdivision of the building is required if at least 15% of the roof area (distributed evenly throughout the firecell) is designed for effective fire venting. Subdividing large industrial buildings is often undesirable for functional reasons, and therefore the roof venting option is a popular one.
- No detailed specification or standard is currently referenced in the compliance document to ensure that fire venting is 'effective'. The current performance and effectiveness of these systems is therefore not well understood.
- There is also the question of the location or distribution of the panels over the area of the roof. An even distribution across the roof area is appropriate for flat

or very shallow roofs, but venting in steep roofs would be more effective if located near the apex.

Detailed guidance on how to assess the effectiveness of roof venting systems leading to appropriate specifications for them is desperately needed. Mechanically operated smoke and heat venting systems for fire are established technology overseas and various codes and standards do exist that may be suitable for use in NZ. Passive systems such as dedicated units utilising drop out panels are less common.

1.2 Objective

The objectives of this report are to:

1. Present the preliminary modelling performed to investigate required general material properties and building design for fire venting using roofing panels that are assumed to form openings when exposed to hot combustion gases.

2. Present recommendations based on the analysis of this investigation.

1.3 Scope

The scope of this series of reports is limited to researching the appropriateness of buoyancy-driven fire roof venting relying on the passive failure and subsequent openings formed in plastics roofing materials to create an opening for the roof to vent hot combustion gases. Other roofing related criteria, such as durability, rain leakage, etc. that are important factors in roof performance, are considered to be outside the scope of this project. Active or mechanically operated venting systems are also outside the scope.

The scope of this report is limited to researching the appropriateness of buoyancy-driven fire venting relying on the passive failure and subsequent dislodgement of plastic materials to create the opening of the roof vent within the limitations of the modelling approaches applied.

2. SUMMARY OF CURRENT C/AS1 REGULATORY REQUIREMENTS

Unsprinklered firecells to which an S Rating applies are required by New Zealand Fire Safety Compliance Documents C/AS1 (2001) (Paragraph 4.2.3) to be limited in floor area with the maximum area depending on the Fire Hazard Category. However Paragraph 4.2.4 permits an exception as follows:

"*In an unsprinklered single floor building where the building elements supporting the roof are not fire rated, the firecell floor area may be unlimited provided that no less than 15% of the roof area (distributed evenly throughout the firecell) is designed for effective fire venting.*"

The benefit in this paragraph is that "the firecell floor area may be unlimited".

The requirements to gain this benefit are:

1. single floor building,
2. building elements supporting the roof are not fire rated,
3. part of the roof area is designed for effective fire venting, and
4. no less than 15% of the roof area (distributed evenly throughout the firecell) is designed for effective fire venting.

2.1 Discussion of the Current Fire Venting Requirements

The requirement for building elements supporting the roof to be not fire rated (Point 3, above) indicates partial roof collapse may be expected from such a design. Furthermore, if an S rating applies, then fire rated walls could not be connected to the roof unless the connections and supports are designed so that the collapse of the roof will not cause collapse of the fire rated elements (P.5.7.8).

However if roof collapse or partial roof collapse occurs, it is typical of fully-developed fire conditions. Therefore passive roof vents may provide venting of the fire during the growth phase up until severe enough fully-developed fire conditions cause partial collapse of the roof, which may subsequently provide the majority of the roof venting capacity. It is important to differentiate between designed fire venting and partial roof collapse. Both strategies provide venting of hot smoke and gases via the building roof area, but at different stages of fire development.

Designed partial roof collapse may reduce the thermal load on the remaining structure by passive venting of larger volume flow rates through the larger roof area opening. In terms of fire-fighter operations, partial roof collapse would be too late for fire-fighter operations within the building. Designed partial roof collapse is outside the scope of this research project.

Considering the stages of total building burn out, a building designed according to P.4.2.4 would mean that during the preflashover growth phase of a fire the effective fire venting would be in play to potentially delay the onset of untenable conditions for fire-fighting operations (which may include rescue, locating the seat of the fire and/or suppression activities) and the onset of fully-developed fire conditions (by reducing the thermal load within the compartment). As the fire continues to grow past the conditions where the designed fire venting can maintain conditions, then conditions may worsen such that partial collapse of the roof may occur and this may provide a larger area of venting.

The options, according to C/AS1 (2001), for maximum firecell floor areas are summarised in Table 1. Thus considering a firecell of unlimited floor area of a single floor building, the options are to sprinkler the building or to provide fire venting. Since fire venting cannot be practically provided for multiple floors of a multiple-floor building of unlimited size, the single floor building part of the requirement for use of fire venting would be an item of practicality. Considering it is implied that fire venting provides an equivalent level of fire protection for this building as a sprinkler system would. However it is noted that a sprinkler system would provide additional benefits that comply with and surpass the intent of C/AS1, such as property protection etc that are not covered by C/AS1 and therefore these extra benefits would not be required from a fire venting solution.

Considering the first alternative, the intent of limiting firecell floor areas is to assist fire-fighting operations and to limit total fire load in unsprinklered firecells, as discussed in the Comment of P.4.2.3. This also follows on to protection of other property.

A sprinkler system supplies water to the area of the building in the immediate vicinity of the sprinkler head(s) affected by the fire. Effectively a sprinkler system works as a fight-in-place on-site fire-fighting service, reducing the time between detection and start of fire control activities.

Therefore it follows that the intent of fire venting is to assist fire-fighting operations and the protection of other property. Fire venting may achieve this by delaying the onset of untenable conditions within the compartment thereby allowing fire-fighter operations within the compartment. Correctly designed passive venting may provide preflashover fire venting than postflashover venting achieved by partial roof collapse.

However the capacity for reducing the thermal conditions in the compartment would not be equivalent to a sprinkler system as for a fire venting system. In addition there are other advantages of a sprinkler system that cannot be matched by fire venting, such as owner property and contents protection, assisting with occupant escape in case of rapid fire growth, etc.

Table 1: Current C/AS1 (2001) options for maximum firecell floor areas.

Fire Protection	General firecell description	Maximum Firecell Floor Area	C/AS1 Paragraph
Compartmentation	Where unsprinklered & S rating applies	Limited	4.2.3
Sprinkler system	Where an S rating applies & no compartmentation	Unlimited	4.2.3
Fire Venting	Where unsprinklered & no compartmentation & single floor building	Unlimited	4.2.4

In general, fire venting may assist fire-fighting operations by:

- removing the hot fire products – reducing radiation from the hot layer to fire-fighters
- removing hot smoke – allowing the seat of the fire to be more easily located
- reducing the fire intensity and its effects on fire-fighters
- potentially delaying flashover of the compartment – allowing more time for fire-fighting operations

In general, fire venting may assist in limiting the fire severity within the compartment by:

- removing the hot fire products – reducing radiation from the hot layer to other combustibles within the firecell, which will assist in delaying the spread of fire by radiation and flashover of the compartment.

It is imperative that the intent of 'effective fire venting' is defined by the regulator. Appropriate quantitative performance criteria are required to assess effectiveness of fire venting designs. For example, values for such parameters as time, visibility, radiation flux and gas temperatures may be appropriate for assessing the assistance for fire-fighting purposes. Definitions and performance criteria used for this research are discussed in the following section.

3. INTENT OF 'EFFECTIVE FIRE VENTING'

Following on from the above discussion of the current C/AS1 (2001) requirements, the intent of fire venting is assumed, for the purposes of this research, to be defined as:

Fire venting is a system designed for the removal of hot fire gases during the preflashover growth phase of the fire in order to reduce the hot smoke logging and radiation from the smoke layer of the compartment to facilitate fire-fighting operations (in terms of rescue, if necessary, and protection of other property) and reduce thermal *loading, from the build-up of combustion products, on the remaining structure during burnout by providing preflashover venting of the hot fire gases (in terms of protection of other property).*

That is fire venting contributes directly to the New Zealand Building Code objectives to:

1. facilitate fire-fighting operations, and
2. protection of other property.

Fire venting alone would not be expected to control a fire but may delay the onset of flashover conditions.

Fire venting may operate within or after the maximum permitted escape times have been surpassed coincidentally, as fire venting design does not relate to occupant escape time (as presumed by no concessions for path lengths associated with fire venting, Part 3 of C/AS1, 2004). Furthermore passive buoyancy-driven fire venting is currently not required, by C/AS1 (2001), to be interlinked with smoke or heat detection or manual call points that would be linked to alerting occupants and is thus potentially interrelated with facilitation of escape. Therefore it is assumed that fire venting is not intended to contribute to life safety of the initial occupants of a building.

Fire venting does not prevent the spread of fire. It is reasonable to assume the firecell and contents will be completely lost in the event of a fire. Fire venting may provide a delay in the onset of untenable conditions for rescue operations. Fire venting may provide a safety factor by reducing the build-up of combustion products within the firecell during the growth phase of the fire. This safety factor is not used in the calculation of the design of the firecell to withstand complete burnout. That is, for the calculation of the S-rating (Table 5.1 Note 4d of C/AS1, 2004), if partial roof collapse is assumed (as implied by the elements supporting the roof not being fire rated, P.4.2.4), then the area designed for fire venting is not added to the 20% horizontal openings assumed during roof collapse. Therefore the fire vents would provide earlier venting than assumed in the calculation of the S-rating.

3.1 Requirements to Fulfil Definition

In order to fulfil the requirements of the above definition, it is necessary for the design of passive fire vents to reduce the build-up of combustion products within the compartment and facilitate fire-fighting operations, which may include such performance criteria as fire fighting tenability limits, estimation of the time to fire service suppression activities, in combination with the maximum fire size that would be manageable by the fire service, etc. Some of these are discussed in the following sections, and the performance criteria used for assessing the effectiveness of fire venting in this study.

3.1.1 Fire Fighting Tenability Limits

Research has been performed, investigating fire fighter performance under different conditions simulating fire suppression operations and rescue. (Optimal Performance Limited, 2004)

Fire fighting tenability limits have been suggested as a maximum radiant flux of 4.5 kW/m² at 1.5 m above the floor and a minimum height to the bottom of the smoke layer of 2.0 m. (AFAC, 2006)

3.1.2 Time to Fire Service Arrival

The conditions at the time estimated for Fire Service start of suppression activities are of interest for the comparison of the thermal and smoke conditions within the modelled building with performance criteria or a base case.

For estimating the time to Fire Service arrival, three scenarios were considered:

1. response time only (from receipt of the 111 call to arrival at the incident)
2. the time until first fire suppression activities for a monitored alarm system, and
3. the time until first fire suppression activities for a direct connection to the fire service.

3.1.2.1 New Zealand Statistics

New Zealand Fire Service statistics are available for the response time to industrial fire incidents (Challands 2007). Details of the analysis and results for the industrial fire incident response time statistics for 2000 to 2008 are included in Appendix 7.2D.2. The 95th percentile for the response time was approximately 700 s, whether outliers are included (Table 14) in the analysis or not (Table 15).

The 95th percentile for the response time for industrial fire incidents was used to refine the distributions for input parameters for the estimated response time based on the Fire Brigade Intervention Model (Figure 141(c) and Table 13). These input parameters were then used in the estimation of the time until first fire suppression activities for a monitored alarm system and a direct connection to the fire service. Details of the calculations and results are included in Appendix 7.2D.1.

The 95th percentile for the time until first fire suppression activities for a monitored alarm system was estimated at approximately 1240 s (Figure 141(a) and Table 13), and the 95th percentile for a direct connection to the fire service was estimated at approximately 1060 s (Figure 141(b) and Table 13).

3.1.2.2 Fire Brigade Intervention Model

The Fire Brigade Intervention Model (AFAC, 2006; Marchant et al, 1999; Marchant et al, 2001; *International Fire Engineering Guidelines,* 2005) approach was used to estimate the time from detection to the time that suppression activities could be started. A list of the variables considered is presented in Table 3.

In consideration of the large number of variables with uncertainty, a generic design approach was taken to incorporate the uncertainty in the results using assumed distributions about the average best guess for the maximum limits expected for current practice. The software package @Risk version 4.0.2 was used to incorporate variable uncertainty into estimating the time taken from detection to when fire service suppression activities could begin.

A summary of the results is presented in Table 2. Details of the model and results are included in Appendix 7.2D.1D.1.

Table 2: Summary of the time to when suppression activities begin for the three scenarios considered.

Statistical Description	Response Time Only	Time to Application of Water to Fire from Time of Detection (s)	
		Direct Connection to Fire Service	Monitored Alarm System
Minimum	467	807	978
Mean	586	939	1120
Maximum	841	1183	1340

3.1.2.3 General

It is assumed that the monitored alarm system does not include a component for sending personnel to check the building state before notifying 111. Therefore it is noted that the time to the beginning of fire suppression activities could, in practice, be significantly longer than the estimate assumed in this study.

A point of note here is that according to Table 4.1 special provision f (*C/AS1* 2001), not all warehouse, factory or storage (WL, WM, or WH) occupancies need to have a direct connection to the fire service. Where the intent of fire venting is to delay fully developed fire conditions and smoke logging such that the conditions are lessened for possible fire service suppression operations to occur compared to conditions where fire venting is not present, a direct connection would reduce the time for fire service dispatch and therefore reduce the potential fire size at the time of the start of fire suppression activities.

3.1.2.4 Summary

Considering the statistical information available in conjunction with the Fire Brigade Intervention Model estimates, it was assumed that a direct connection to the Fire Service was reasonable for a building relying on effective fire venting given the objective of facilitating Fire Service operations. A time of 1,000 s was assumed for the time to Fire Service suppression activities for this study.

Table 3: Summary of the parameter values used for a reasonably conservative case using the approach of the Fire Brigade Intervention Model

Suppression Method Description	Estimated Minimum Value	Estimated Mean Value	Estimated Maximum Value	Units
Fire Alarm Received by Brigade				
Activation of detection system	110	120	130	s
Monitoring company notified 111	50	60	70	s
Dispatch time	25	30	40	s
Dispatch Resources and Travel to Fire Scene				
Manning of fire station		Permanent or Volunteer		
Fire fighter preparation before leaving station – permanent	80	90	110	s
Fire fighter preparation before leaving station – volunteer	450	480	510	s
Average speed to incident – urban	30	50	60	km/h
Average speed to incident – rural	30	50	60	km/h
Distance from closest fire station to incident	4.5	5	6	km
Determine Fire Location and Investigate				
Fire fighter preparation at scene	120	130	150	s
OIC assesses situation	50	60	70	s
Additional Appliances Requested Based on Fire Size at Time of 1st Appliance Assessment of Incident				
Number of additional appliances requested		1 (up to 3 possible)		
OIC requests additional appliances	25	30	35	s
Prepare to Attack Fire				
Pumper positioning & hose connection	4.5	9	13	s
Flush feed hydrant at booster assembly	50	60	70	s
Connect & charge hose from hydrant to appliance	90	100	110	s
Control and Extinguish Fire				

3.1.3 Maximum Fire Size Manageable by Fire Service

Assuming structural stability of the large firecell, it is of interest to estimate the maximum fire size that the fire service might manage and compare it to modelling results. Estimates were based on the average water flow for various suppression methods available and the fire size to water flow rate coefficient, as published in SNZ PAS 4509 (2003) (see Table 5).

Estimates of the maximum fire size manageable by Fire Service for unlimited firecell floor areas based on SNZ PAS 4509 (2003) requirements are presented in Table 4. The water supply must be calculated for the specific design for a water classification of W8. Therefore these will be calculated for the specific designs used in the modelling section for comparison with model results.

Furthermore, the theoretical fire-fighting water for boundary protection is 0.1 l/s/m², e.g. a building with an exposed perimeter of 50 m by 8 m high could require 40 l/s alone.

Table 4: Maximum firecell floor area, water supply classification, FLED and estimate of maximum manageable fire for an unsprinklered firecell without fire venting.

FHC	Maximum Allowable Firecell Floor Area [a]	Water Supply Classification for Floor Areas Greater than the Maximum Allowable Firecell Floor Area [b]	Associated Water Flow Required [b] (l/s)	Fire Load Energy Density [c] (MJ/m²)	Estimate of Maximum Fire this Water Supply Classification can Successfully Manage [d] (MW)
1	5000	W7	100 @135 m +100 @270 m	400	344
2	2500	W8	To be calculated for specific case	800	To be calculated for specific case
3	1500	W8	To be calculated for specific case	1200	To be calculated for specific case
4	Specific Engineering Design	W8	To be calculated for specific case	-	To be calculated for specific case

Notes:
[a] from Paragraph 4.2.3, C/AS1 (2001).
[b] from Table 2 of SNZ PAS 4509 (2003). Note that these classifications are the same when considering unlimited firecell floor areas.
[c] from Paragraph 2.2.1 Comment 3, C/AS1 (2001).
[d] assuming a fire size to water coefficient of 0.58 l/MW.s from SNZ PAS 4509 (2003).

Table 5: Average water flow rate available from various suppression methods (Davis, 2007).

Suppression Method Description	Average Water Flow Rate (l/s)	Maximum Fire Size (MW)
Low pressure delivery	15	25
Monitor on an appliance	25	43
Appliance pump	50	86

Notes:
[a] assuming a fire size to water coefficient of 0.58 l/MW.s from SNZ PAS 4509 (2003).

3.1.4 Thermal Loading of Firecell

Fire venting may reduce the fire severity within a firecell during a fire event by allowing hot gases and smoke to escape through openings in the roof. Designing fire venting for a building to maintain upper layer temperatures below a maximum specified temperature may be one approach.

This selected maximum temperature would be used to check that vents open and are placed appropriately, e.g. the vents should be fully open when the surrounds reach 300°C (based on AS 2428 Part 3, 2004) and there should be no 'hot spots' (i.e. localised pockets of the roof structure where hot gases may collect where venting opportunities are not available). Therefore one example of a worst-case scenario would be the location of the seat of a fire beneath non-venting roofing material between two venting panels. The temperatures directly above the seat of the fire may exceed the maximum temperature, but the temperatures beyond the surrounding vents would not be permitted to be above the maximum temperature.

If the vents are tested to the requirements of AS 2428 Part 3 (2004), then it would be expected that, depending on the heating regime, the vents would be open by 300°C. Therefore a maximum temperature allowable within the hot layer might be set as 300°C, which would allow for a reasonable safety factor when comparing to upper layer temperatures required for flashover (~660°C for cellulosic materials).

3.2 Performance Criteria for Fire Venting

Combining the points discussed above, for this study the performance criteria for fire venting is defined as:

At the time first fire suppression activities begin the conditions within the building are:

- *a maximum incident radiation flux of 4.5 kW/m² at 1.5 m above the floor,*
- *a minimum height to the bottom of the smoke layer of 2.0 m, and*
- *a maximum gas temperature of 573 K at ceiling.*

The time to when the first fire suppression activities begin was assumed to be 1000 s.

4. PRELIMINARY ROOF VENTING MODELLING

Preliminary modelling of roof venting scenarios was performed to investigate the possible problems associated with modelling passive roof venting methods as well as determining initial modelling parameters and approaches.

For this theoretical investigation of passive buoyancy-driven fire venting, additional comparisons were made to scenarios where:

- no venting was present,
- thermally-activated buoyancy-driven vents were present, and
- smoke reservoirs were included.

The results for scenarios with passive fire venting panels were compared to results for no vents (i.e. when either no venting is present or it fails to work), and to results for passive venting using dedicated vent systems activated using fusible links and interlinked for activation (i.e. systems based on AS 2665 2001).

4.1 Objectives of the Preliminary Roof Venting Modelling

The objectives of the preliminary modelling of passive buoyancy-driven roof vents were:

1. to theoretically investigate under what conditions of ‘operation’ passive roof venting would be possible.
2. to provide an estimate of the range of temperature conditions that would be required for passive panels to work as roof venting.

It is to be noted that the “success” of the venting in this modelling investigation is based on the performance criteria discussed in Section 3.2.

4.2 Generic Large Single Firecell Model Description

An empty generic single-space flat-roofed warehouse was selected for the preliminary modelling investigation. The general description and scenarios selected for modelling were based on the current New Zealand C/AS1 (2001) requirements as well as AS 2665 (2001) requirements, for comparison and to provide a common basis for areas of C/AS1 requirements that are not defined. The general model description is as follows:

- Firecell Dimensions: 60 m × 60 m × 6 m (see Figure 1).
  - Note the stud height is in accordance with the conditions for the application of AS 2665 (2001).
- Model Fire: an ideal steady-state 8 MW propane burner located at firecell floor level.
  - A large model fire was specifically selected for this preliminary investigation, to ensure that the ratio of fire size to compartment size would be less likely to contribute to the potential erroneous nature of modelling fires in large volumes. Investigation of the critical limits of this ratio is recommended for future work and is not included in the scope of the investigation presented here. 8 MW was selected, based on the minimum value suggested for steady design fire sizes used for atria with combustibles (5 MW) and the suggested value for a large fire (25 MW) (Klote 1994).
  - Modelled uniformly over a 4 m² area, located centrally in the firecell.
  - Assumed soot production rate of 0.01 g_{soot}/g_{fuel}.
- Ambient Conditions: 293 K, 101.325 kPa, 60% relative humidity, still air.
- Construction Materials:
  - Walls and floor were modelled as inert concrete.
  - Roof was modelled as inert steel sheeting.
  - Vents were modelled as inert roof material.
- Smoke Reservoirs:
  - Smoke baffle depth: 1.5 m in accordance with AS 2665 (2001).
  - Four evenly-spaced smoke reservoirs (see Figure 1 for schematic of locations of smoke baffles).
    - Maximum Plan Area of Smoke Reservoir: 60 m × 15 m = 900 m² (< 1500 m², in accordance with AS 2665, 2001).
- Fire Vents (see Figure 2 for schematic of vent locations):
  - Two conditions for vent area were considered:
    - 15% firecell floor area, in accordance with C/AS1 (2001), or

        - 3% smoke reservoir plan area, in accordance with AS 2665 (2001).

    - Activation Temperature: 120ºC as an initial estimate for PVC, 68ºC in accordance with AS 2665 (2001) for thermal activation via heat detector(s), and 300°C as an upper temperature for a “generic” model for passive venting panels (based on requirements of AS 2428 Part 3 2004).

        - Modelled using a heat detector, or a virtual heat detector for the passive venting panel cases, with the appropriate activation temperature and a response time index (RTI) 132 $\sqrt{m.s}$ as initial estimate (located centrally under each vent area in FDS models).

    - Two conditions for activation were considered:

        - Localised opening of the vents using virtual heat detectors (set to an activation temperature of 120ºC or 300°C and RTI of 132 $\sqrt{m.s}$), to simulate passive venting relying on the failure of roofing material, as described above. Virtual heat detectors were used to provide an estimate of the panel temperature and subsequent formation of an opening. In the cases where no vents were present, virtual heat detectors were included to provide an indication of what the panels would experience if they were present and to observe the spread of the hot layer across the ceiling. The virtual heat detectors were located at 1 m intervals over the area of the panels. The sizes of the venting areas for the passive fire venting panel approach is discussed in the results and discussion sections.

        - For thermally-activated vents: Heat detectors were used to open all vents in the smoke reservoir of the activated heat detector (set to an activation temperature of 68ºC and RTI of 132 $\sqrt{m.s}$), in accordance with AS 2665. The heat detectors were located at the centre of each vent.

- Permanently-Open Make-up Air Vents:

    - Twice the area of the total fire vents in the largest smoke reservoir.

    - Located evenly around the compartment and at a low height (chosen as 2 m above the compartment floor – to simulate permanently-open make-up air inlets), in accordance with AS 2665 (2001).

- Output parameters:

    - those relating to the performance criteria (Section 3.2): temperatures within the compartment (slice files at 0.5 m intervals over the height of the compartment), incident radiation intensity at 1.5 m from the floor height, and visibility at 2 m from the floor height; and

    - those related to the opening of the vents: virtual heat detector activation.

A summary of the select scenarios modelled as part of this preliminary investigation is presented in Table 7.

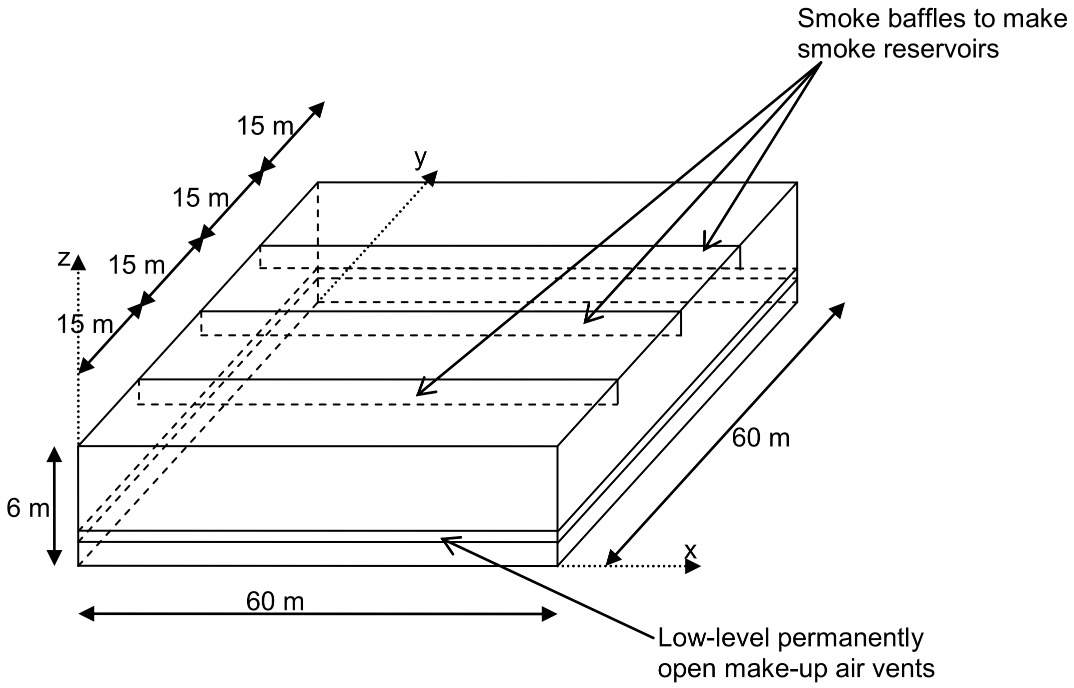


Figure 1: Schematic of the generic warehouse used for modelling. (N.B. Not to scale.)

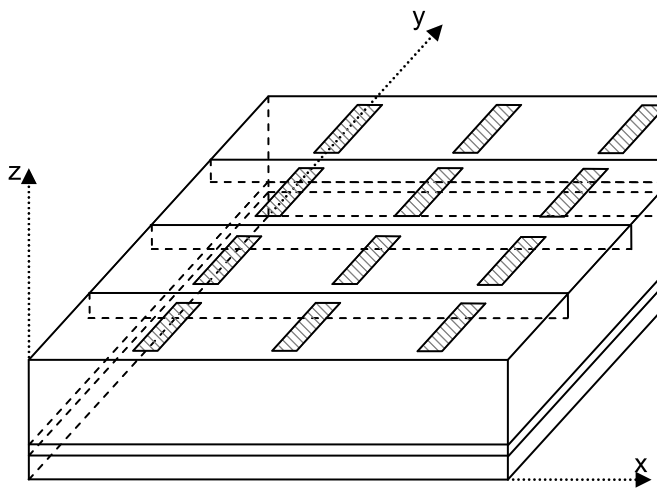


Figure 2: Schematic of the generic warehouse showing the general placement of the roof vents used in modelling when applying a CFD approach. (N.B. Not to scale.)

Table 6: Summary of Parameters for Preliminary Scenarios Modelled

General Description	Parameter Description	Range Considered for Sensitivity	Comments
Grid Size	Uniform vs non-uniform grid	Uniform	Initial modelling results indicated that grid stretching is not appropriate for single large space, as too much local volume distortion is introduced over the computational domain
	Multiple meshes	N/A	Not appropriate for single large space
	Uniform grid sizes	0.15 & *0.5 m	0.5 m was determined to be appropriate
Design Fire	Growth rate/ Peak heat release rate	Steady/ 5, *8 ± 10%, 12 MW	8 MW as the base case
	Storage rack fire	Wood cribs stacked 3 m high, FHC 3 equivalent fire load	This was used for comparison with the steady fire
Vent Parameters	Effective Activation Temperature – passive panels	*120°C ± 10% & *300°C ± 10%	Initially based on PVC estimate from published experiments (Edwards et al. 2007), then based on results from experimental study (Robbins & Wade 2008a)
	Effective Activation Temperature – activated by fusible link	*68°C ± 10%	
	RTI	*132 $(m.s)^{1/2}$ ±10%	
	Area – passive	*15%	Individual vents 1 m²
	Area – active	*3%	Individual vents 1 m²
	Location	1 m widths 2 m widths *3 m widths	Evenly distributed
Compartment Parameters	Floor area	*3600 m²	
	Ratio of length to width	*1: 1	
	Height	*6 m 10 m 15 m	
	Location of smoke baffles	None, or 4 reservoirs	Depending on Scenario considered
	Roof	*flat	
Wind Conditions	Wind speed	*0, 2, 5 & 10 m/s	Wind velocity was assumed to be parallel to ground, using one side of the domain as an effective fan and the other four sides of the domain left as open.

Note:
* Denotes the base cases.

Table 7: Summary of Preliminary Scenarios Modelled

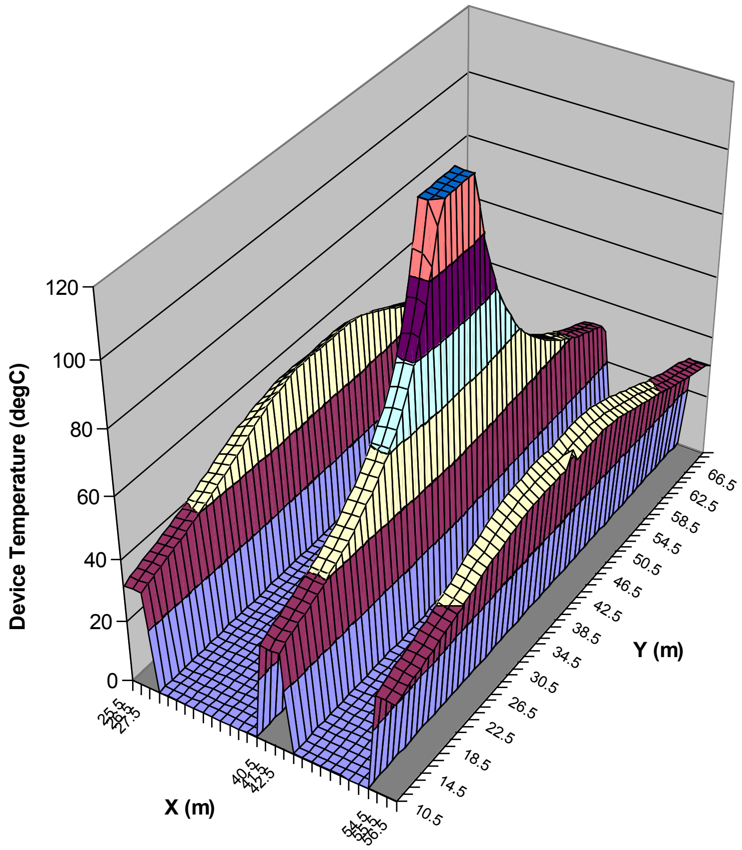
Scenario Number	Number of Smoke Reservoirs	Smoke Reservoirs Area (m² per reservoir)	Total Area Modelled (m²)	Linkages of Vent Activation	Vent Activation Temperature (ºC)	Total Vent Area (% Smoke Reservoir Plan Area)
1	1	3600	3600	-	-	-
1b *	1	900	900	-	-	-
2	4	3600	3600	Local only	120	15
3 ‡	4	900	3600	Local only	120	15
3b ‡	4	900	900	Local only	300	15
4	4	900	3600	All vents in each smoke reservoir	68	3

Notes:
* That is, one smoke reservoir of the setup shown in Figure 1.
‡ As shown in Figure 2.

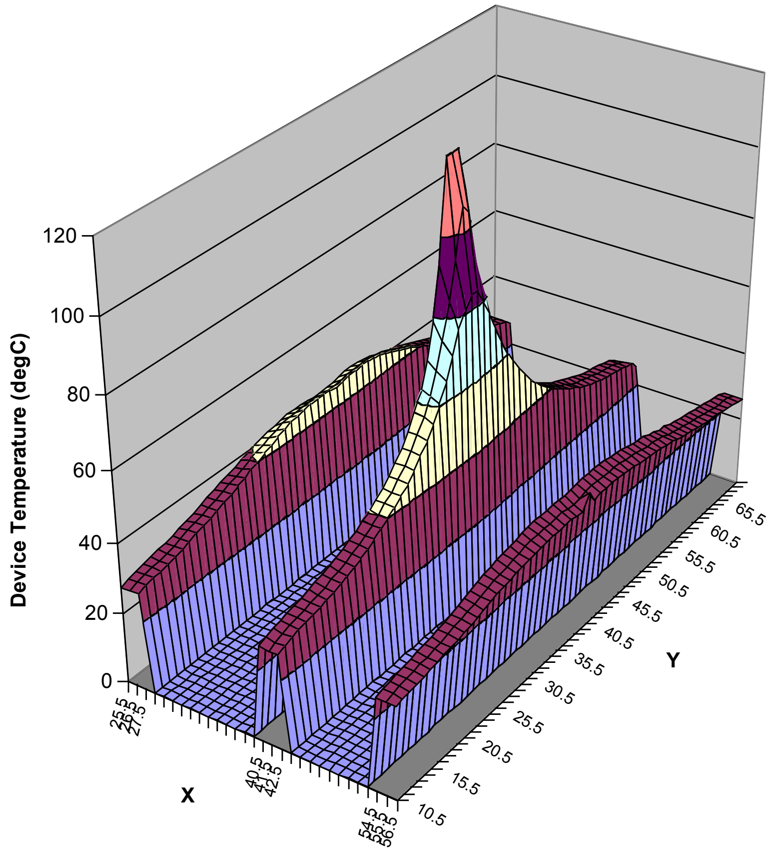
4.3 Summary of Roof Venting Modelling Results

4.3.1 Base Cases

Examples of the virtual heat detector data at selected times during the model scenario are shown for the base cases in Figure 3 to Figure 5. The spread of the hot layer across the entire ceiling of the compartment for Scenario 1, with no vents and no smoke reservoirs, is obvious in Figure 3a, Figure 4a and Figure 5a. The spread of the hot layer across the entire ceiling of the compartment for Scenario 2, with passive panel vents and no smoke reservoirs, is obvious also in Figure 3b, Figure 4b and Figure 5b, although the spread is slower than observed for Scenario 1. The spread of the hot layer across the ceiling of the compartment for Scenario 3, with passive panel vents and smoke reservoirs, is obviously hindered by the smoke baffles Figure 3c, Figure 4c and Figure 5c. The temperatures at the ceiling in the smoke reservoirs adjacent to the central two that are affected by the fire have much lower temperatures. The limited spread of the hot layer across the ceiling of the compartment for Scenario 4, with thermally activated vents and smoke reservoirs, is obvious in Figure 3d, Figure 4d and Figure 5d, with similar ceiling temperatures as Scenario 2 remote from the seat of the fire and a reduced spread of the hot layer across the ceiling as Scenario 3.

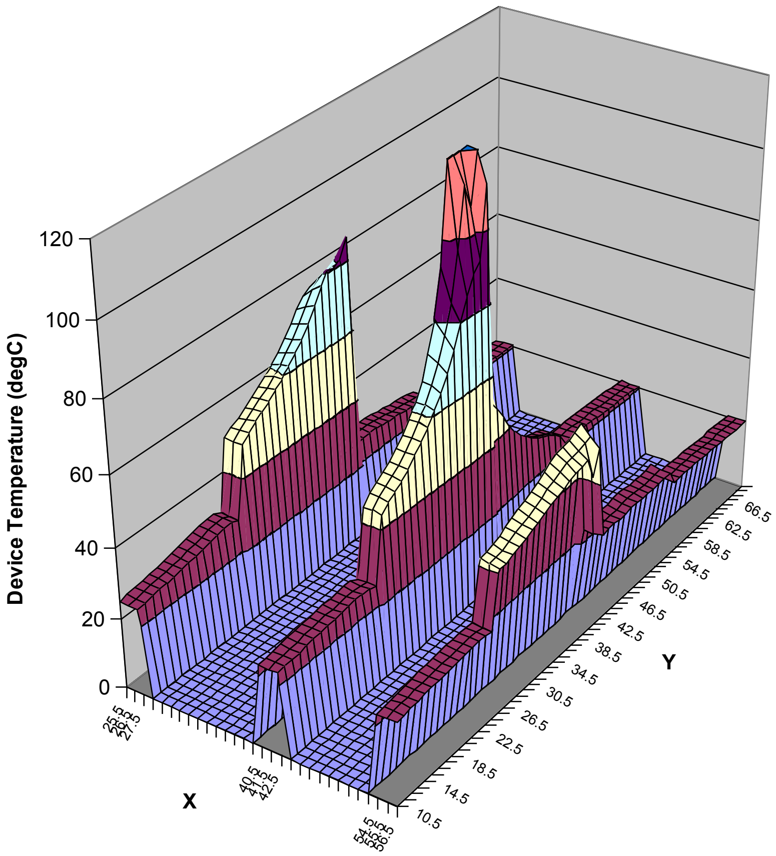


(a)



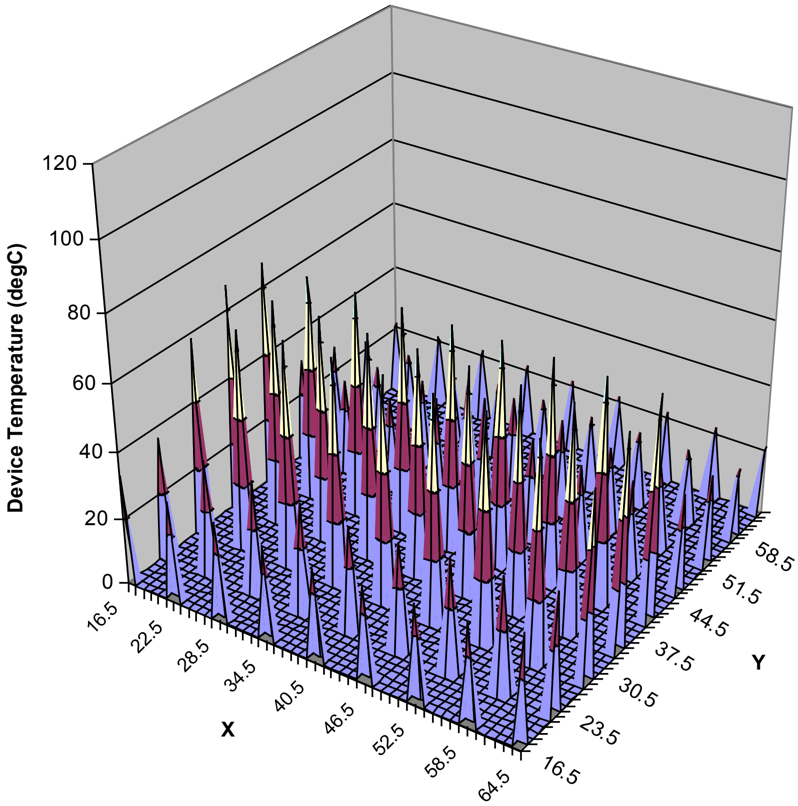
Device Temperature (degC)
120
100
80
60
40
20
0
X
Y
65.5
60.5
55.5
50.5
45.5
40.5
35.5
30.5
25.5
20.5
15.5
10.5

(b)



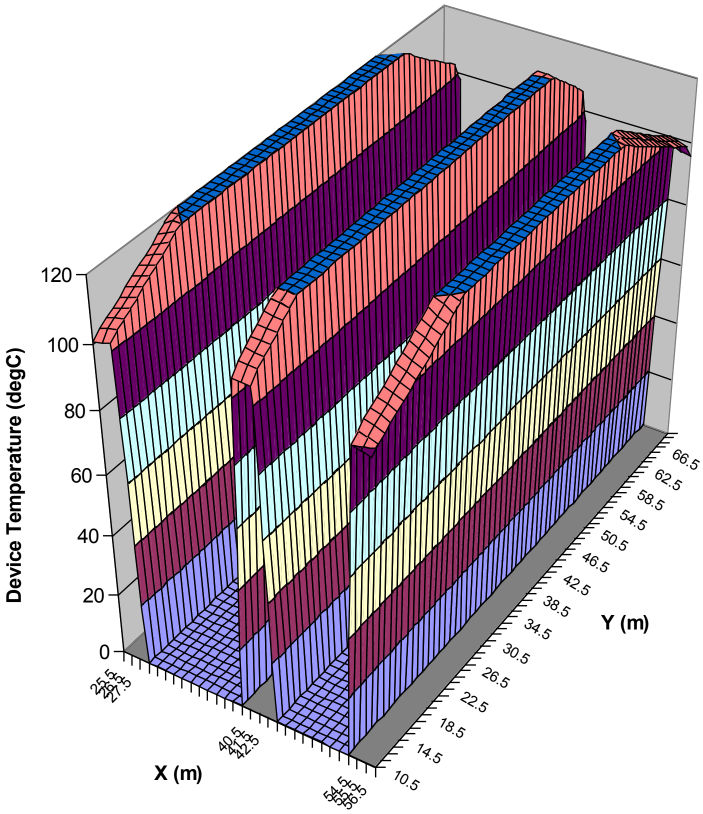
Device Temperature (degC)
120
100
80
60
40
20
0
X
Y
66.5
62.5
58.5
54.5
50.5
46.5
42.5
38.5
34.5
30.5
26.5
22.5
18.5
14.5
10.5

(c)



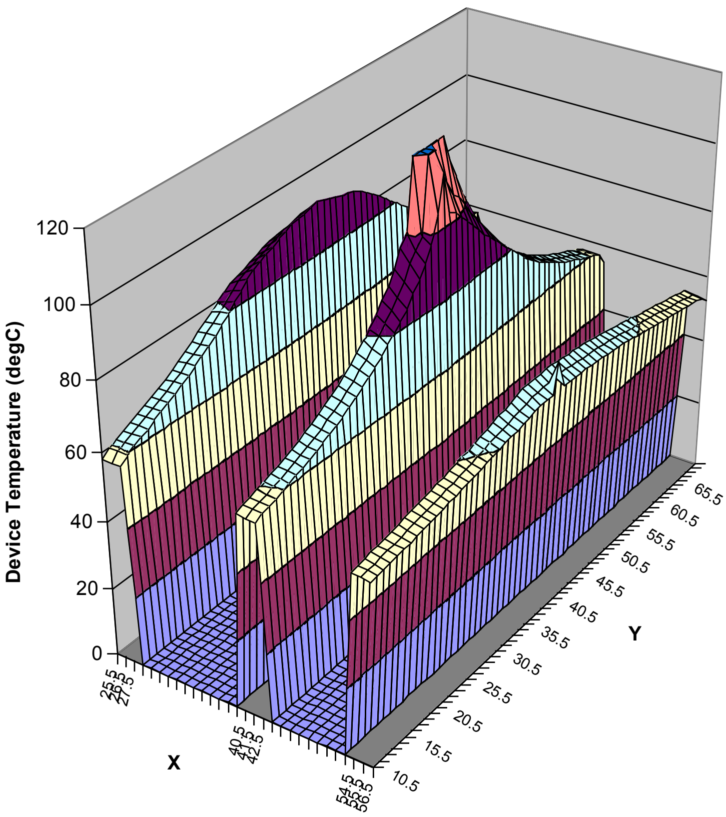
(d)

Figure 3: Examples of the base case virtual heat detector temperature results at 100 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.



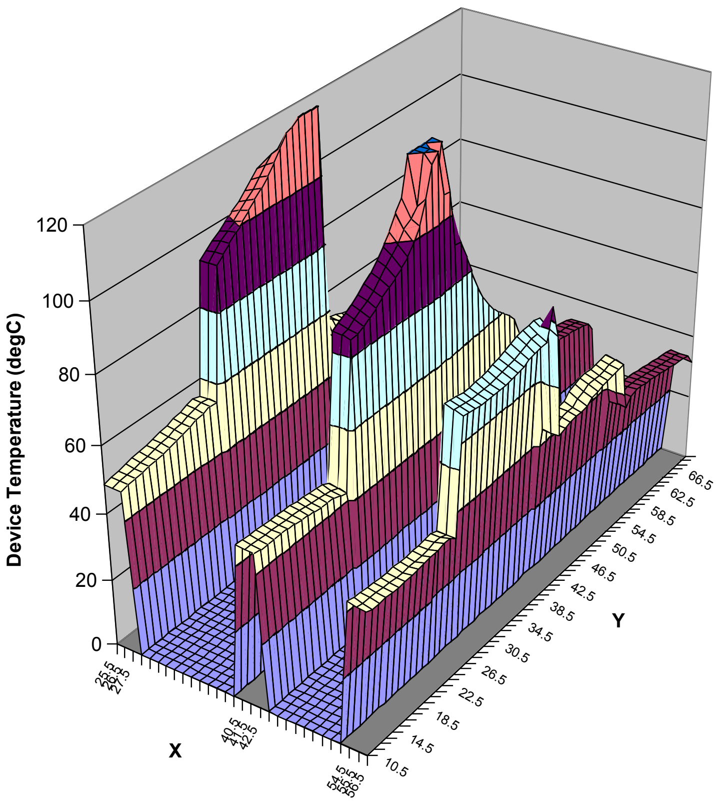
Device Temperature (degC)
120
100
80
60
40
20
0
X (m)
Y (m)

(a)

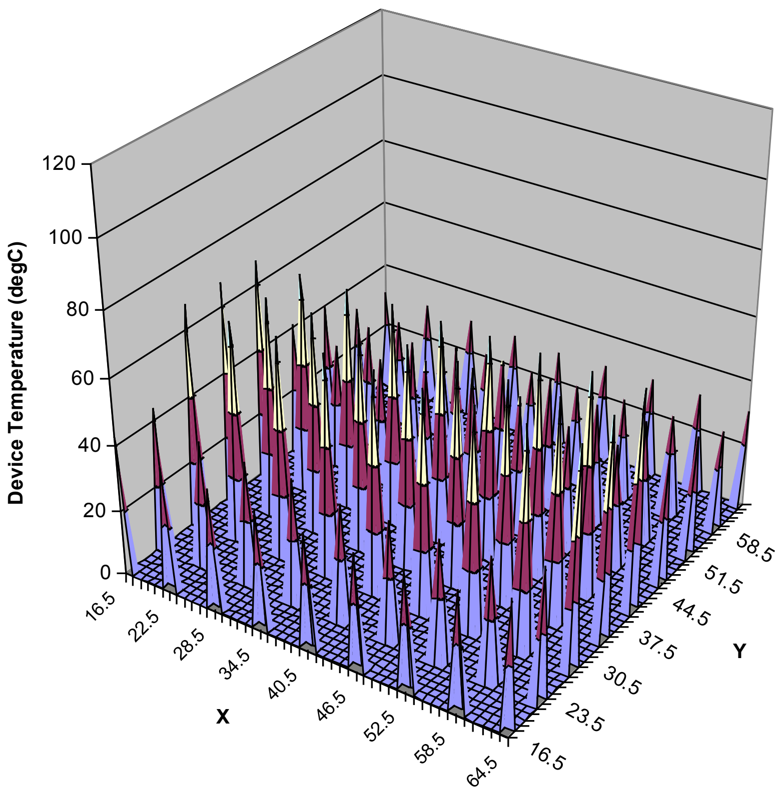


Device Temperature (degC)
120
100
80
60
40
20
0
X
Y

(b)

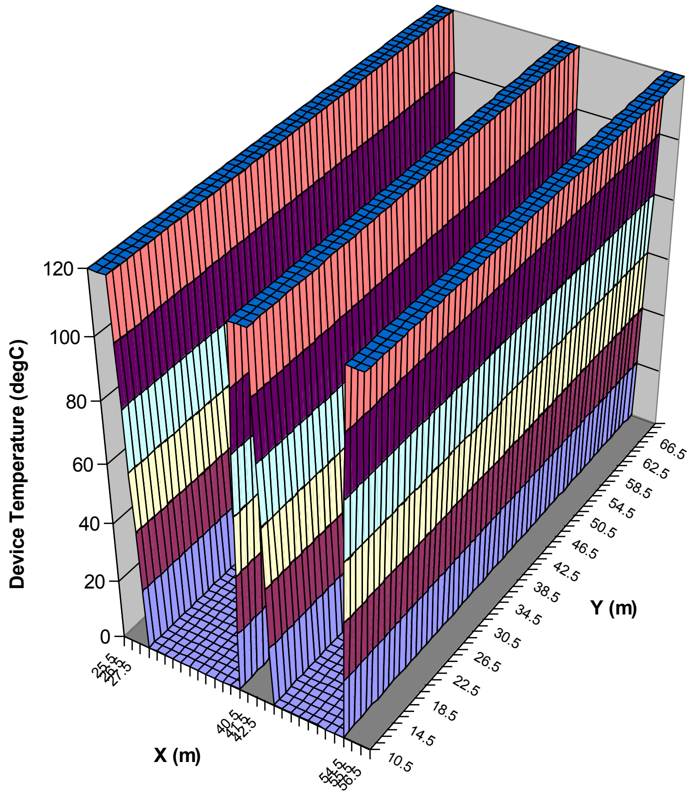


(c)

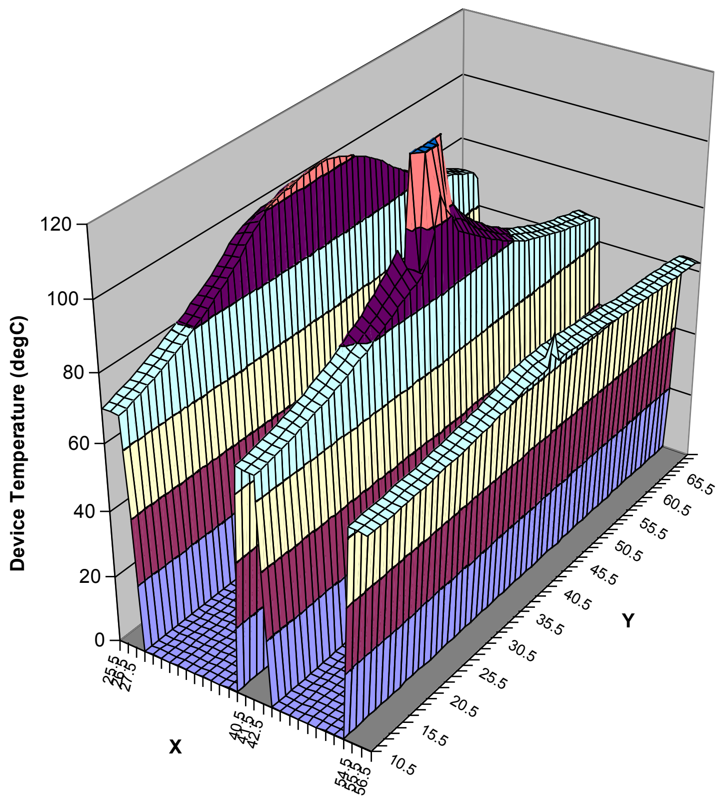


(d)

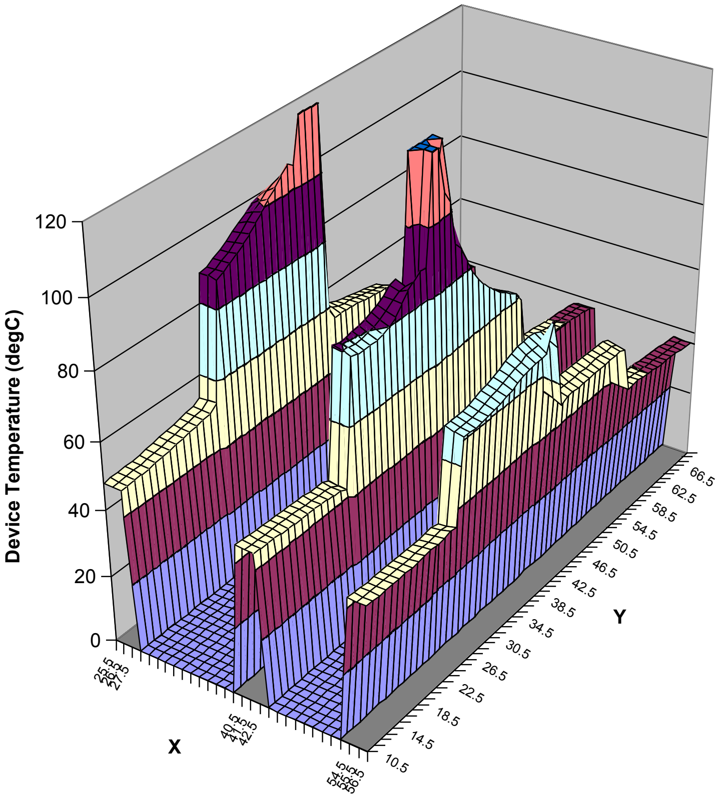
Figure 4: Examples of the base case virtual heat detector temperature results at 500 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.


Device Temperature (degC)
120
100
80
60
40
20
0
X (m)
Y (m)
10.5
14.5
18.5
22.5
26.5
30.5
34.5
38.5
42.5
46.5
50.5
54.5
58.5
62.5
66.5

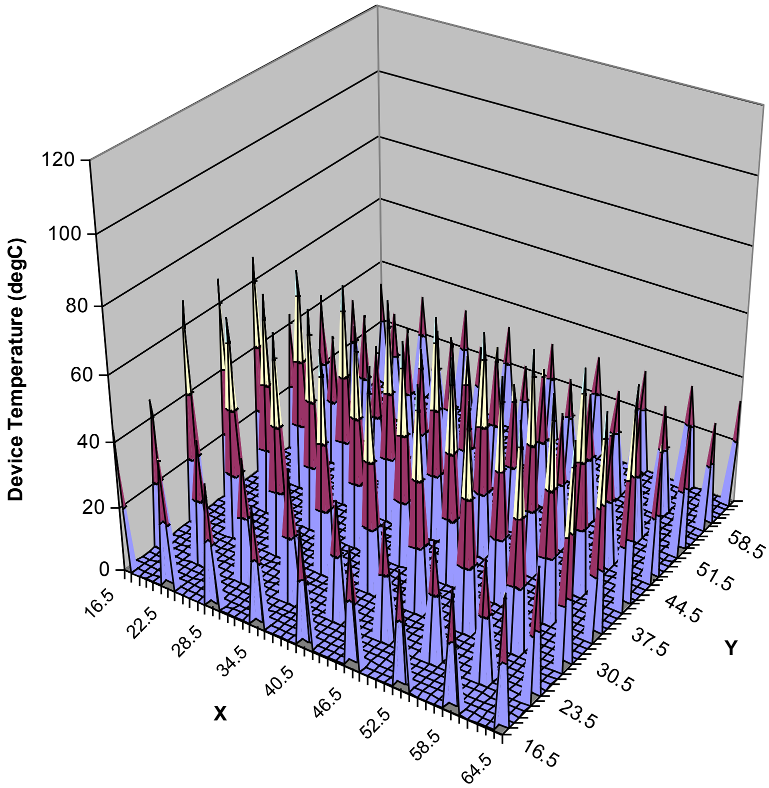
(a)


Device Temperature (degC)
120
100
80
60
40
20
0
X
Y
10.5
15.5
20.5
25.5
30.5
35.5
40.5
45.5
50.5
55.5
60.5
65.5

(b)



(c)



(d)

Figure 5: Examples of the base case virtual heat detector temperature results at 1,000 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.

Examples of the incident radiative intensity data at 1.5 m above the floor height at selected times during the model scenario are shown for the base cases in Figure 6 to Figure 8. The spread of the incident radiative intensity across the compartment is more subtle than the spread of temperature at ceiling height. Results for Scenario 1, with no vents and no smoke reservoirs, are shown in Figure 6a, Figure 7a and Figure 8a. Results for Scenario 2, with passive panel vents and no smoke reservoirs, are shown in Figure 6b, Figure 7b and Figure 8b. Results for Scenario 3, with passive panel vents and smoke reservoirs, are shown in Figure 6c, Figure 7c and Figure 8c. Results for Scenario 4, with thermally activated vents and smoke reservoirs, are shown in Figure 6d, Figure 7d and Figure 8d. Comparing the radius at which the incident radiative intensity equals 4.5 kW/m² between the scenarios considered shows that Scenario 1 has the greatest range of radiative intensity, Scenario 3 has the least radiative intensity, and Scenarios 2 & 4 have similar radiative intensity results.

Examples of the gas temperature data at 5.5 m above the floor level at selected times during the model scenario are shown for the base cases in Figure 9 to Figure 11. The spread of the gas temperatures across the compartment similar to that observed for the spread of temperature, based on virtual heat detectors, at ceiling height, is as expected. The spread of the hot gases across the entire ceiling of the compartment for Scenario 1, with no vents and no smoke reservoirs, is obvious when comparing Figure 9a, Figure 10a and Figure 11a. Similarly the spread of the hot gases across the entire ceiling of the compartment for Scenario 2, with passive panel vents and no smoke reservoirs is obvious when comparing Figure 9b, Figure 10b and Figure 11b. However the spread of the hot gases is more limited than observed in Scenario 1, which is expected as the hot gases escape through the opening panels. The spread of the hot gases across the ceiling of the smoke reservoir directly over the fire for Scenario 3, with passive panel vents and smoke reservoirs, is limited when comparing Figure 9c, Figure 10c and Figure 11c. The spread of the hot gases across the ceiling of the smoke reservoir directly over the fire for Scenario 4, with thermally activated vents and smoke reservoirs, is rapid at first and then quickly subsides when comparing Figure 9d, Figure 10d and Figure 11d.

A summary of the results of the base cases of the six scenarios considered are presented in Table 8.

Examples of the code used in modelling are included in Appendix A as well as more details of the results.

Table 8: Summary of a selection of results for comparison of the base case scenario results for the generic warehouse.

Description of Parameters for Comparison	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Time to first vent opens (s)	N/A	~30 s	~ 30 s	~16 s
Radius (m) where radiant intensity exceeds 4.5 kW/m² at t = 1,000 s	~13 m	~11 m	~10 m	~11 m
Time (s) when visibility is less than 20 m, at 2 m above floor level	~410 s	N/A [a]	N/A [a]	N/A [a]
Time (s) when visibility is less than 15 m, at 2 m above floor level	~560 s	N/A [a]	N/A [a]	N/A [a]

Note:
[a] Model results for visibility did not fall below 20 m. This was expected considering the location of the permanently-open make-up air vents.

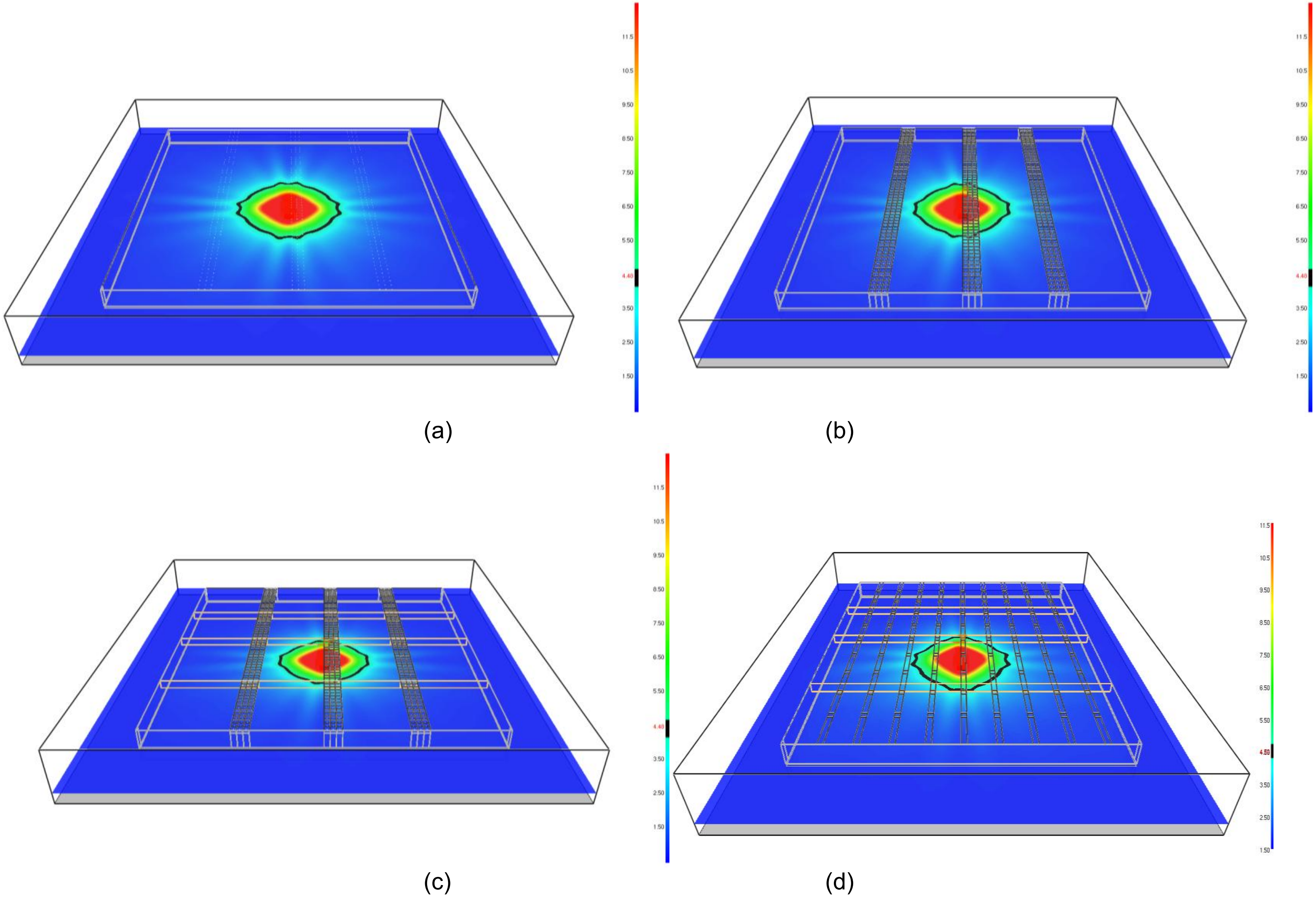
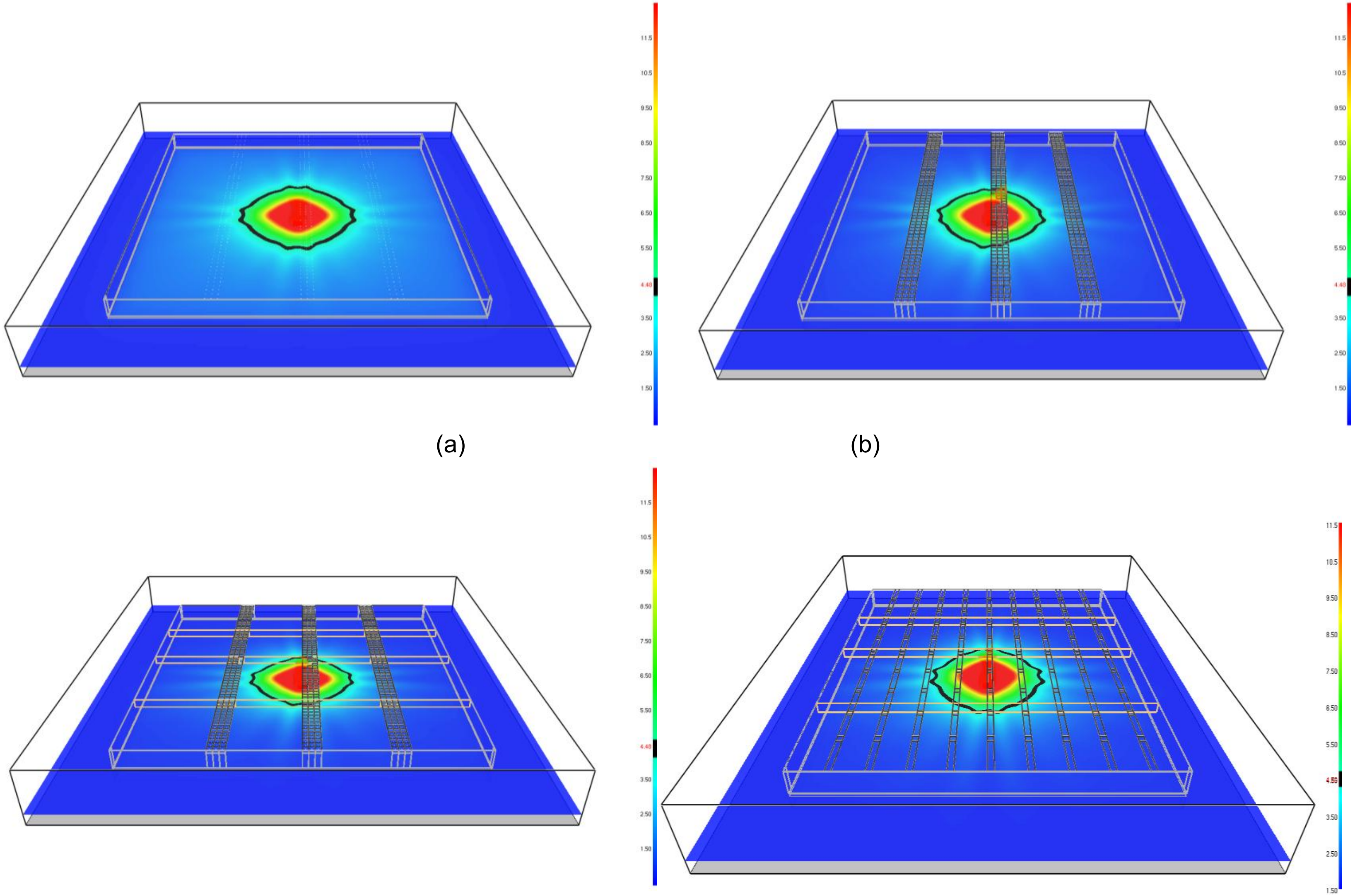


Figure 6: Examples of the base case incident radiant intensity (kW/m²) results at 1.5 m above floor at 100 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.



(a) (b) (c) (d)

Figure 7: Examples of the base case incident radiant intensity (kW/m²) results at 2 m above floor at 500 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.

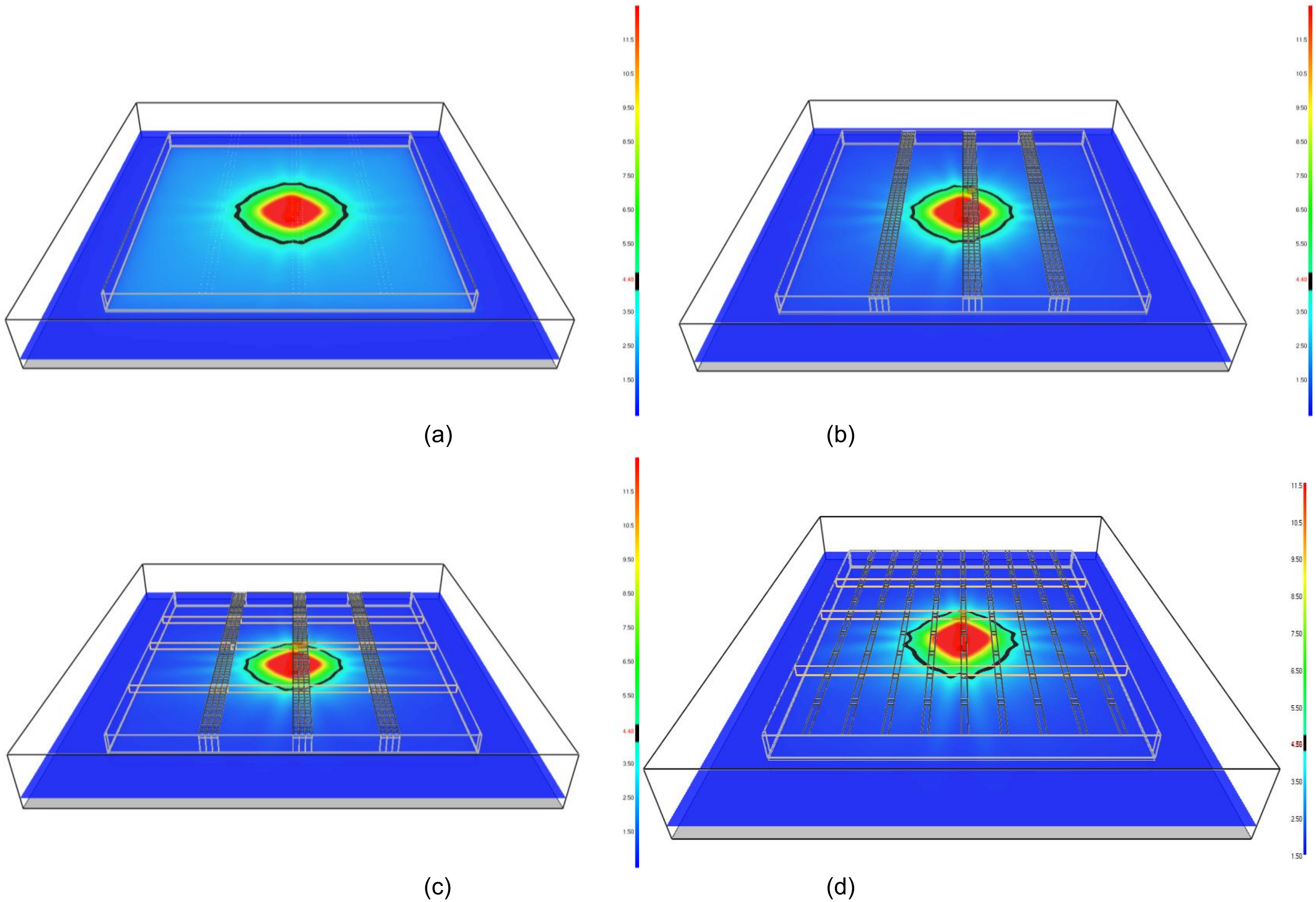


Figure 8: Examples of the base case incident radiant intensity (kW/m²) results at 2 m above floor at 1,000 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.

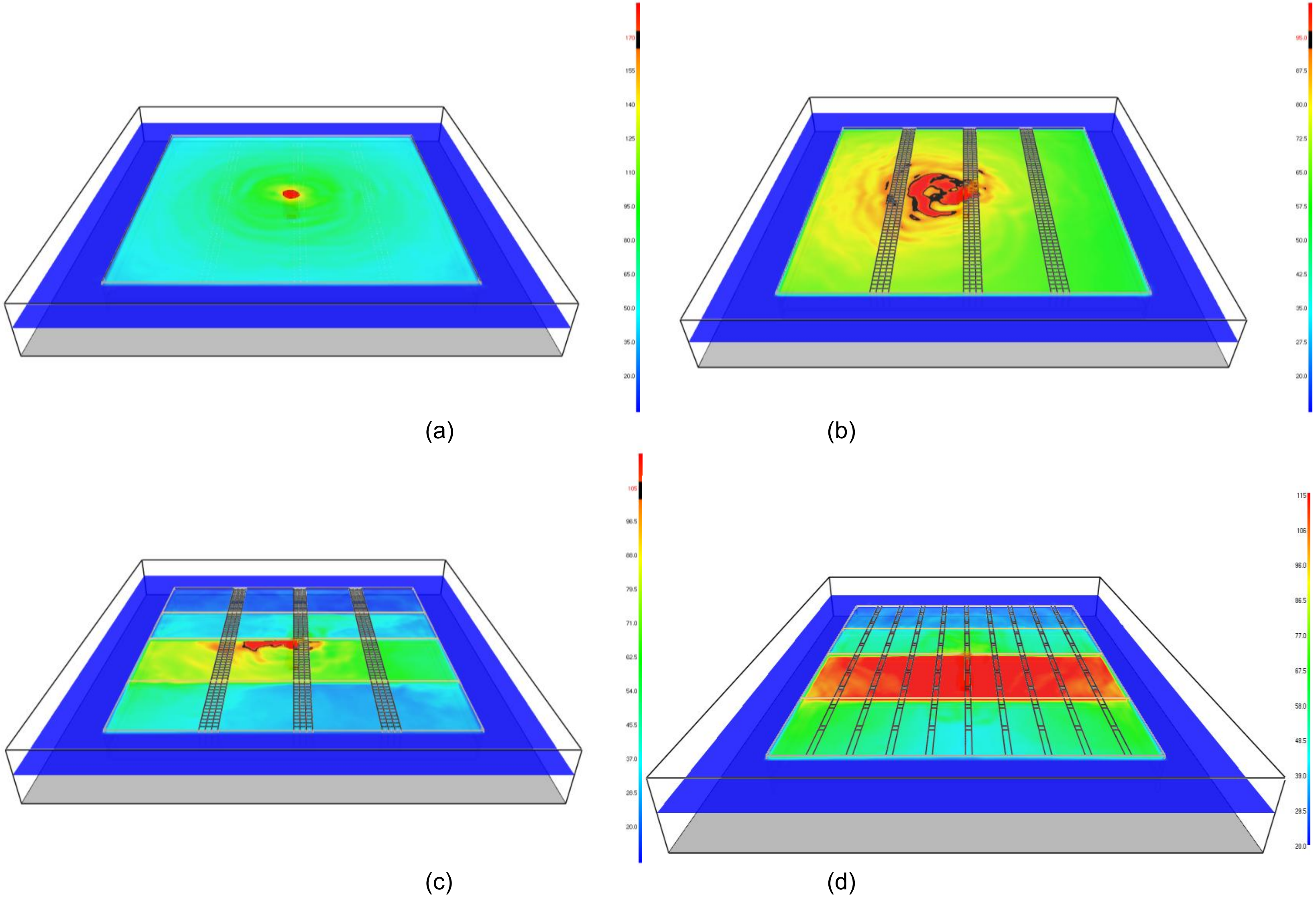


Figure 9: Examples of the base case gas temperatures (°C) results at 5.5 m above floor at 100 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.

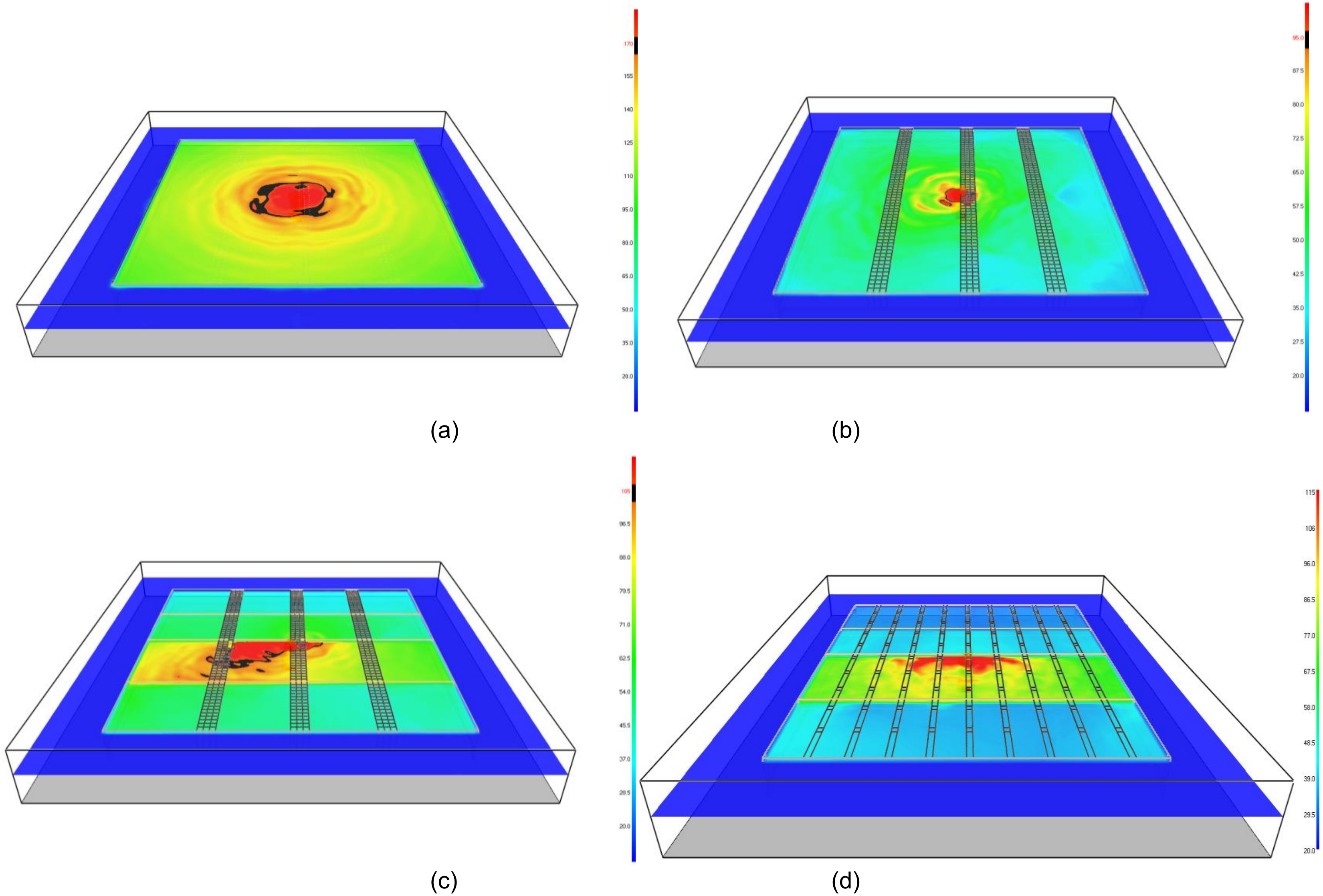
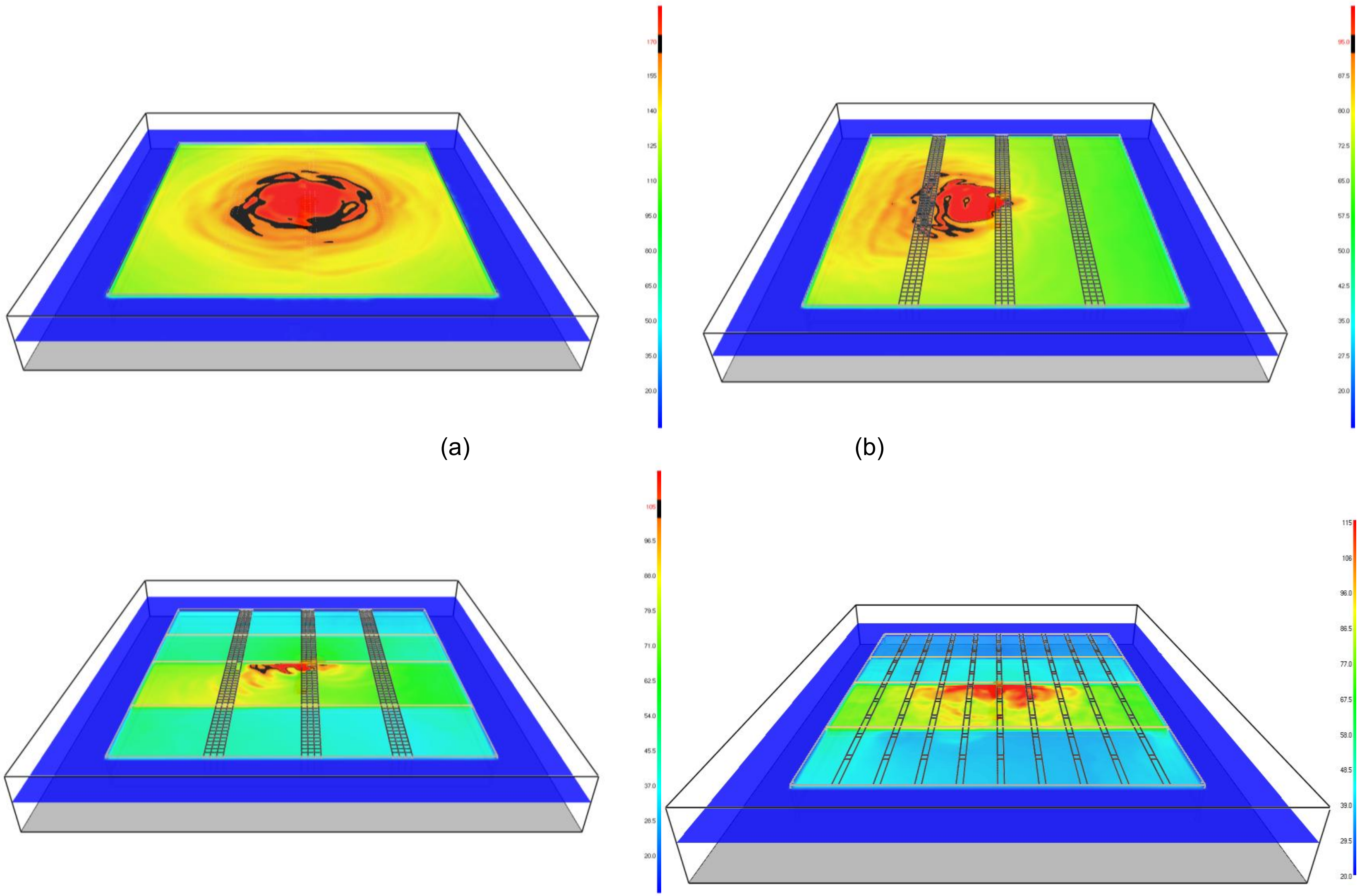


Figure 10: Examples of the base case gas temperatures (°C) results at 5.5 m above floor at 500 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.

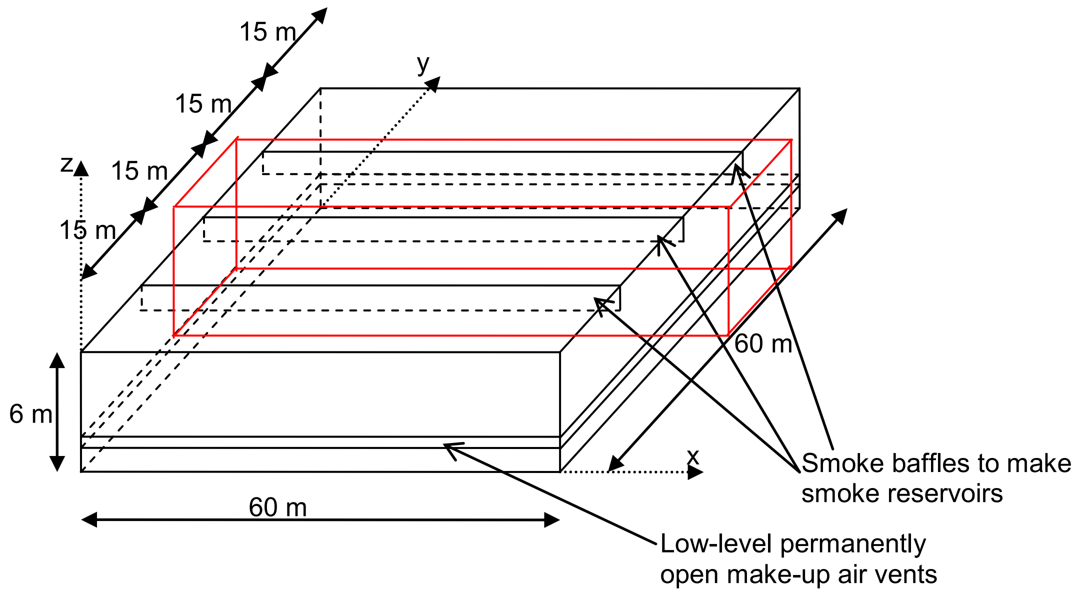


(a) (b) (c) (d)

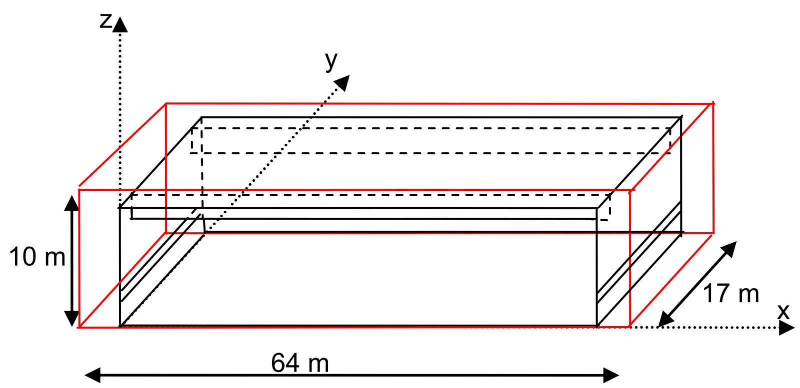
Figure 11: Examples of the base case gas temperatures (°C) results at 5.5 m above floor at 1,000 s from ignition for (a) scenario 1 – no vents and no smoke baffles, (b) scenario 2 – roof panel vents and no smoke baffles, (c) scenario 3 – roof panel vents with smoke baffles, and (d) scenario 4 – thermally activated dedicated vents with smoke baffles.

4.3.2 Sectioned Cases

The other cases considered were based upon the same generic warehouse scenarios where the warehouse had been sectioned, so that the focus is the one smoke reservoir directly above the fire. That is, a reduced area of the warehouse was modelled, so that only the equivalent of the one smoke reservoir containing the fire was modelled with the boundaries just outside of the smoke baffles being modelled as 'open'. Since Scenarios 1 and 2 have no smoke reservoirs, they were not suitable for this approach. Therefore Scenario 1 was modified as Scenario 1b (Table 7), with no vents but a single smoke reservoir. A similar modification of Scenario 2 leads to the same scenario as Scenario 3, therefore this was not conducted. In addition, an effective activation temperature of 300°C was assumed for the virtual heat detectors, which is Scenario 3b.



(a)



(b)

Figure 12: Schematic of the generic warehouse, where the red outline indicates the section of the warehouse that was modelled in the "sectioned cases". Not to scale.

Similar results were found when comparing each of the base cases, as had been found for the results for the scenarios using the whole warehouse. Comparing the results for the scenarios with sectioned compartments and the scenarios with whole compartments, the trends are the same, but the values for temperature and incident radiative intensity are higher for the sectioned scenarios. This is expected because the sectioned scenarios were conducted at a finer mesh size than used for the majority of the whole warehouse scenarios. The higher compartment temperatures subsequently resulted in earlier vent opening times.

Of most interest are the results from Scenario 3 and Scenario 3b, comparing one smoke reservoir with passive panel venting with an effective activation temperature of 120°C with 300°C. The 300°C effective activation temperature value was selected based on the upper temperature of the test method, AS 2428 Part 3 (2004). The time to vent opening was slower for the 300°C (Scenario 3b) case compared to the 120°C (Scenario 3) case, but still the first opening in the passive venting panel was opened before 50 s from ignition (Figure 113 and Figure 118). The gas temperatures in the section of compartment were higher for Scenario 3b than for Scenario 3 (e.g. Figure 115d and Figure 120d), as gas temperatures in Scenario 3b exceeded the effective activation temperature of Scenario 3. Although a smaller section of the passive venting panel opened during Scenario 3b than during Scenario 3, a seemingly quasi-steady-state gas temperatures within the sectioned compartment was observed by 1,000 s for both scenarios, with higher gas temperatures for Scenario 3b than Scenario 3 (Figure 115d and Figure 116d, and Figure 120d and Figure 121d).

Examples of the code used in modelling are included in Appendix B as well as more details of the results.

4.3.3 Sensitivity Analysis

The sensitivity of the base case scenarios was investigated for a range of parameters, as listed in Table 6. The results for Scenarios 3 & 4 were of most interest.

Reducing the effective activation temperature of the virtual heat detectors used within Scenario 3 to open sections of the panel for venting from 120°C to 100°C (Figure 51 and Figure 52), resulted in lower virtual heat detector temperatures by a maximum of 30°C that occurred directly over the fire and a slightly faster opening time by 2 to 3 s.

The effective RTI of the virtual heat detectors used within Scenario 3 to open sections of the panel for venting was reduced from 132 to 119 $(m.s)^{1/2}$ (Figure 53 and Figure 54). That is, making the response of the detector to heat faster by 10%. There is little difference in the results (Figure 53) after the initial opening of the vents (Figure 54), when the smaller RTI value means detectors increase in temperature faster. Similarly increasing the effective RTI by 10%, from 132 to 145 $(m.s)^{1/2}$ (Figure 55 and Figure 56), showed a slower increase in device temperature and subsequent opening of the venting panels. However the differences in temperature associated with the increase in effective RTI by 10% are not proportional to the temperature differences associated with the decrease in effective RTI by 10%. The differences in device temperature were greater for the 10% increase in effective RTI (Figure 55 and Figure 56) than for the 10% decrease (Figure 53 and Figure 54). This is associated with the relationship between RTI and device temperature not being linear.

Considering the location of passive venting panels, three widths of a "long run" approach were modelled: 1, 2 and 3 m widths that run the entire length of the compartment. The temperature profiles for the virtual heat detector devices are similar for the three widths considered (Figure 38, Figure 58 and Figure 64). The radius associated with an incident radiant intensity 4.5 kW/m² increased slightly with decreasing panel width (Figure 40, Figure 59 and Figure 65). This is expected because of the initial location of the fire being closer to more panel area for the 3 m widths scenario, decreasing down to the 1 m widths scenario. The gas temperatures were also higher for the smaller passive venting panel widths (Figure 43, Figure 62 and Figure 68), decreasing in spread with increasing passive venting panel widths. This is also attributed to the location of more panels nearer to the seat of the fire for the 3 m width scenario compared with the 1 and 2 m width scenarios.

A 10% increase or decrease in the peak HRR value caused less than a 5° difference in virtual heat detector temperatures (Figure 85 and Figure 86). Reducing the peak HRR from 8 MW to 5 MW produced a difference in virtual heat detector temperatures of up to 20°C (Figure 84). Increasing the peak HRR from 8 MW to 12 MW produced a difference in virtual heat detector temperatures of up to 10°C (Figure 87). Although even the maximum difference of temperature observed here of 20°C does not seem like much. A higher temperature at the vent location leads to earlier opening of the vent. This leads to the obvious problem of passive vents that rely on the local temperature to open potentially not being heated sufficiently to form openings and subsequently the compartment would fill with smoke. Potentially in this situation, the fire would grow and spread, which may provide sufficient heat to form openings in the passive venting panel at a later time.

A range of wind speeds were considered; 3, 5 and 10 m/s. All wind was assumed to be horizontal. The results for the range of wind speeds considered showed little difference in the temperature of the virtual heat detectors compared with the still ambient air conditions (Figure 88, Figure 89 and Figure 90). Subsequently the opening times of the vents also showed little difference compared with the base case. However the wind did make a difference to the visibility within the compartment, since it could flow in and out of the permanently open make-up air vents and stirred up the bottom of the hot layer more than was observed for the still conditions (Figure 91). In addition smoke escaping out of the vents was obviously blown about by the wind conditions.

Additional compartment heights of 10 and 15 m were considered. The maximum difference in virtual heat detector temperatures were approximately 13 to 15°C (Figure 95 and Figure 100). The difference in the opening times of the vents was an increase of approximately 30 s for the 15 m high compartment (Figure 106).

Examples of the code used in modelling these scenarios for checking sensitivities are included in Appendix A as well as more details of the results.

4.4 Discussion of Modelling Results

The more potential roof venting area close to the seat of the fire, the more effective the venting is at reducing the temperatures within the compartments.

When modelling passive venting panels, an effective RTI value would need to be estimated from testing. If the modelling RTI is an over-estimate of the representative value, then the modelling results could be highly conservative. However the estimation of the effective activation temperature is more significant. Furthermore testing results for the passive venting panels may not provide separation of values for effective RTI and effective activation temperature without using several temperature versus time regimes.

Smoke baffles limit the spread of hot gases across the ceiling of the compartment. This aids venting by concentrating the hot gases into a smaller area, increasing the heat flux to the vents, therefore assisting in opening vents earlier. Smoke baffles also aid venting by collecting the hot layer in a smaller area, which will assist in reducing plugholing at the vents.

A higher temperature at the vent location leads to earlier opening of the vent. This leads to the obvious problem of passive vents that rely on the local temperature to open (potentially not being heated sufficiently to form openings) and subsequently the compartment would fill with smoke. Potentially in this situation, the fire would grow and spread, which may provide sufficient heat to form openings in the passive venting panel at a later time.

A preliminary sensitivity analysis was also performed to determine the appropriate magnitude for the grid size. It was found that decreasing the height of the compartment required a smaller grid size. Therefore care must be applied such that appropriate grid sizing is chosen and re-checked after important parameter values are changed. It was also found that increasing the width and length of the square compartment had a negligible effect on the results. This is expected to be reasonable.

These preliminary fire venting model results using FDS indicate that a similar approach would be useful in the further investigation of roof venting and comparison of results with experimental investigations as well as zone model results.

Mild ambient wind conditions were observed to affect the visibility within the compartment. This was attributed to the altered flow through the permanently open make-up air vents. The bottom of the smoke layer seemed to be the most affected by this change in flow and the smoke escaping through the openings. Vent opening times were not affected by the wind conditions considered, however much stronger winds may affect the heating of the panels by providing a more effective heat sink and slow the time to potential openings being formed in a panel.

Increasing the compartment height delays the time at which roof vents will open. Considering this in conjunction with the results with changes in the design fire, it is therefore important to consider the compartment size in conjunction with a design fire appropriate to the intended fire load. Overestimating the potential fire will provide faster vent opening time estimates than would be expected. Therefore care must be applied in choosing an appropriate scenario to challenge the design with.

Scenario results also showed that quasi-steady-state conditions may form within the vented compartment. Therefore finding a combination of appropriate materials and appropriate location of passive venting panels for a compartment design may be able to achieve the performance criteria, discussed in Section 3.2, or other values for a defined range of design fires for the ambient conditions considered in this study. It is important to note that the ambient conditions considered in this study are relatively mild and that passive venting is expected to be affected by windy turbulent conditions.

4.4.1 Coding

One particular problem with modelling multiple detectors activated by any heat detector within an area was highlighted with the results. It was found that creating openings in the roof on the activation of heat detectors worked well when each vent was allocated a single heat detector and the results were as expected, with vents opening upon detector activation. However when all vents in a smoke reservoir were linked to the activation of any heat detector in the same smoke reservoir then all the vents opened upon the activation of the last heat detector in the same smoke reservoir instead of the first. This is related to the order of creation of objects within each simulation. Two solutions are suggested for this. One option is to order the lines of code so that lines of code creating holes in objects (in order to open vents) are ordered in relative radial location to the centre of the fire and then checked against heat detector activation results, however considering the number of lines of code involved (see Appendix B) this can be relatively time consuming and would have to be re-coded for each change in geometry. An alternative solution is to create a small module to link the activation of any heat detector in each smoke reservoir, similar to the ‘ANY’ command currently available for the activation of any heat detector in the entire simulation.

Each modelling package is expected to be different. Therefore care must be applied in the way that the passive vents are modelled.

4.4.2 Limitations of this Study

For the scenarios considered here and for the specific FDS package used, a multiple-mesh approach is not appropriate for use in a large single firecell, since interactions with walls provide flow that is counter to the direction of the flow accounted for when passing information between meshes (i.e. from a lower numbered mesh to a higher numbered mesh).

Scenarios considered here used either a 0.5 m or 0.15 m uniform mesh. In particular, the 0.5 m mesh provided conservative results concerning the activation time of thermally activated devices since the temperatures were lower than expected. The results for maximum temperatures and radiative intensity are considered to be lower than expected in reality, however the focus of this study was the modelling of vents and the comparison between the scenarios considered.

A more refined mesh was not considered necessary for modelling the entire generic warehouse for the objectives of this stage of the study. A more refined mesh is recommended for further study, when the fire venting characteristics of potential panel materials are better known and can be more confidently modelled using an effective activation temperature and an effective Response Time Index (RTI) that are appropriate for the material and installation.

Entire sections of the passive venting panel are not expected to form a clean opening at the time the virtual heat detector activates. Instead sections are expected to melt and drip (in the case of thermoplastic materials) and form non-uniform holes. Therefore there may be a more appropriate way of modelling the behaviour of the panels. The characteristics and behaviour of different materials is expected to vary with panel material. Therefore appropriate modelling approaches may be different for different panel materials and the associated construction technique by which it is intended to be included in a building. Testing results would provide more information on this for each material of interest.

5. HAND CALCULATIONS

This section summarises the analytical estimates that may be applied to estimate design aspects associated with fire venting.

5.1 Design Wind Speed and Direction

A limited range of wind speeds were included in this investigation, whereas wind direction was considered outside of the scope of this study. However it is acknowledged that wind is an important consideration when estimating the performance of buoyancy-driven vents.

For example the wind direction in this study was assumed to be parallel to the flat, horizontal ground and only from one direction. In addition the fire venting panels were assumed to drop inwards, and therefore not be affected by wind. Furthermore the roof was assumed to be flat with no projections that may also disturb the flow across the top of the roof. Whereas in actuality the wind would be expected to come from a range of directions (Figure 13 shows an example for the Wellington airport), to show local disturbances from hills, trees, other buildings, the shapes of the target building and other obstacles, and would not be horizontal.

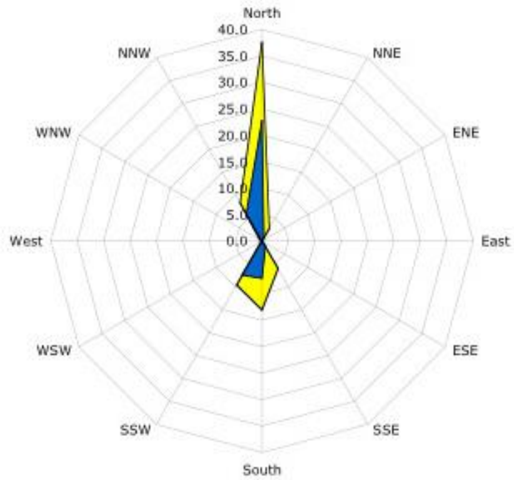


Figure 13: Example of the wind speed and direction data summarised over a year. Yellow corresponds to winds over 15 knots and blue to over 20 knots. Extracted from Court (2008).

5.2 Wind Velocity Pressure

The wind velocity pressure can be represented by (ASHRAE 1997):

$$P_w = \frac{1}{2} C_w \rho_o U_z^2$$

Where P_w refers to wind pressure (Pa), C_w refers to wind pressure coefficient, ρ_o refers to the ambient air density (1.2 kg/m³), and U_z refers to the wind speed at height z (m/s). The design wind speeds for structural analysis in Wellington, New Zealand are currently 50 m/s. The wind pressure coefficient value depends on the angle of attack of the wind to the building. The typical range for the wind coefficient value is 0.2 to 0.8.

The results for Eq. 1 are shown in Figure 14, and the results for a design wind speed of 50 m/s is summarised in Table 9.

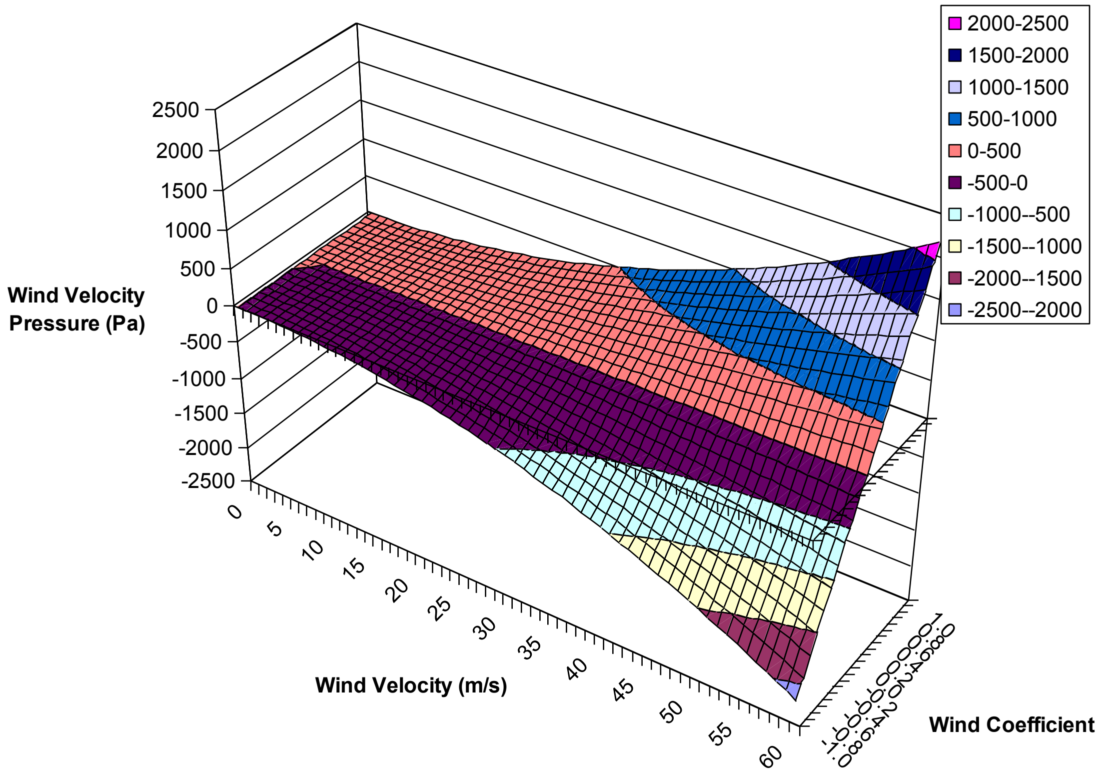


Figure 14: Wind velocity pressure versus wind velocity and wind coefficient

Table 9: Wind velocity pressure versus wind coefficient at a design wind velocity of 50 m/s

Wind Pressure Coefficient	Wind Velocity Pressure (Pa)
1.0	1500
0.7	1050
0.6	900
0.5	750
0.4	600
0.3	450
0.2	300
0.1	150
0	0
-0.1	-150
-0.2	-300
-0.3	-450
-0.4	-600
-0.5	-750
-0.6	-900
-0.7	-1050
-1	-1500

The negative wind pressure coefficient values of Figure 14 and Table 9 indicate a negative pressure difference. That is, air may (depending on the pressure associated with the developing hot layer) be pushed into the building through the passive roof vents.

In addition the simple estimations for wind velocity pressure and wind pressure coefficients discussed here assume that the flow is not disturbed by the surrounding built environment or other obstacles around or on the building of interest.

5.3 Smoke Layer Height

Estimates of the ratio of clear height to ceiling height from the base of the fire, using the empirical equation in NFPA 92B (2005), for steady fires:

$$\frac{z}{H} = 1.11 - 0.28 \ln\left(\frac{t\dot{Q}^{1/3} H^{-4/3}}{A/H^2}\right)$$

Or for t-squared fires:

$$\frac{z}{H} = 0.91\left[\frac{t}{t_g^{2/5} H^{4/5} (A/H^2)^{3/5}}\right]^{-1.45}$$

Where z is the clear height from the base of the fire (m), H refers to the ceiling height from the base of the fire (m), t refers to time (s), A refers to the area of the compartment (m), $\dot{Q}$ refers to the heat release rate (kW), and t_g refers to the growth time (s.m$^{-4/5}$).

For a floor area of 900 m² and ceiling height of 6 m (equivalent to one smoke reservoir used in the modelling of the generic warehouse), a range of steady fires and t-squared fires are shown in Figure 15. However the ratio of ceiling height to floor area is beyond the limits of the correlation for both steady fires and t-squared fires, therefore more cooling and subsequent thickening of the smoke layer would be expected for the generic warehouse case and only the indicative results of Figure 15 are used for comparison with modelling outputs.

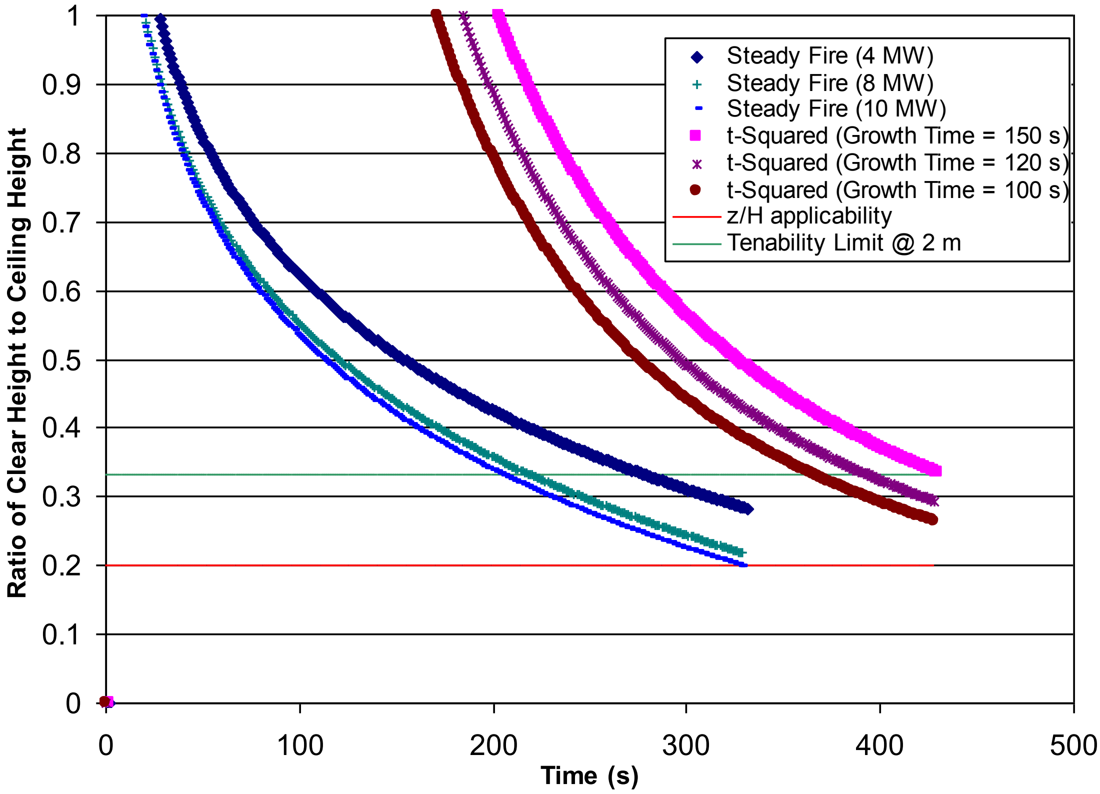


Figure 15: Estimates of the ratio of the clear height to the height from fire base to ceiling for a range of steady fires and t-squared fires, for a floor area of 900 m², using the estimates presented in NFPA 92B (2005).

As an alternative estimate method for the smoke layer height, the time to fill the enclosure with smoke was used. The estimate of the time to fill the smoke layer was based on the smoke production rate (Section 5.7):

$$t_s = \frac{A(H-z)}{\dot{V}_{smoke}}$$

The results for these estimates of ratio of clear height to ceiling height are shown in Figure 16 for a 900 m² enclosure, with a ceiling height from the base of fire of 6 m, with steady fires and assuming the convective proportion of the heat release rate to be 70%. Estimates for a 500 m² and 200 m² enclosure are shown in Figure 17 and Figure 18 respectively.

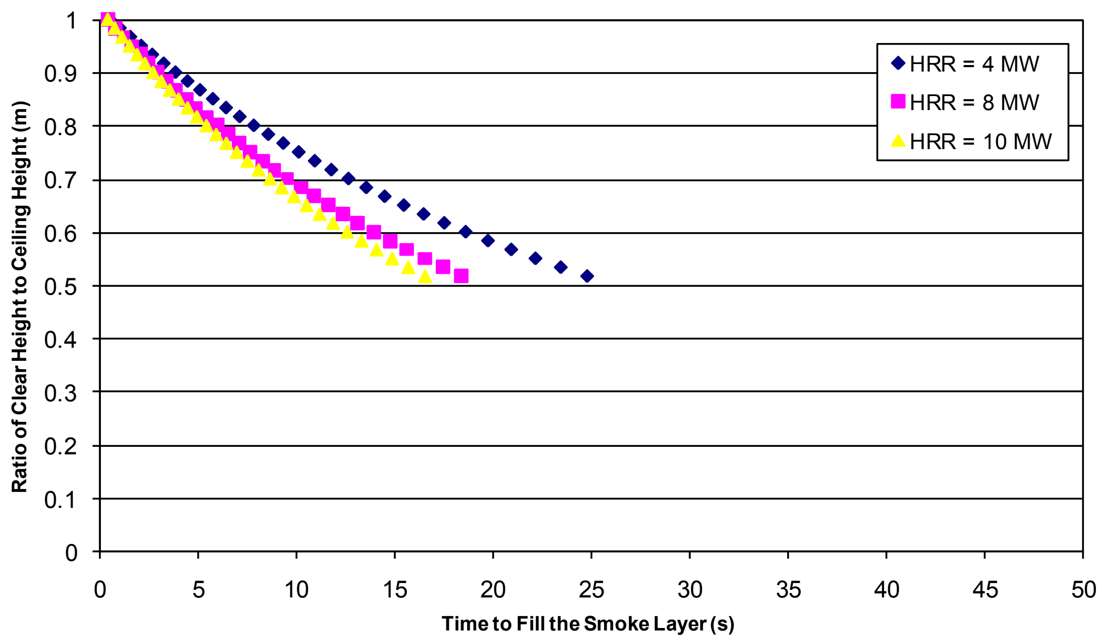


Figure 16: Estimates of the ratio of the clear height to the height from fire base to ceiling for a range of steady fires and t-squared fires, for a floor area of 900 m², using the estimates of smoke production rates.

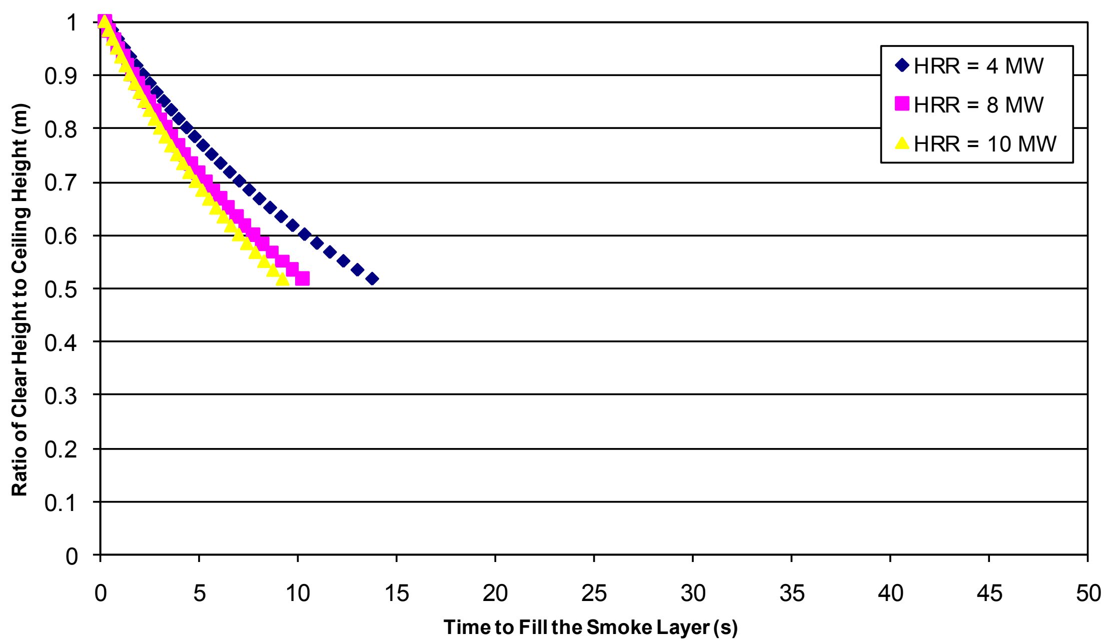


Figure 17: Estimates of the ratio of the clear height to the height from fire base to ceiling for a range of steady fires and t-squared fires, for a floor area of 500 m², using the estimates of smoke production rates.

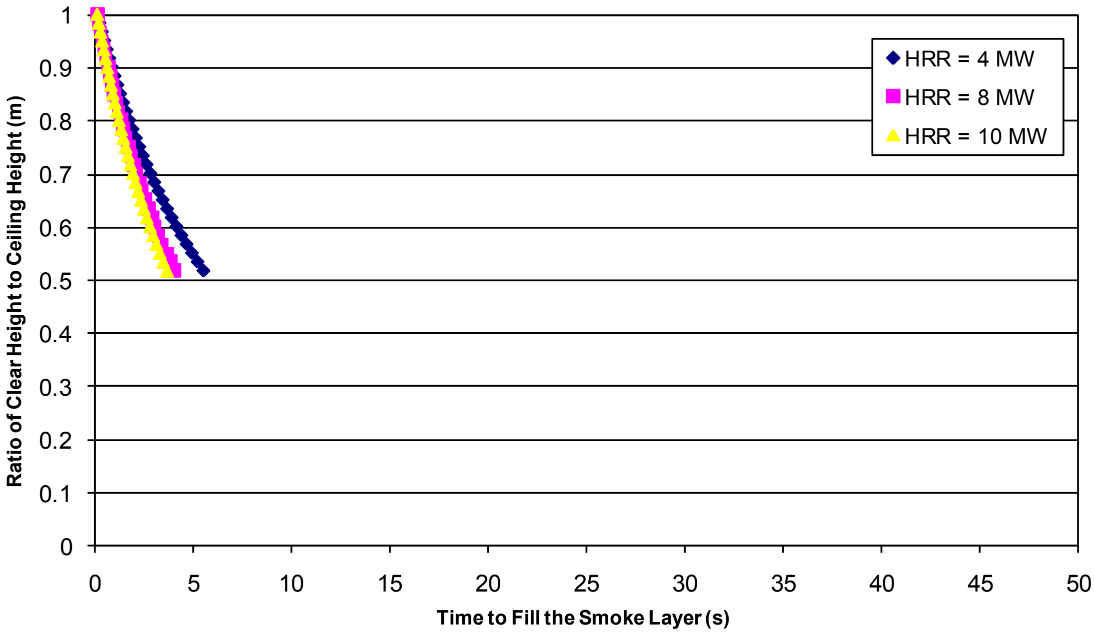


Figure 18: Estimates of the ratio of the clear height to the height from fire base to ceiling for a range of steady fires and t-squared fires, for a floor area of 200 m², using the estimates of smoke production rates.

5.4 Average Smoke Layer Temperatures

The average smoke layer temperature estimate is (Milke & Klote, 1998):

$$T_s = T_o \exp\left[\frac{(1-\chi_s)\dot{Q}t_s}{\rho_o C_P T_o A(H-z)}\right]$$

Where T_s refers to the average smoke layer temperature (K), T_o refers to the ambient temperature (293 K), χ_s refers to the heat loss fraction from smoke to the enclosure, $\dot{Q}$ refers to the total heat release rate for steady fires (kW), t_s refers to time to fill the smoke layer to a certain depth (which is based on the estimate of the volumetric smoke production rate, as discussed in Section 5.7), ρ_o refers to the ambient density (1.292 kg/m³), C_P refers to specific heat of ambient air (1.004 kJ/kg.K), A refers to the horizontal cross-sectional area of the enclosure (m²), H refers to the height of the ceiling above the base of the fire (m), and z refers to the clear height above the base of the fire (m).

It is noted that the assumption of adiabatic conditions $(\chi_s = 0)$ for small enclosures, such as enclosures with less than 10 m ceiling height, may result in significant overestimates of the average smoke layer temperature (Milke & Klote, 1998).

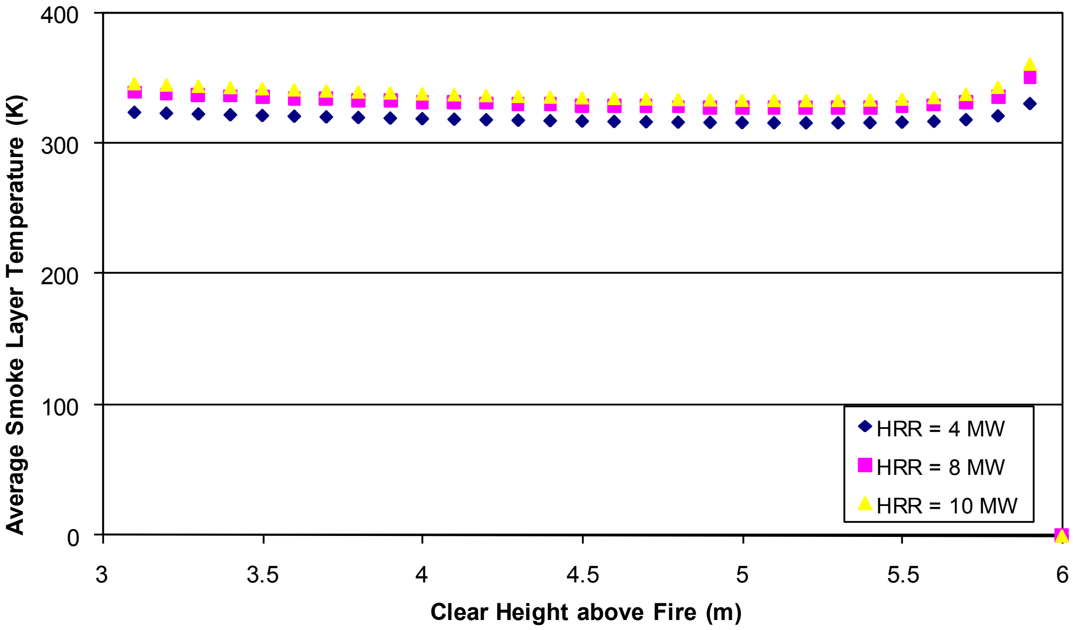


Figure 19: Average smoke layer temperature for a 900 m² enclosure, assuming a steady fire and no heat losses to enclosure.

5.5 Ceiling Jet Temperatures

Estimates of the ceiling jet temperatures for steady fires assuming a weak plume-driven flow field using Alpert's correlations (SFPE Handbook, 2002) are shown in Figure 20. Estimates of the ceiling jet temperatures for steady fires assuming a strong plume-driven flow field using Heskestad and Hamada correlations (SFPE Handbook, 2002) are shown in Figure 21. The proportion of convective heat release rate was assumed to be 70%.

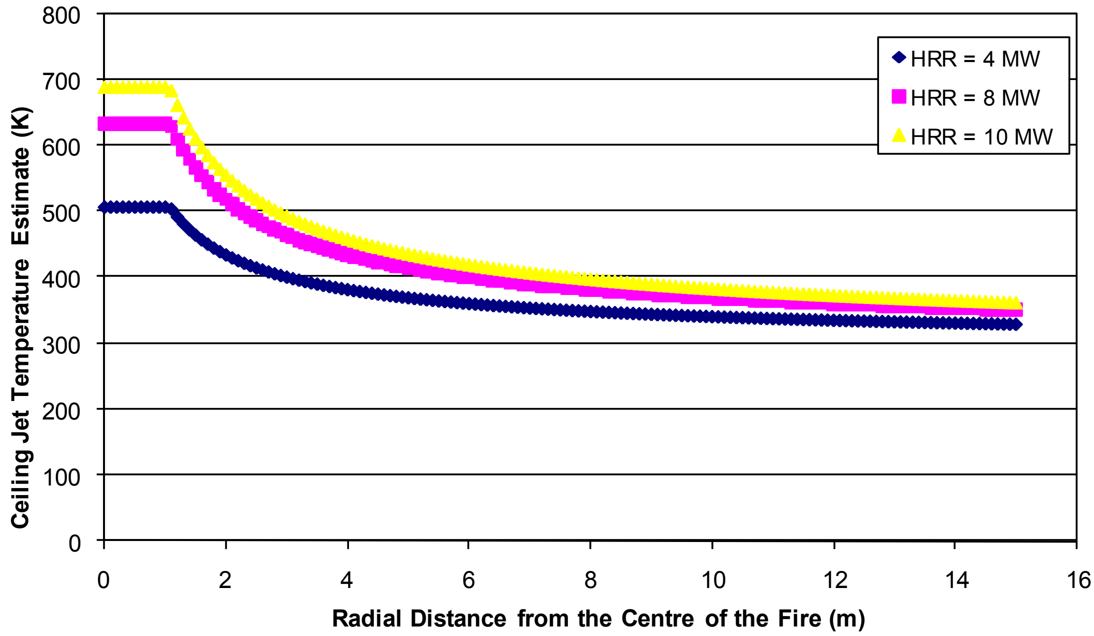


Figure 20: Ceiling jet temperature estimates at radial distances from the centre of a steady fire with weak plume-driven flow fields for various heat release rates.

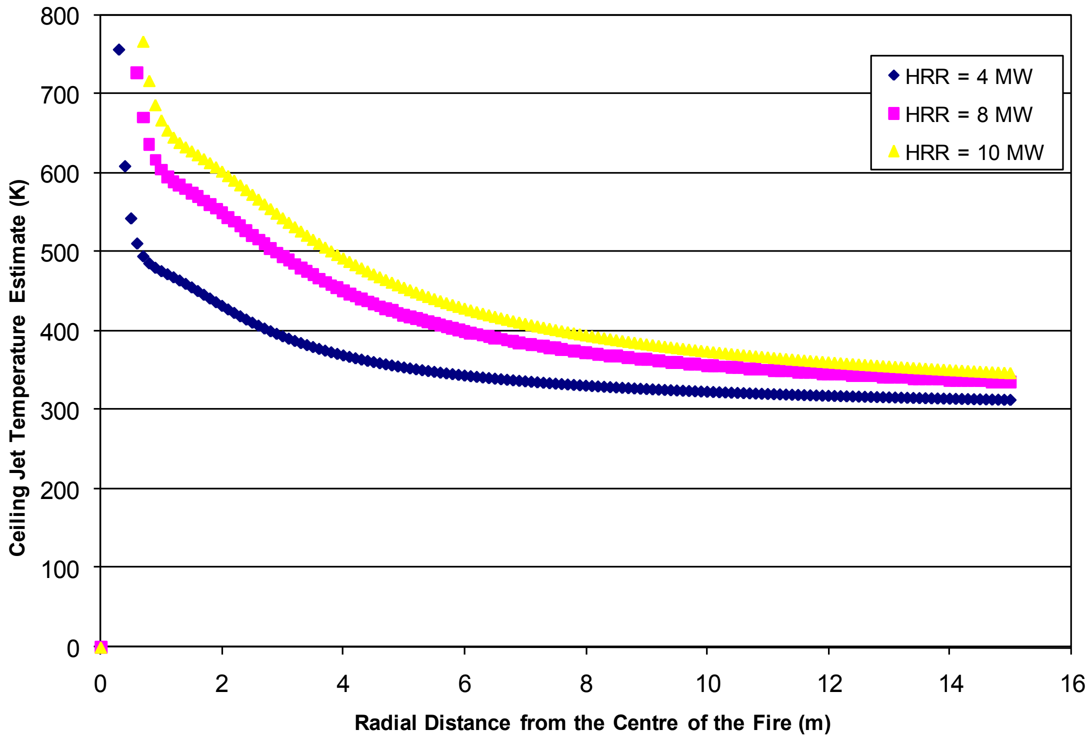


Figure 21: Ceiling jet temperature estimates at radial distances from the centre of a steady fire with strong plume-driven flow fields for various heat release rates.

5.6 Plume Diameter

Assuming an axisymmetric plume and using the empirical equation presented in NFPA 92B (2005) the plume diameter can be estimated using:

$$d_{plume} = K_d z$$

Where d_{plume} refers to the plume diameter in meters, K_d refers to the plume diameter constant (recommended values are 0.5 for plume contact with walls and 0.25 for beam detection of the plume), and z refers to the clear height above the base of the fire.

That is, the diameter of the plume is directly proportional to the clear height above the base of the fire.

5.7 Smoke Production Rate

Assuming an axisymmetric plume, based on Heskstad's correlation (NFPA 92B, 2005), the mass flow rate in the plume can be estimated by:

$\dot{m}_{plume} = 0.071\dot{Q}_c^{1/3} z^{5/3} + 0.0018\dot{Q}_c$, where the clear height is greater than the flame height, or

$\dot{m}_{plume} = 0.032\dot{Q}_c^{3/5} z$, where the clear height is less than the flame height.

Where $\dot{m}_{plume}$ refers to the mass flow rate in the plume (kg/s), $\dot{Q}_c$ refers to the convective portion of heat release rate (kW), and z refers to the clear height from the base of the fire.

Assuming the smoke plume can be modelled as an ideal gas and using the specific gas constant for dry air, then the density of the plume can be estimated by:

$$\rho_{air} = \frac{P}{RT}$$

Where ρ_{air} refers to the density of air (kg/m³), P refers to pressure (Pa), T refers to temperature (K), and $R = 287.05$ refers to the specific gas constant for dry air (J/kg.K).

Estimating the average plume temperature using the equation presented in NFPA 92B (2005):

$$T_{plume} = T_o + \frac{\dot{Q}_c}{\dot{m}_{plume} C_P}$$

Where T_{plume} refers to the average temperature of the plume (K), T_o refers to the ambient temperature (K), $\dot{Q}_c$ refers to the convective component of the heat release rate.

Then assuming the portion of convective heat release rate to total heat release rate is approximately 70% (assuming a range of fuels, estimated from tables of chemical, convective and radiative heats of combustion in SFPE Handbook (2002)), then an estimate of the smoke volumetric production rate would be:

$$\dot{V}_{smoke} \approx \frac{R}{P}\left(T_o \dot{m}_{plume} + \frac{\dot{Q}_c}{C_P}\right)$$
$$= \frac{R}{P}\left(T_o (0.071 \dot{Q}_c^{1/3} z^{5/3} + 0.0018 \dot{Q}_c) + \frac{\dot{Q}_c}{C_P}\right)$$

The results of this equation are shown in Figure 22.

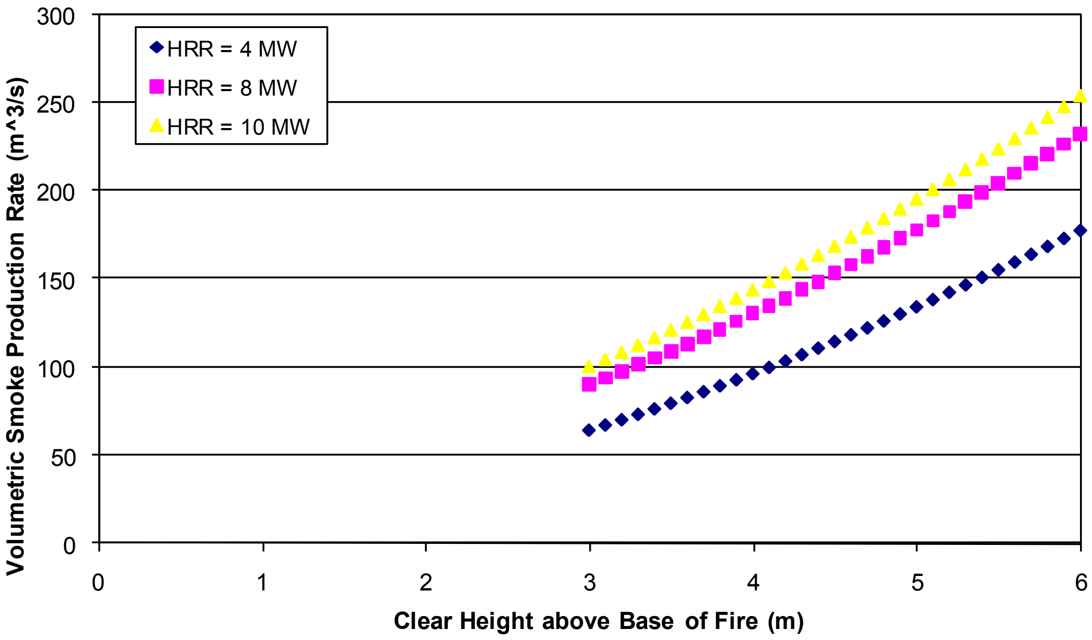


Figure 22: Volumetric smoke production rate versus the clear height above the base of fire.

5.8 Maximum Volumetric Flow Rate

An estimate for the maximum volumetric flow rate without plugholing is (NFPA 92B, 2005):

$$\dot{V}_{max} = 4.16 \gamma d_{smoke}^{5/2} \left(\frac{T_s - T_o}{T_o}\right)^{1/2}$$

Where $\dot{V}_{max}$ refers to the maximum volumetric flow rate without plugholing (m³/s), γ refers to an exhaust location factor (1 when centre of vent is located more than twice the vent diameter from a wall, or 0.5 when centred closer), $d_{smoke} = H - z$ refers to the thickness of the smoke layer (m), T_s refers to the temperature of the smoke layer (K), and T_o refers to the ambient temperature (K). Estimates for the maximum volumetric flow rate for vents with centres located further than twice the vent diameter are shown in Figure 23 and for vents with centres located closer than twice the vent diameter in Figure 24.

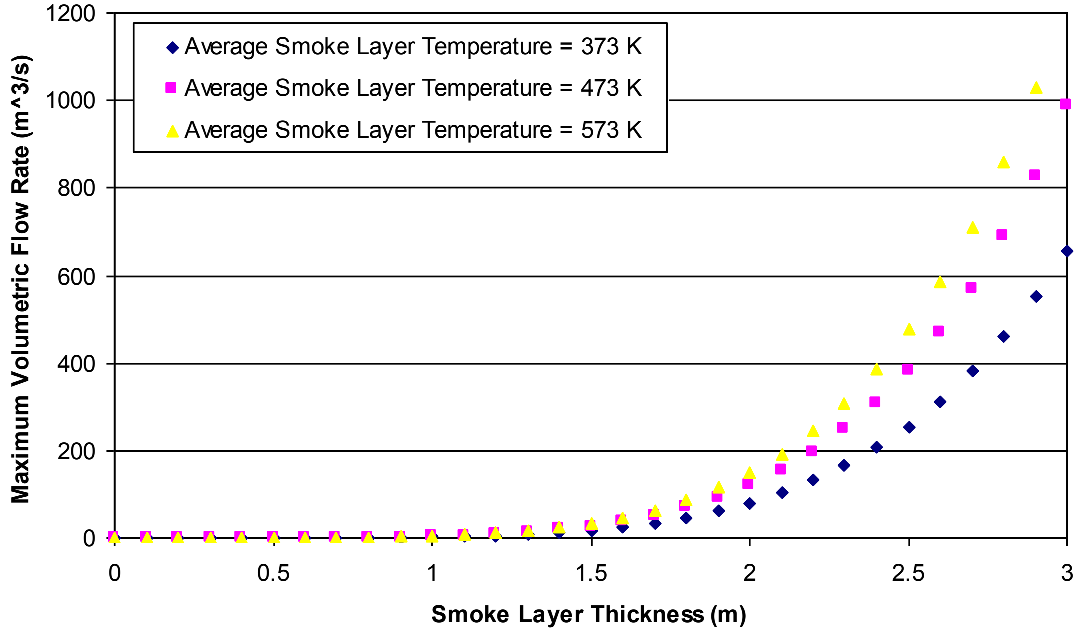


Figure 23: Estimate of the maximum volumetric flow rate without plugholing for vents with centres located more than two vent diameters from a wall.

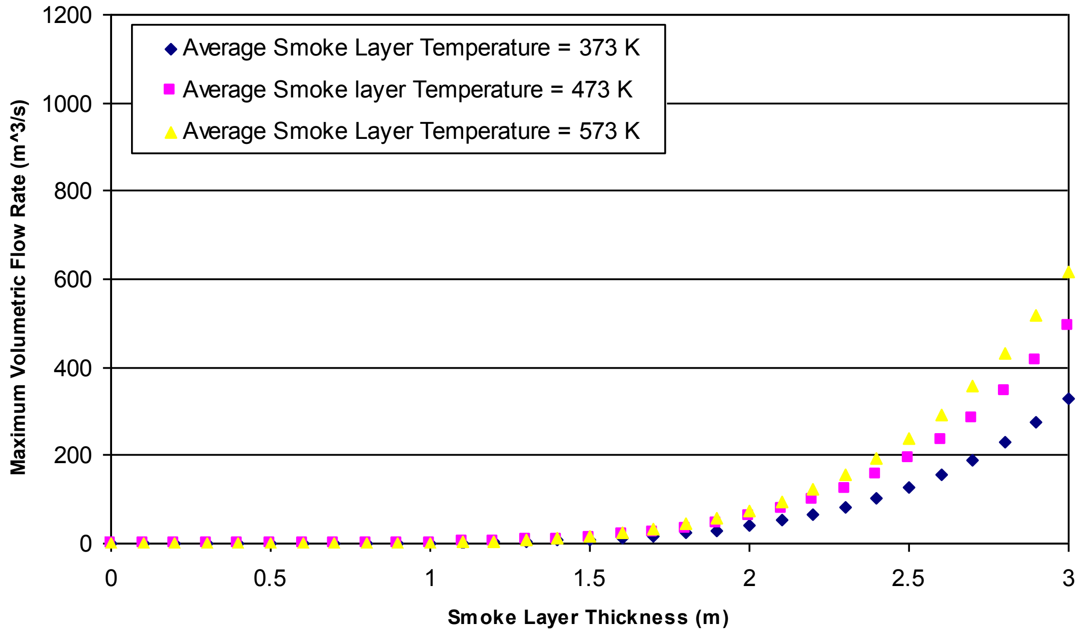


Figure 24: Estimate of the maximum volumetric flow rate without plugholing for vents with centres located less than two vent diameters from a wall.

5.9 Discussion of Vent Dimensions and Locations

The ratio of smoke layer thickness to effective vent diameter must be greater than two (NFPA 92B, 2005). For rectangular vents, the effective diameter is the vent area divided by the average of the length and width.

The minimum edge-to-edge separation distance between adjacent vents to prevent plugholing is:

$$S_{\min} = 0.9\dot{V}_{vent}^{1/2}$$

Where $S_{\min}$ refers to the minimum edge to edge separation distance between adjacent vents (m), and $\dot{V}_{vent}$ refers to the volumetric flow rate of one exhaust inlet (m³/s). Assuming the volumetric flow rate through the vent equals the volumetric smoke production rate ($\dot{V}_{smoke}$ of Section 5.7) produces the results shown in Figure 25.

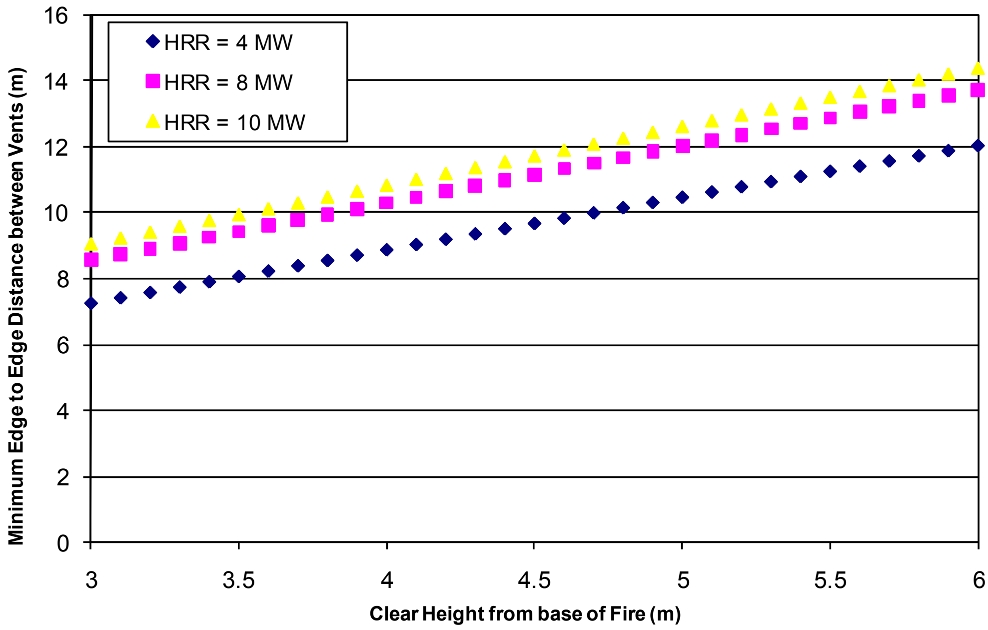


Figure 25: Minimum edge to edge separation between adjacent vents versus clear height from the fire base.

An estimate of the vent area, based on the capacity of natural vents, is (Milke & Klote, 1998):

$$A_{vent} = \frac{\dot{m}_{vent}}{C_d \rho_o} \sqrt{\frac{T_s \left[T_s + \left(\frac{A_{vent}}{A_{inlet}} \right)^2 T_o \right]}{2gT_o(H-z)(T_s - T_o)}}$$

Which can be re-written as:

$$A_{vent} = \sqrt{\frac{T_s \dot{m}_{vent}}{T_o} \left[\frac{2C_d^2 \rho_o^2 g}{T_s}(H-z)(T_s - T_o) - \frac{\dot{m}_{vent}}{A_{inlet}^2} \right]}$$

Where A_{vent} refers to the vent area (m²), A_{inlet} refers to the inlet area (m²), T_s refers to the average smoke layer temperature (K) (as discussed in Section 5.7), T_o refers to the ambient temperature (K), $\dot{m}_{vent}$ refers to the mass flow rate through the vent (kg/s), C_d refers to the coefficient of discharge (~0.6 (Heskestad, 1997)), ρ_o refers to the ambient density (kg/m³), H refers to the ceiling height above the base of the fire (m), and z refers to the clear height above the base of the fire (m).

Assuming that the mass flow rate through the vents $(\dot{m}_{vent})$ is equal to the mass flow rate of smoke into the smoke reservoir via the plume $(\dot{m}_{plume})$, then the vent area varies with clear height above the base of the fire. Substituting in the estimations for the mass and volumetric smoke production rate ($\dot{m}_{plume}$ and $\dot{V}_{smoke}$, Section 5.7), time to fill the smoke layer (t_s, Section 5.3), and the average smoke layer temperature (T_s, Section 5.4):

$$\dot{m}_{plume} = 0.071\dot{Q}_c^{1/3}z^{5/3} + 0.0018\dot{Q}_c$$

$$\dot{V}_{smoke} \approx \frac{R}{P_o}\left(T_o(0.071\dot{Q}_c^{1/3}z^{5/3} + 0.0018\dot{Q}_c) + \frac{\dot{Q}_c}{C_P}\right)$$

$$t_s = \frac{A(H-z)}{\dot{V}_{smoke}}$$

$$T_s = T_o \exp\left[\frac{(1-\chi_s)\dot{Q}t_s}{\rho_o C_P T_o A(H-z)}\right]$$

into the equation estimating the required vent area, results in:

$$A_{vent} = \frac{0.071\dot{Q}_c^{1/3}z^{5/3} + 0.0018\dot{Q}_c}{C_d\rho_o}\sqrt{\frac{T_s\left[T_s + \left(\frac{A_{vent}}{A_{inlet}}\right)^2 T_o\right]}{2gT_o(H-z)(T_s-T_o)}}$$

Where $T_s = T_o \exp\left[\frac{(1-\chi_s)\dot{Q}P_o}{\rho_o C_P T_o R\left(T_o(0.071\dot{Q}_c^{1/3}z^{5/3} + 0.0018\dot{Q}_c) + \frac{\dot{Q}_c}{C_P}\right)}\right]$

From this analysis neither the average smoke layer temperature (T_s) nor the required vent area to vent the equivalent of the smoke production rate (A_{vent}) are dependent on the horizontal cross-sectional area of the enclosure (A). Therefore it is counter intuitive to require a fixed ratio of vent area to horizontal cross-sectional area (i.e., A_{vent}/A) unless a maximum enclosure (or smoke reservoir) is defined and a worst case scenario is considered. However the required vent area is dependent on the ratio of vent to inlet area (A_{vent}/A_{inlet}), the heat release rate $(\dot{Q})$, portion of convective heat release rate $(\dot{Q}_c)$, ceiling height above base of fire (H), clear height above base of fire (z), fraction of smoke heat lost to surrounds (χ_s), and the ambient conditions. A reasonable comparison may be between required vent area and the estimated area for which the local thermal environment would provide openings in the roofing materials. However the estimated area for possible openings relies on the roofing material characteristics and the size of the design fire. Therefore better characterisation of potential roofing materials is required before discussion and analysis can be furthered.

The results for the estimates of required vent area to vent the equivalent of the smoke production rate are shown in Figure 28.

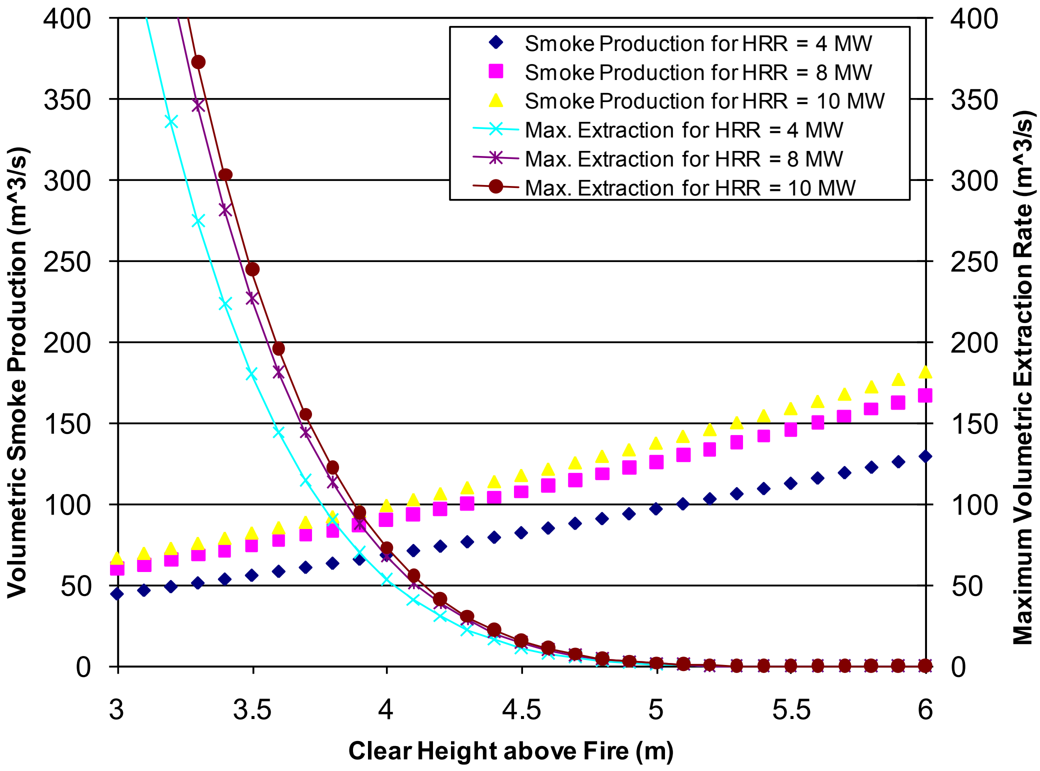


Figure 26: Volumetric smoke production rates for the plume and maximum volumetric extraction rate without plugholing relative to the clear height above a fire for a 6 m high ceiling for a location extract coefficient of 1.

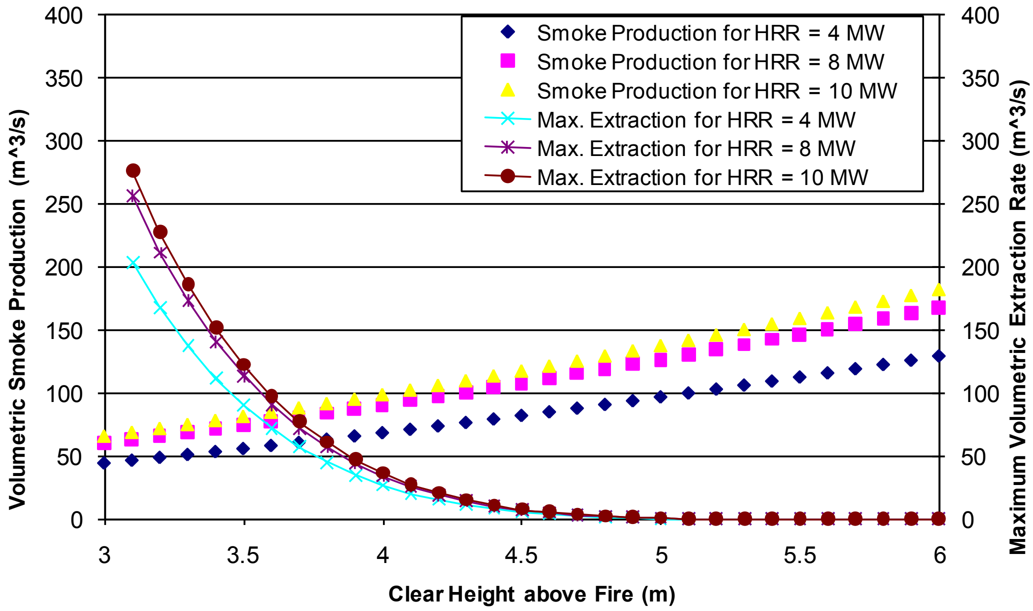
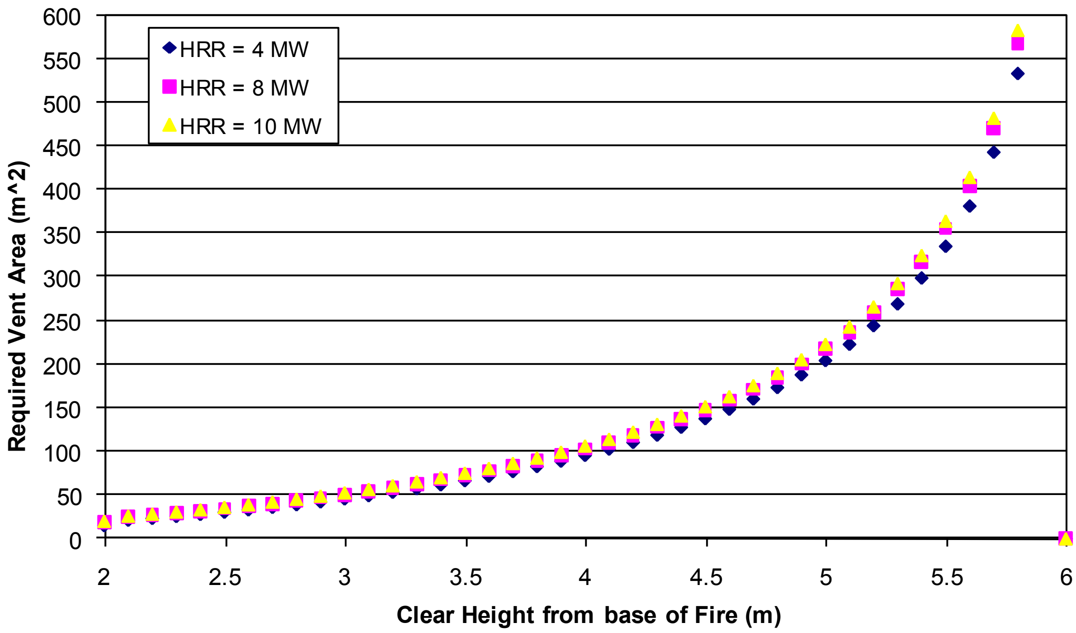
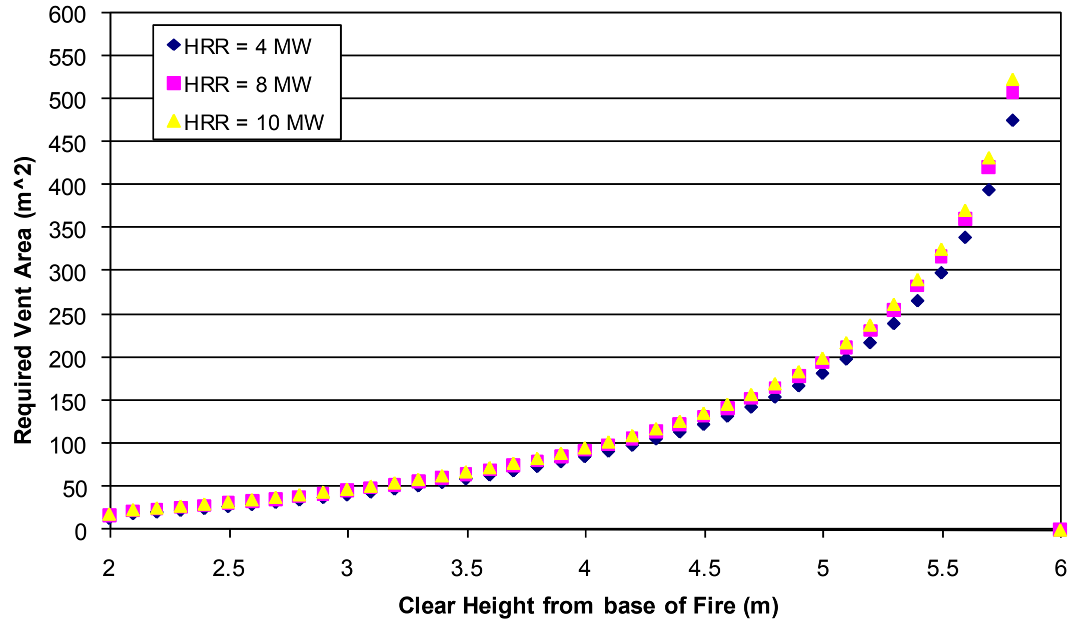


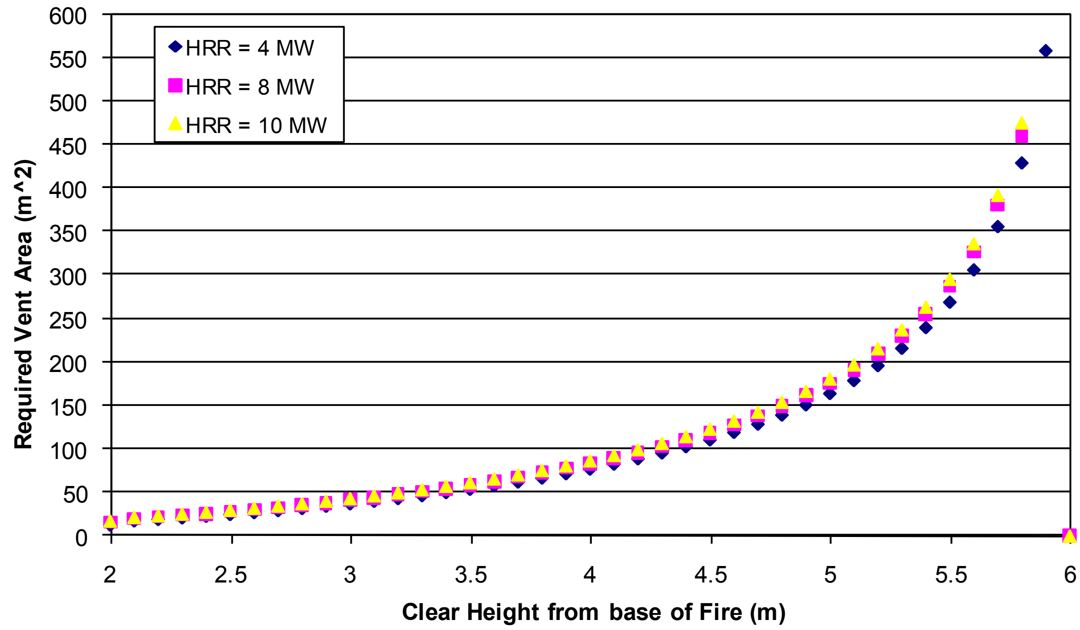
Figure 27: Volumetric smoke production rates for the plume and maximum volumetric extraction rate without plugholing relative to the clear height above a fire for a 6 m high ceiling for a location extract coefficient of 0.5.


HRR = 4 MW
HRR = 8 MW
HRR = 10 MW
Required Vent Area (m^2)
Clear Height from base of Fire (m)
600
550
500
450
400
350
300
250
200
150
100
50
0
2
2.5
3
3.5
4
4.5
5
5.5
6

(a)



(b)



(c)

Figure 28: Exhaust vent area required to vent the smoke production rate for a range of total heat of release rates for average smoke layer temperatures as estimated in Section 5.7 and for a ratio of exhaust to inlet vent area of (a) 1, (b) 0.75, and (c) 0.5.

6. CONCLUSIONS & SUMMARY

The intent and associated performance criteria for fire venting must be defined by the regulator or, in the case of an Alternative Solution, by the design team.

The intent of fire venting, in terms of the New Zealand Compliance document C/AS1, assumed for this study is:

- Fire venting is to reduce the hot combustion products contained within the firecell and help reduce hot smoke logging of the firecell.
- Fire venting is not associated with protection of property or contents of the burning building.
- Fire venting is not associated with the escape of initial building occupants in the event of a fire.
- Fire venting is to assist in potential rescue and suppression operations of the Fire Service. The presence of fire venting does not imply the Fire Service can/would or should enter the building. Reliance on intervention by the Fire Service is not included in a building design.
- Fire venting, in conjunction with other design features, may assist in the protection of other property during the total burnout of the building by reducing fire severity via preflashover venting.

From the analysis presented here alone a definitive answer cannot be ascertained for the potential use of plastic panels for passive fire venting. Experimental investigation of the plastic panels is necessary before a definitive conclusion can be drawn. However several important aspects were highlighted in the results of this study.

The useful results of this study include:

1. Buoyancy-driven vents have a high sensitivity to ambient wind conditions. This is expected in particular for winds that are not parallel to the ground.
2. Since not all potential passive roof venting panel points open in a smoke reservoir in the event of a fire in the design considered here, the location of panels relative to every point on the floor is important. It is essential that the design for the width and spacing of the passive fire venting panels and building height ensures sufficient panel area for potential exposure to sufficiently hot gases to form holes in the material no matter where a fire may occur within the compartment.
3. Larger fires provide heat to a vent earlier, therefore openings form earlier. Conversely a fire may be sufficiently small as to not provide sufficient heat to a passive venting panel to form any openings and the compartment may subsequently smoke log. Therefore in this situation or other situations of failure of the passive venting panels to form holes, a way to manually open the panels may be desirable. Similarly higher compartment heights lead to a delay in gas temperatures under the vents. Therefore the selection of the design fire in combination with the building design is important to ensure conservative model results. For example, including a design fire that is slightly smaller than what would be required to form openings or have vents activate is recommended.
4. The more potential roof venting area close to the seat of the fire the more effective the venting is at reducing the temperatures within the compartments.

5. The effective RTI and effective activation temperature values would need to be estimated from testing for each material and building design. Underestimating these values would provide model results that overestimate the fire venting effectiveness in the design.
6. Smoke baffles limit the spread of hot gases across the ceiling of the compartment and aid passive venting of hot gases and smoke.
7. Quasi-steady-state conditions were observed to form within the vented compartment for the scenarios considered. Therefore finding a combination of appropriate materials and appropriate location of passive venting panels for a compartment design may be able to achieve the performance criteria, discussed in Section 3.2, or other selected values for a defined range of design fires and the ambient conditions.

These results are important aspects of design of passive buoyancy-driven roof venting and should be considered in both design and assessment stages.

Specific modelling related conclusions:

- Passive roof venting can be modelled using the FDS package. However care must be taken when defining the model and the conditions to which it would be subjected.
- For the scenarios considered here and for the specific FDS package, the multiple-mesh approach is not appropriate for use in a large single firecell, since interactions with walls provide flow that is counter to the direction of the flow accounted for when passing information between meshes (i.e. from a lower numbered mesh to a higher numbered mesh).
- The scenarios considered here used a 0.5 m or a 0.15 m uniform mesh. In particular, the 0.5 m mesh provided conservative results concerning the activation time of thermally activated devices since the temperatures were lower than expected. The results for maximum temperatures and radiative intensity are considered to be lower than expected in reality, however the focus of this study was the modelling of vents and the comparison between modelled scenarios.

6.1 Recommendations for Future Work

Focusing primarily on the first point raised above as well as determining the full extent of the problem underlying the second point, the following are summaries of the recommended experimental and modelling work required to determine

1. whether passive buoyancy-driven venting utilising roof sheeting provides “effective fire venting”, and if so

2. the appropriate test methods and performance criteria to qualify “effective fire venting”.

Recommended further Modelling Research:

- Investigation of ratios of fire to compartment volume for modelling using different approaches for this scale of building to determine appropriate limits for future design analysis.

- Investigation of modelling using small-scale experiment data compared to large- or full-scale experiment results to determine appropriate modelling limits and criteria for use in future design analysis.

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APPENDIX.A GENERIC WAREHOUSE MODELLING RESULTS - FDS

Modelling results for an ideal 8 MW propane fire in an empty generic flat roofed warehouse (60 x 60 x 6 m). Walls and floor were modelled as inert concrete. Roof was modelled as inert steel sheeting.

A.1 Scenario 1: Single Smoke Reservoir and no Fire Venting

A.1.1 Input

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&TIME TWFIN=1000/

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&VENT CB='XBAR', SURF_ID='OPEN' /
&VENT CB='YBAR0', SURF_ID='OPEN' /
&VENT CB='YBAR', SURF_ID='OPEN' /
&VENT CB='ZBAR', SURF_ID='OPEN' /

/wind

/walls of warehouse
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/flat roof
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/fire
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/roof vents in flat roof

/outputs
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&SLCF PBY=55.0, QUANTITY='TEMPERATURE'/
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&SLCF PBY=45.0, QUANTITY='TEMPERATURE'/
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&SLCF PBY=15.0, QUANTITY='TEMPERATURE'/
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&SLCF PBZ=2.0, QUANTITY='visibility'/
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&SLCF PBZ=2, QUANTITY='extinction coefficient'/
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&SLCF PBZ=1.5, QUANTITY='TEMPERATURE' /
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&SLCF PBZ=2.5, QUANTITY='TEMPERATURE' /
&SLCF PBZ=3, QUANTITY='TEMPERATURE' /
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&SLCF PBZ=6, QUANTITY='TEMPERATURE' /

&TAIL /
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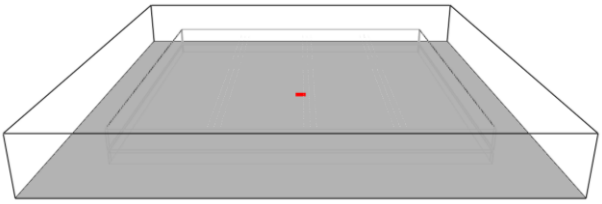
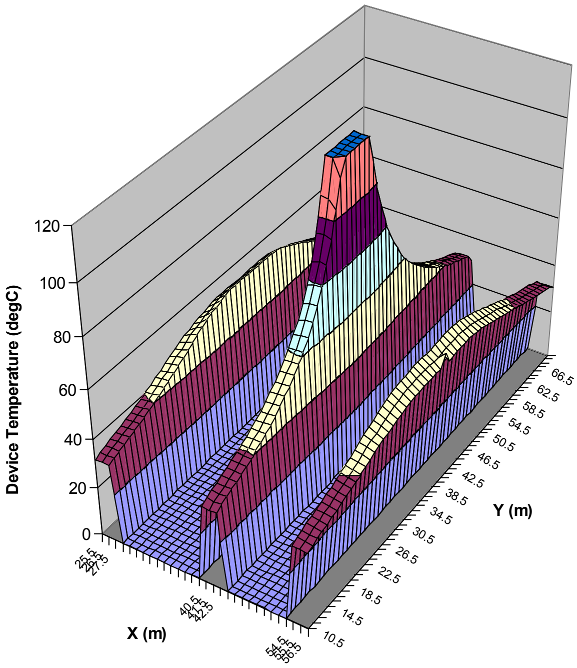
A.1.2 Results

(a)

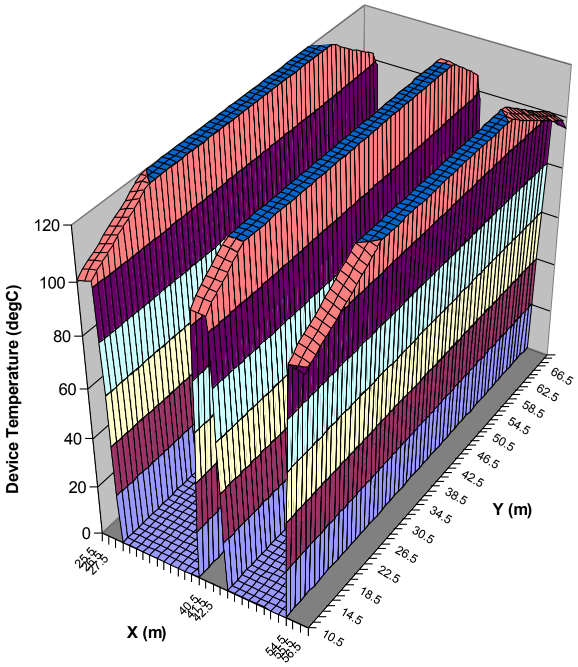


(b)

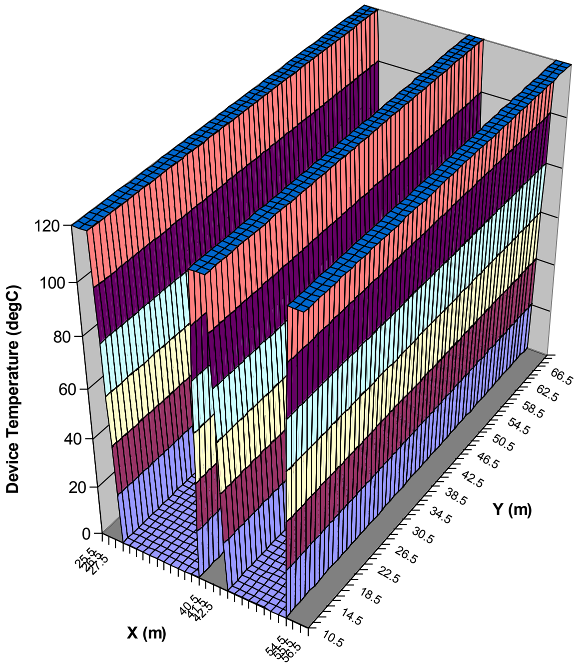
Figure 29: Indicative visual representation of the geometry for the scenario, with (a) solid blockages, and (b) the outline of blockages.



(a)



(b)



(c)

Figure 30: Device temperatures (ºC), at (a) t = 100 s, (b) t = 500 s, and t= 1000 s.

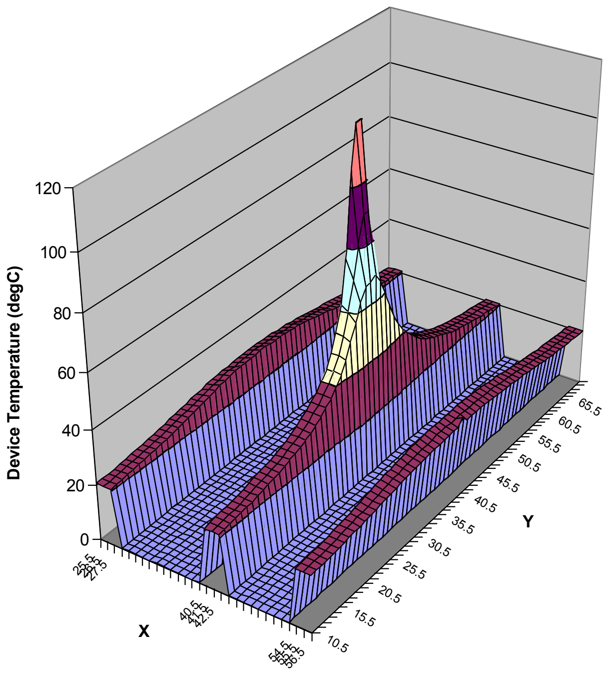
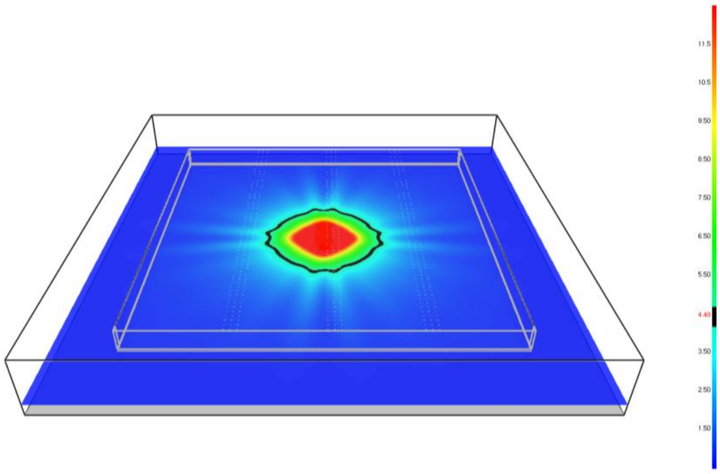
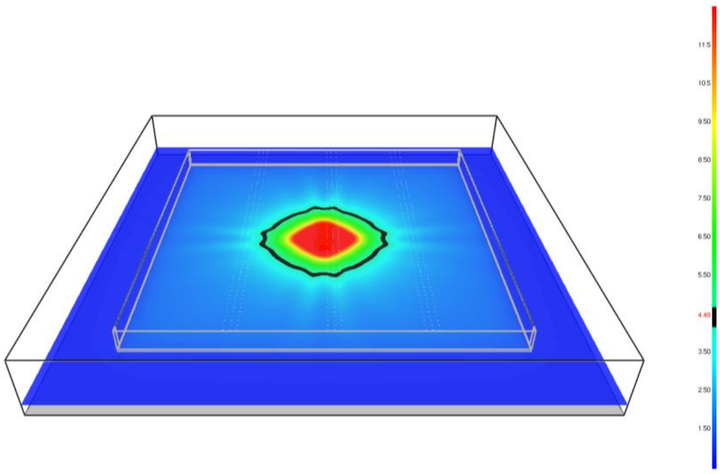


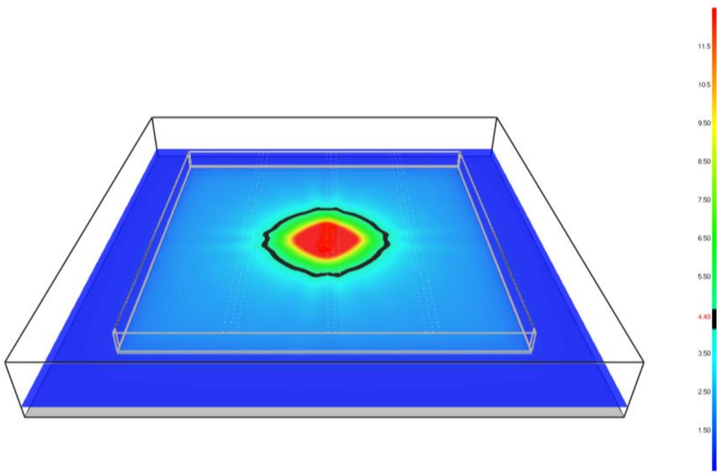
Figure 31: Device temperatures (ºC), at t= 30 s.



(a)

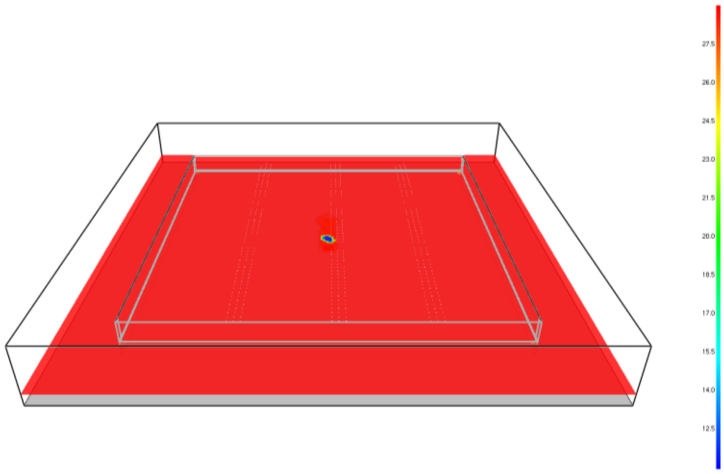


(b)

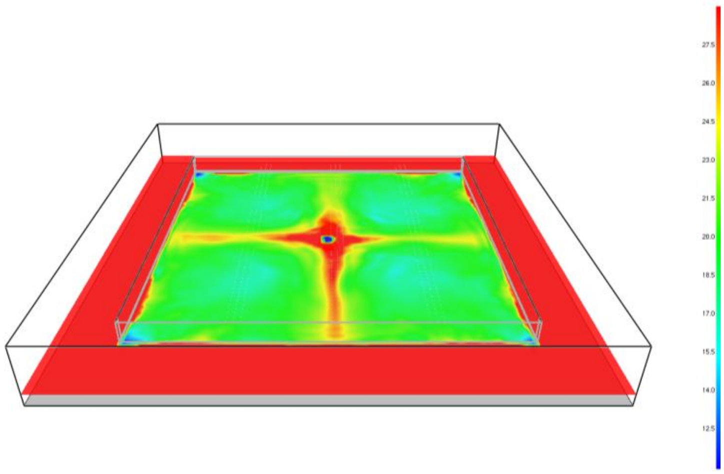


(c)

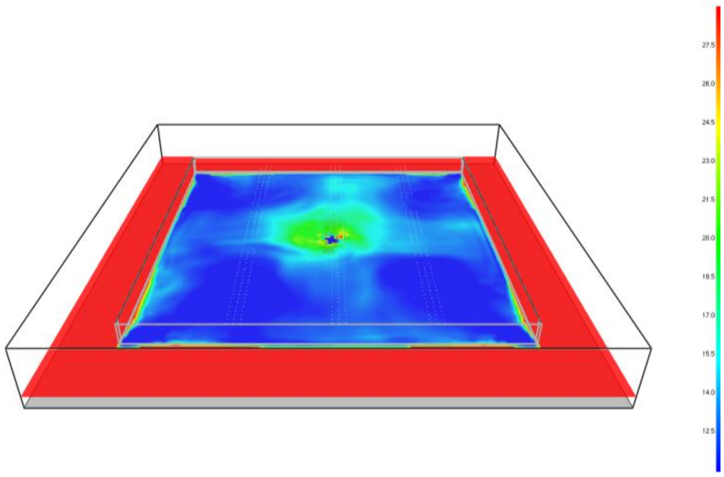
Figure 32: Radiant intensity (kW/m²) at 2 m above floor, at (a) t = 100 s, (b) t = 500 s, and (c)t = 1,000 s.



(a)

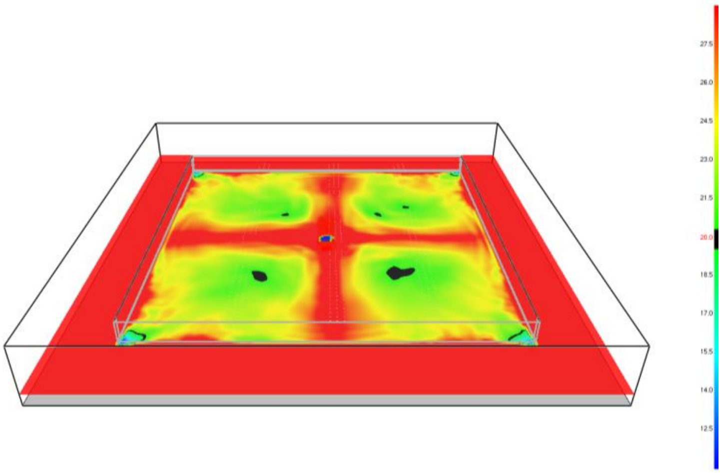


(b)

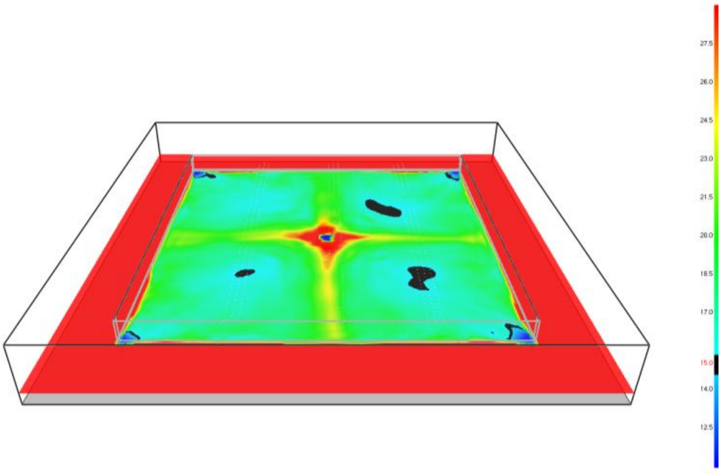


(c)

Figure 33: Visibility (m) at 2 m above the floor height, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.



(a)



(b)

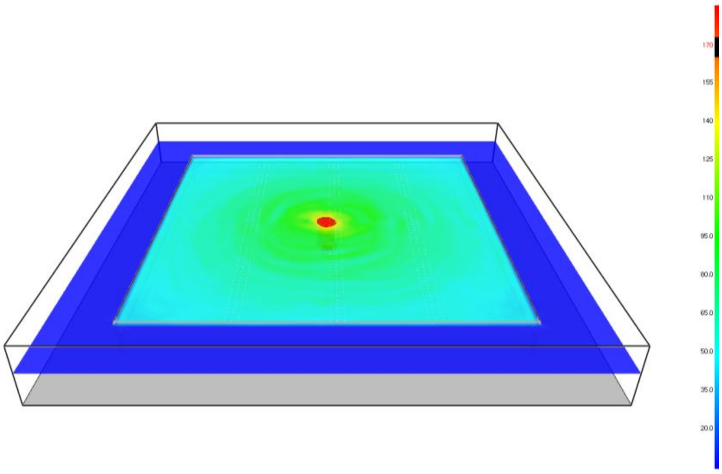
Figure 34: Time where the visibility (m) starts to reduce below 15 m remote from the seat of fire, at (a) t = 410 s, and (b) t = 560 s.

(a)

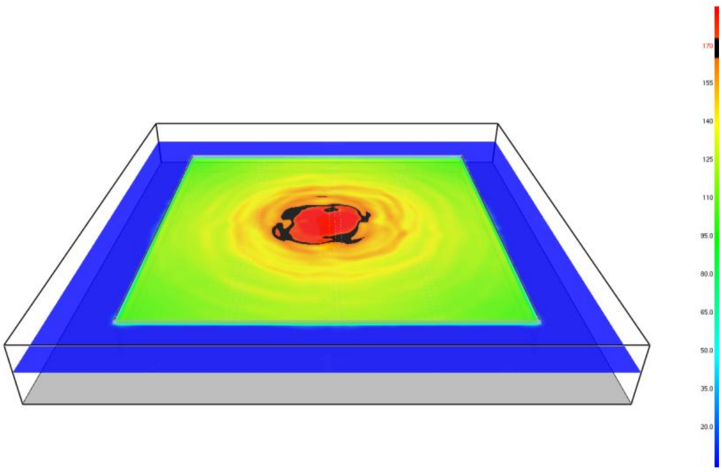
(b)

(c)

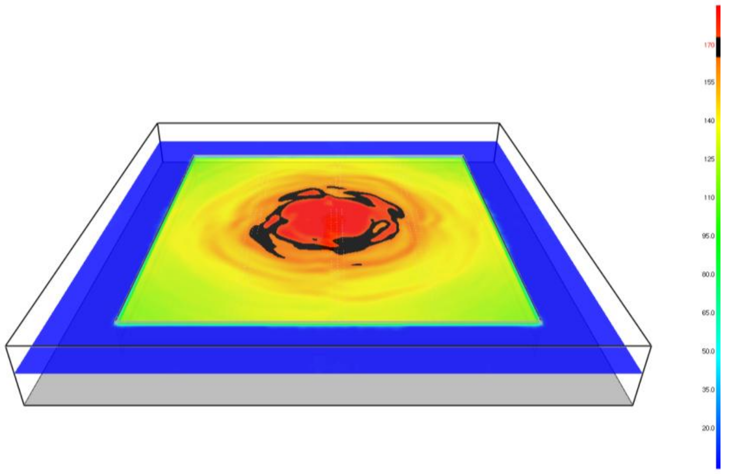
Figure 35: Visual representation of the soot density at (a) t = 100 s, (b) t = 500 s, and (c) = 1,000 s.



(a)



(b)



(c)

Figure 36: Gas temperatures (ºC) at 5.5 m from the floor, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

A.2 Scenario 2: Single Smoke Reservoir and Local 120ºC Fire Venting and Vent Area of 15% Floor Area

A.2.1 Input

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&HEAD CHID='warehouse_01', TITLE='Generic Warehouse - vents in roof open individually' /

&MISC RESTART=.TRUE., DTCORE=10, DATABASE_DIRECTORY='C: \nist\fds\database4\' /
 &MISC SURF_DEFAULT='CONCRETE', REACTION='PROPANE'/

&PDIM XBAR0=0, YBAR0=0, ZBAR=0, XBAR=80, YBAR=80, ZBAR=10 /
&GRID IBAR=160, JBAR=160, KBAR=20 /

&TIME TWFIN=1000/

/open computational boundaries
&VENT CB='XBAR0', SURF_ID='OPEN' /
&VENT CB='XBAR', SURF_ID='OPEN' /
&VENT CB='YBAR0', SURF_ID='OPEN' /
&VENT CB='YBAR', SURF_ID='OPEN' /
&VENT CB='ZBAR', SURF_ID='OPEN' /

/wind

/walls of warehouse
&OBST XB=10,70,10,10.1,0,6, SURF_ID='CONCRETE'/
&OBST XB=10,70,69.9,70,0,6, SURF_ID='CONCRETE'/
&OBST XB=10,10.1,10,70,0,6, SURF_ID='CONCRETE'/
&OBST XB=69.9,70,10,70,0,6, SURF_ID='CONCRETE'/

/low-level permanently-open replacement-air vents 2x15% of floor area (based on AS 2665: 2001), since it is a single
firecell and smoke reservoir
&HOLE XB=10,70,9,11,2,2.375/
&HOLE XB=10,70,69,71,2,2.375/
&HOLE XB=9,11,10,70,2,2.375/
&HOLE XB=69,71,10,70,2,2.375/

/flat roof
&OBST XB=10,70,10,70,6,6.05, SURF_ID='SHEET METAL'/

/fire
&SURF ID='FIRE_01', HRRPUA=2000, TAU_Q=-1.0/
&VENT XB=39,41,39,41,0,0, SURF_ID='FIRE_01', VENT_COLOR='RED'/

/smoke reservoirs

/heat detectors
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/roof vents in flat roof
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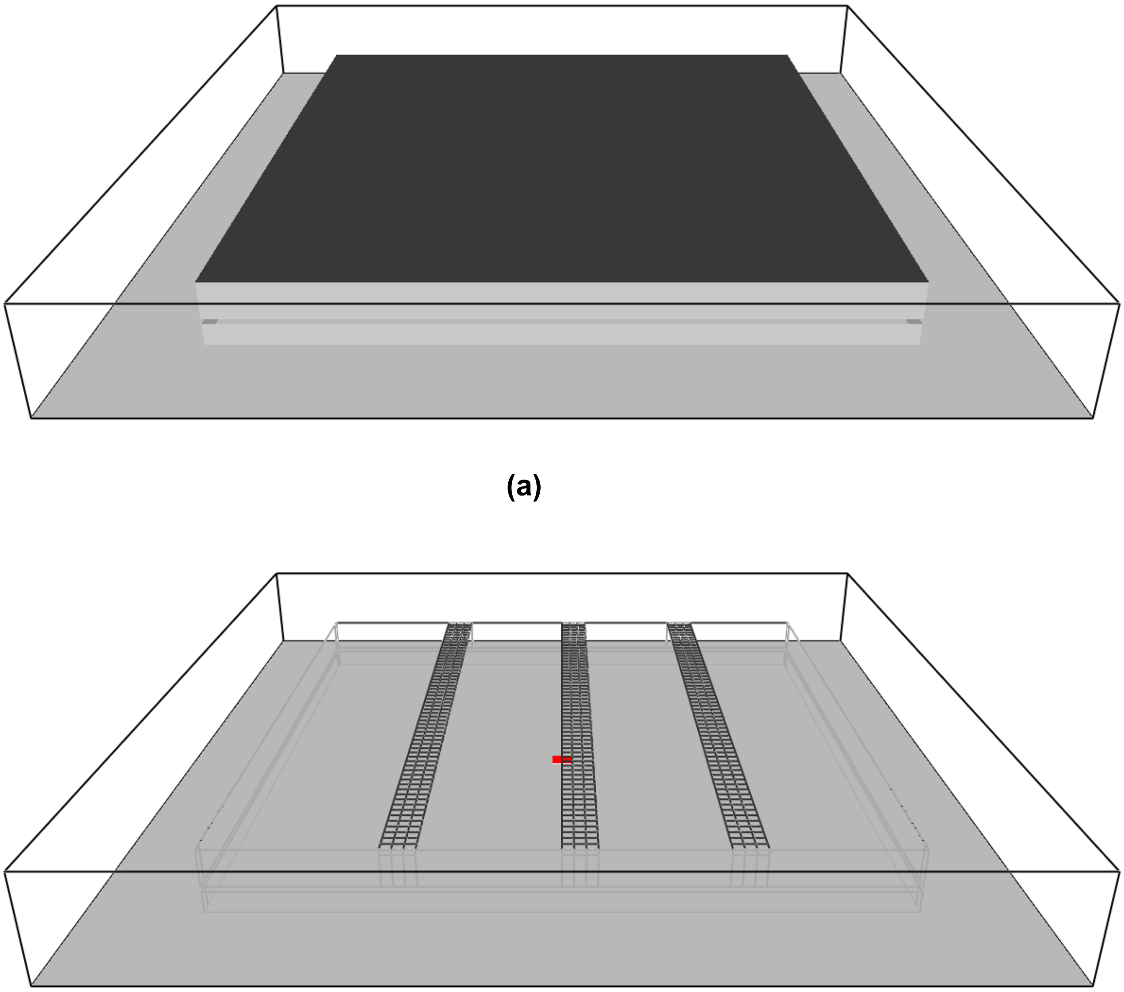
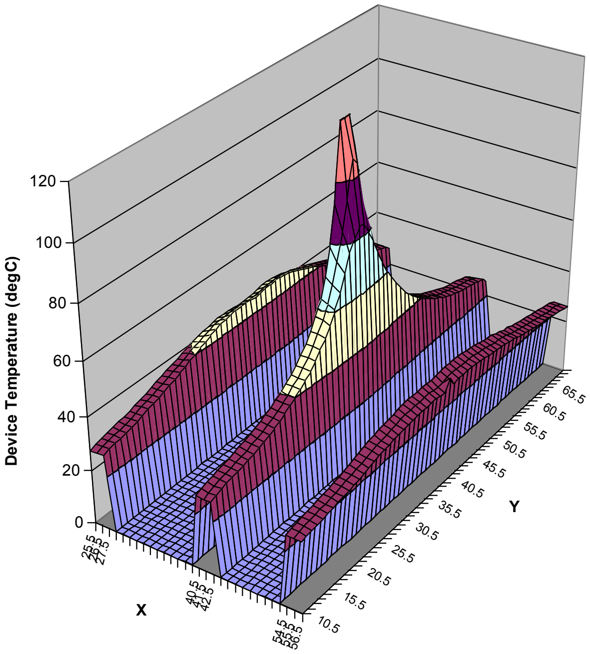
A.2.2 Results



(a)

(b)

Figure 37: Indicative visual representation of the geometry for the scenario, with (a) solid blockages, and (b) the outline of blockages.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Y
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40.5
42.5
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10.5
15.5
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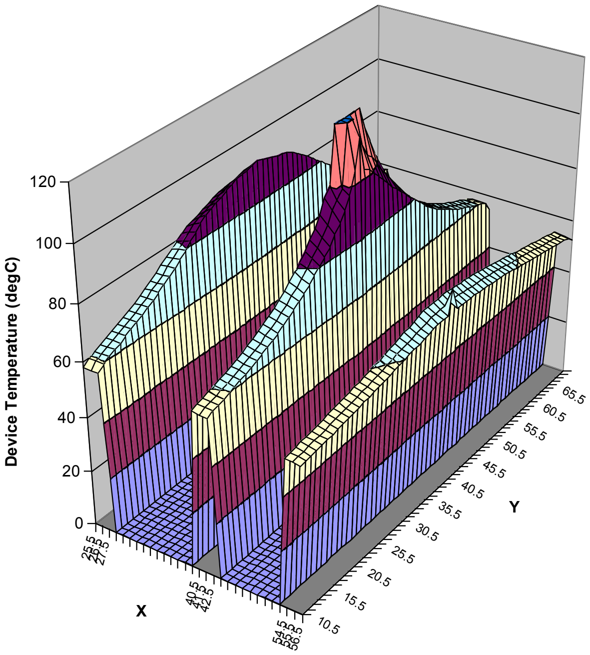
40.5
45.5
50.5
55.5
60.5
65.5

(a)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80
60
40
20
0
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Y
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27.5
40.5
42.5
54.5
10.5
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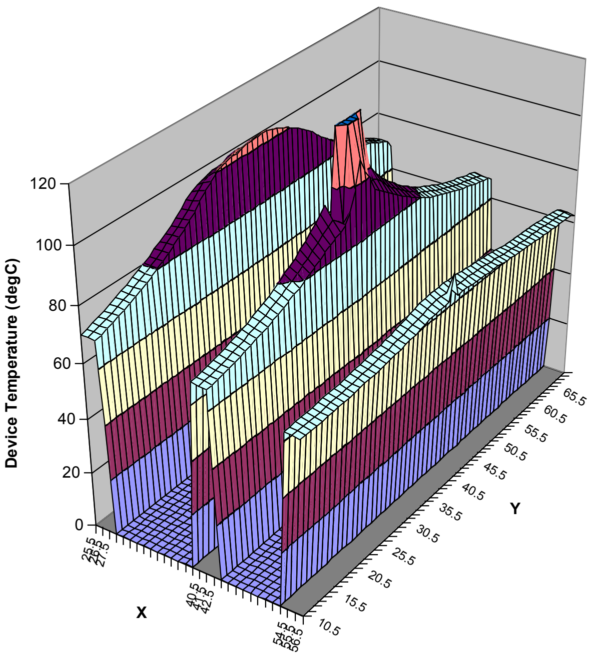
40.5
45.5
50.5
55.5
60.5
65.5

(b)



(c)

Figure 38: Device temperatures (ºC), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

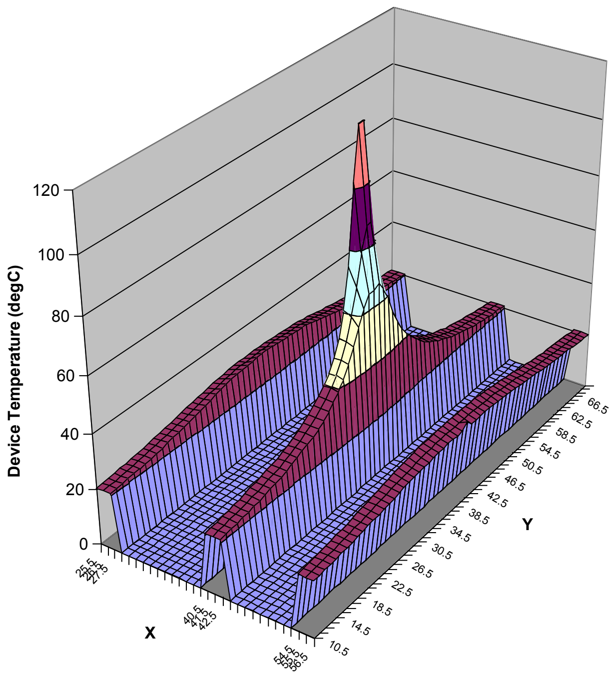
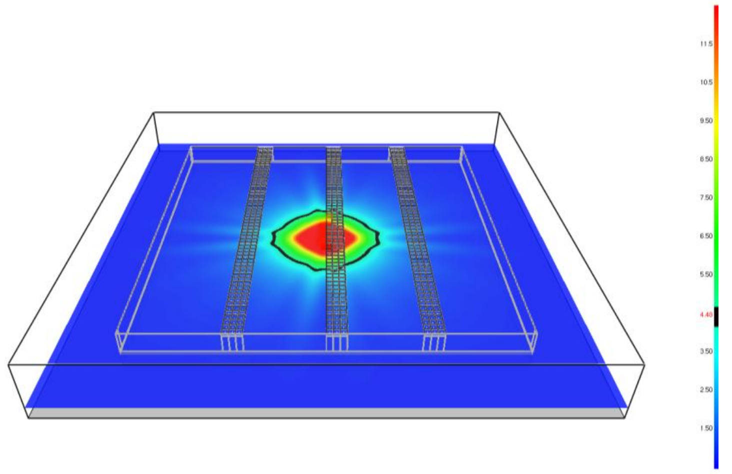
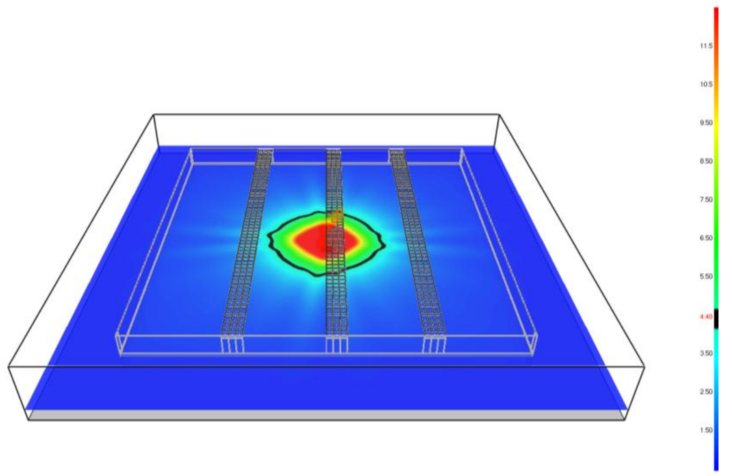


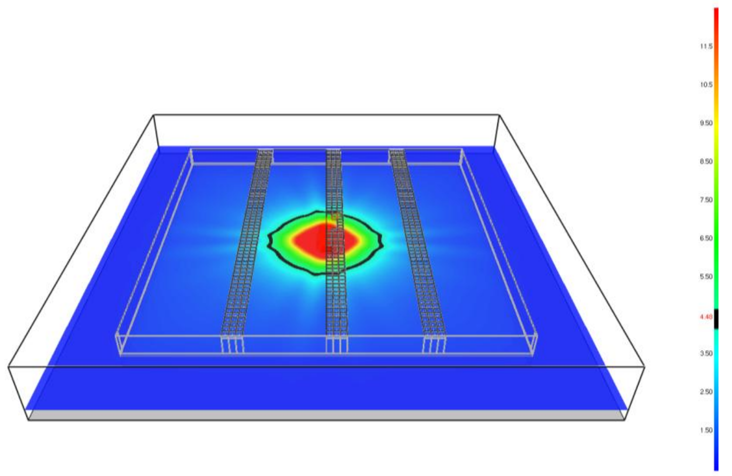
Figure 39: Device temperatures (ºC), at t = 30 s.



(a)



(b)



(c)

Figure 40: Radiative intensity (kW/m²) at 2 m above floor height, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

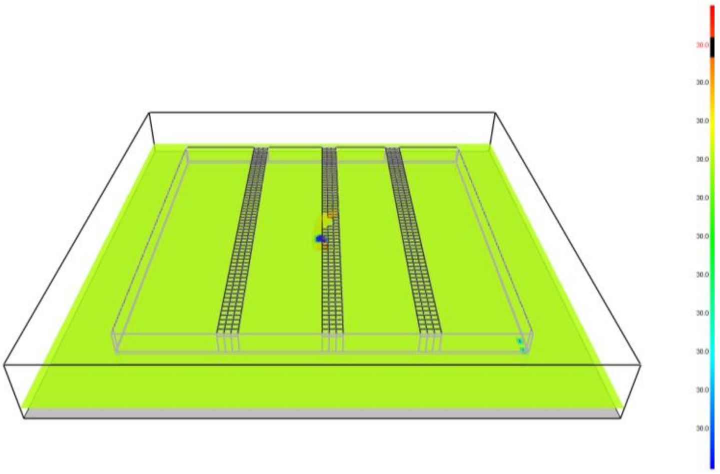
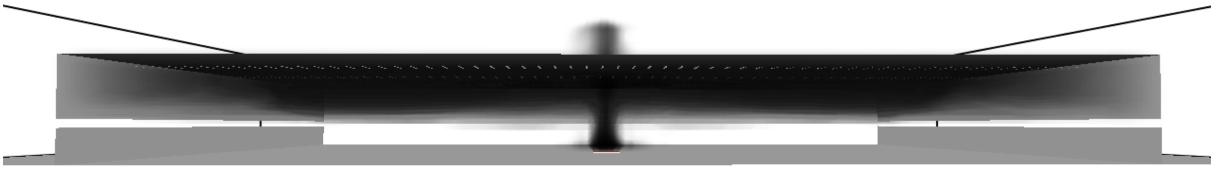
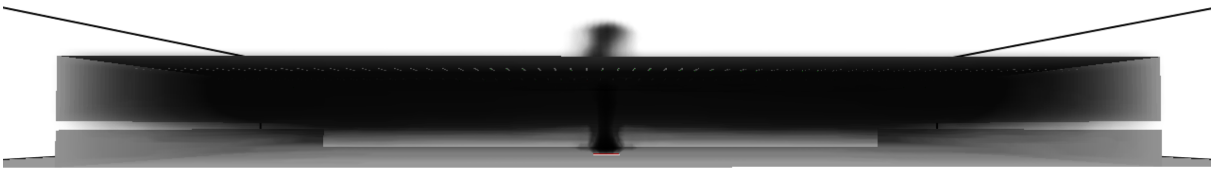


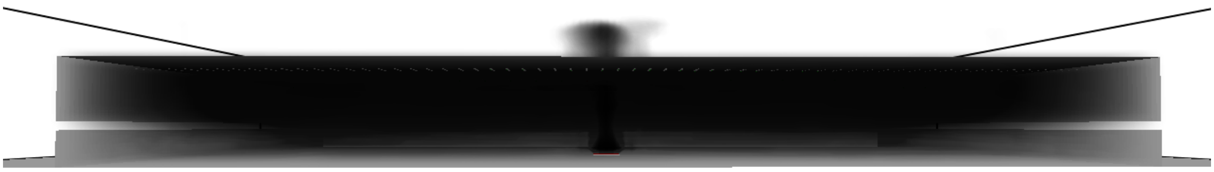
Figure 41: Visibility (m) at 2 m above floor height at t = 1,000 s.



(a)

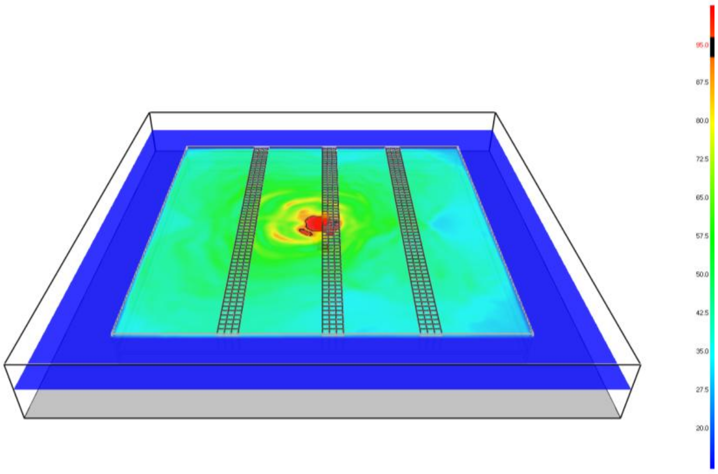


(b)



(c)

Figure 42: Visual representation of the soot density at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.



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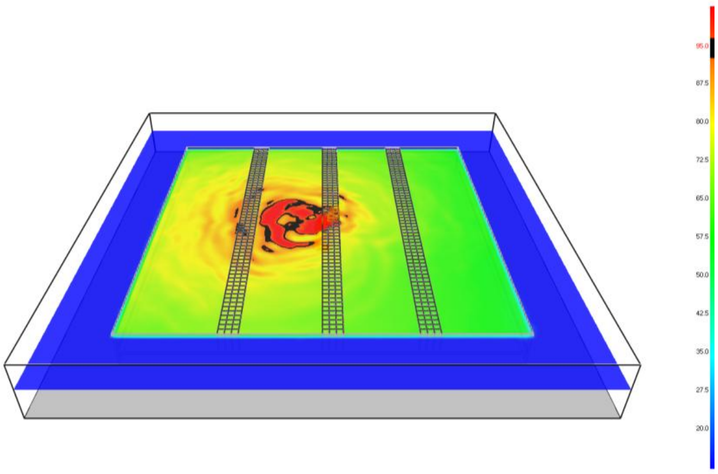

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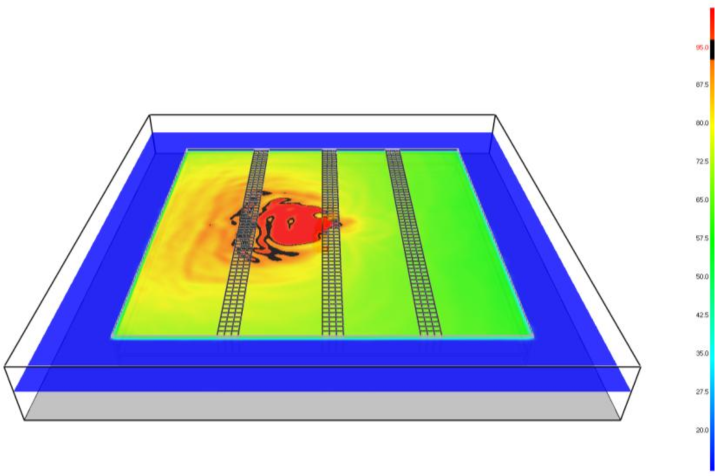

(c)

Figure 43: Gas temperatures (ºC) at 5.5 m above floor height, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

A.3 Scenario 3: Four Smoke Reservoirs and Local 120°C Fire Venting and Vent Area of 15% Reservoir Floor Area

A.3.1 Input

```
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&TIME TWFIN=1000/

/open computational boundaries
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&VENT CB='XBAR', SURF_ID='OPEN' /
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&VENT CB='ZBAR', SURF_ID='OPEN' /

/wind

/walls of warehouse
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/low-level permanently-open replacement-air vents 2x15% of floor area (based on AS 2665: 2001)
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&HOLE XB=10,70,69,71,2,2.375/
&HOLE XB=9,11,10,70,2,2.375/
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/flat roof
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/fire
&SURF ID='FIRE_01', HRRPUA=2000, TAU_Q=-1.0/
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/smoke reservoirs
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/roof vents in flat roof
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&SLCF PBX=25.0, QUANTITY='TEMPERATURE'/
&SLCF PBY=25.0, QUANTITY='TEMPERATURE'/
&SLCF PBX=20.0, QUANTITY='TEMPERATURE'/
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&SLCF PBX=15.0, QUANTITY='visibility'/
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&SLCF PBZ=2, QUANTITY='extinction coefficient'/
&SLCF PBZ=1, QUANTITY='TEMPERATURE' /
&SLCF PBZ=1.5, QUANTITY='TEMPERATURE' /
&SLCF PBZ=2, QUANTITY='TEMPERATURE' /
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&SLCF PBZ=5, QUANTITY='TEMPERATURE' /
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&SLCF PBZ=6, QUANTITY='TEMPERATURE' /

&TAIL /
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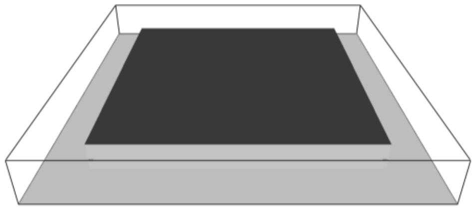
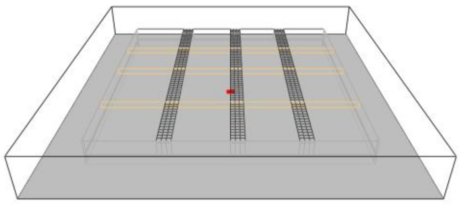
A.3.2 Results – Base Case

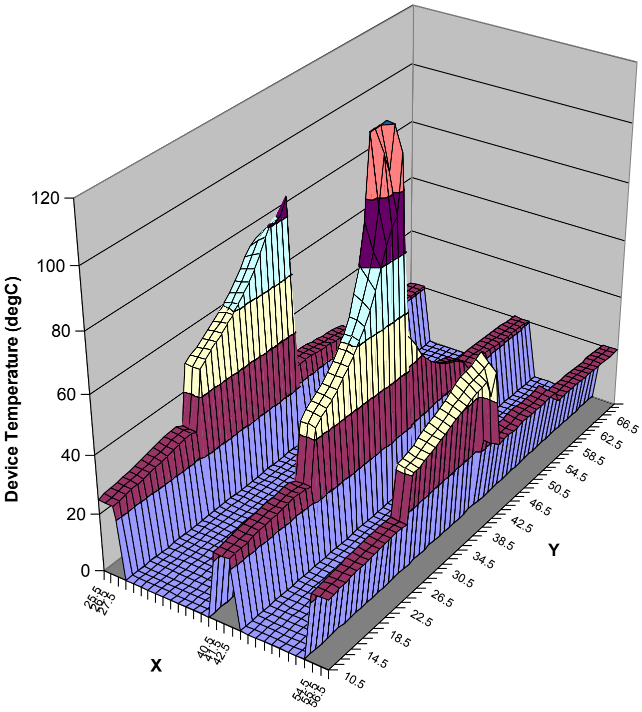


(a)

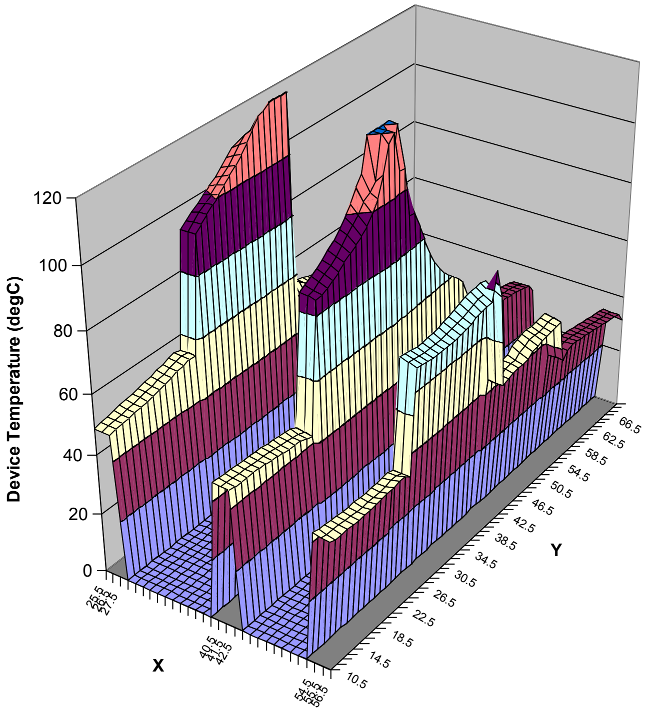


(b)

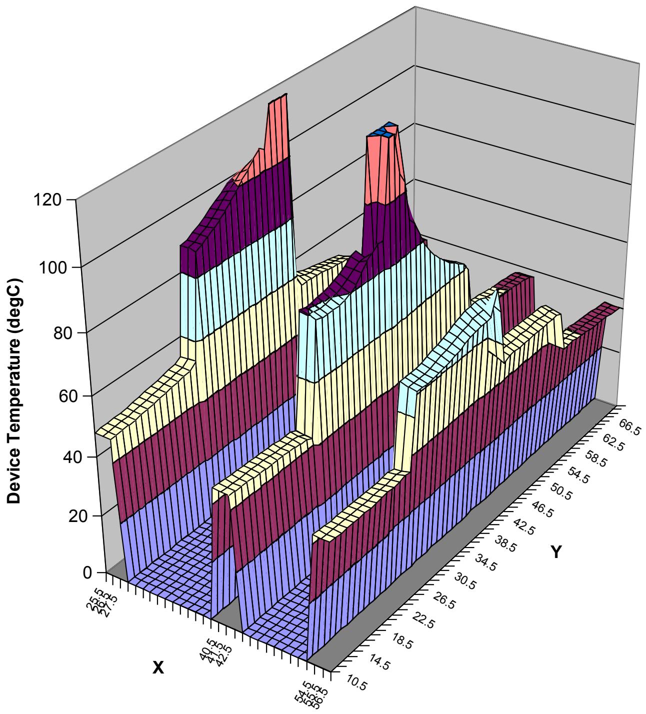
Figure 44: Indicative visual representation of the geometry for the scenario, with (a) solid blockages, and (b) the outline of blockages.



(a)



(b)



(c)

Figure 45: Device temperatures (ºC), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

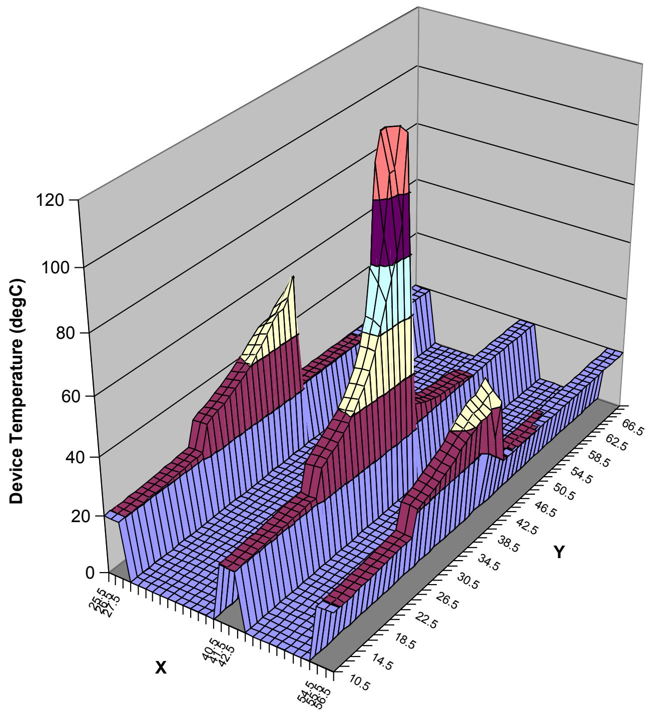
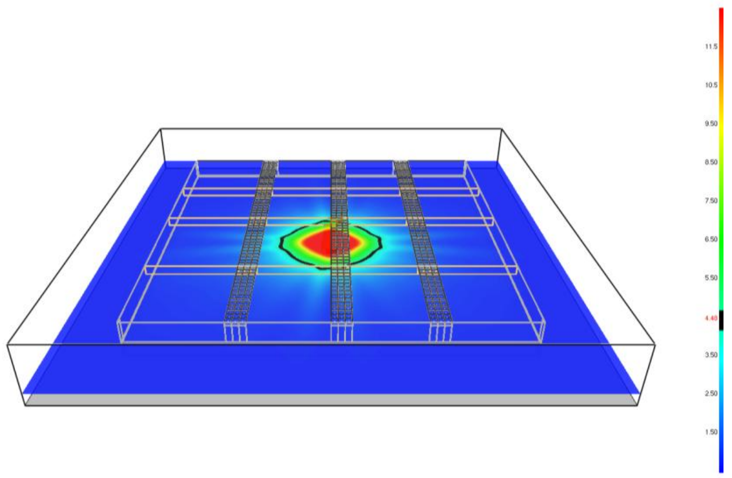
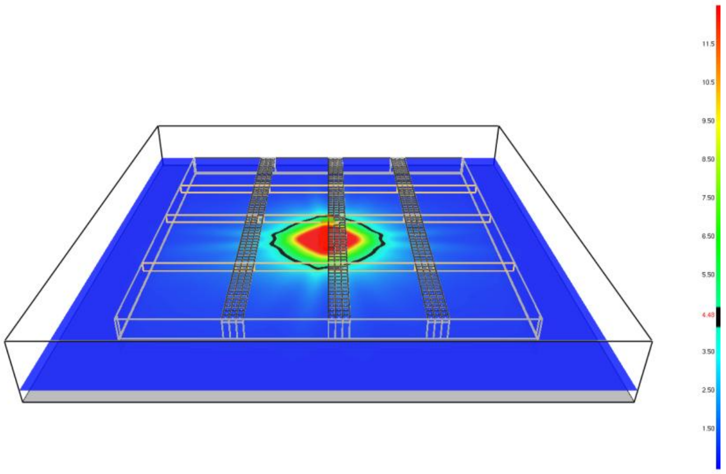


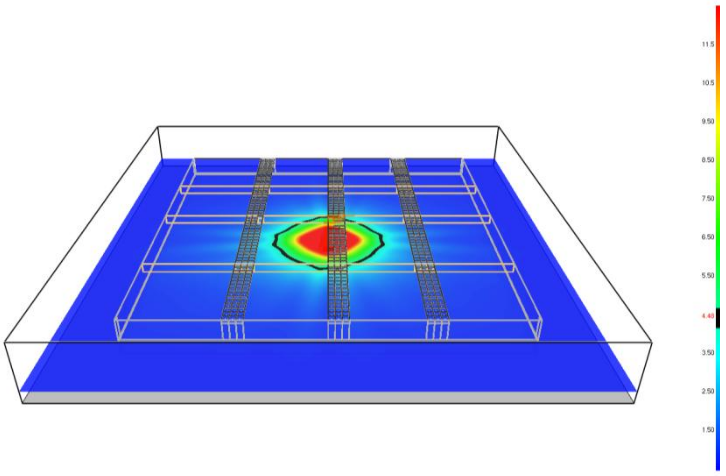
Figure 46: Device temperatures (ºC), at t = 35 s.



(a)



(b)



(c)

Figure 47: Radiant intensity (kW/m²), at (a) t = 100 s, (b) t = 500 s, and t = 1,000 s.

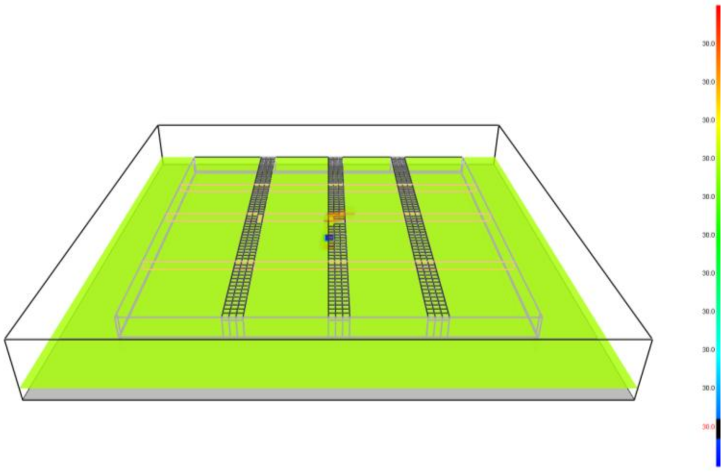
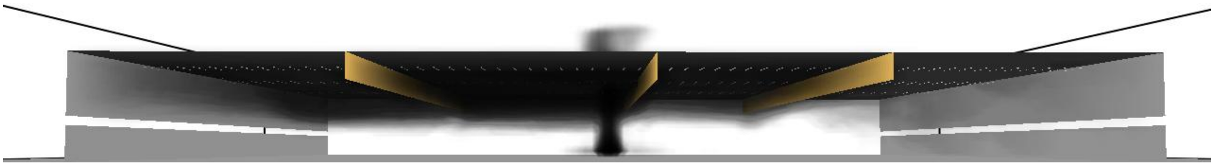
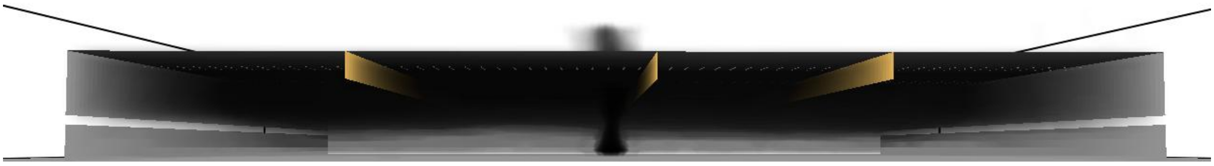


Figure 48: Visibility (m) at 2 m above floor height, at t = 1,000 s.



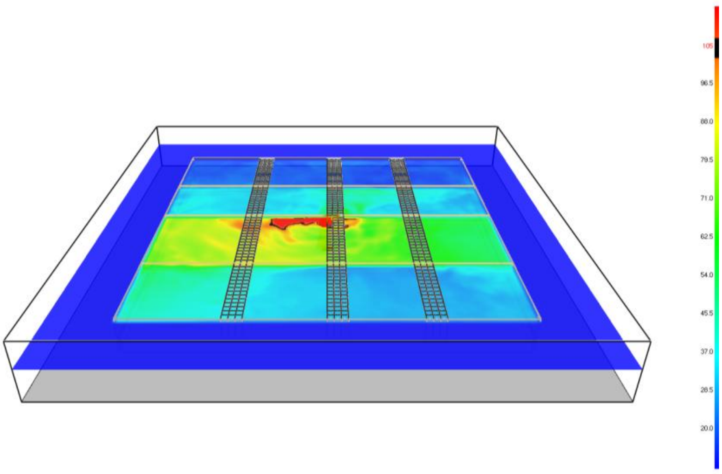
(a)



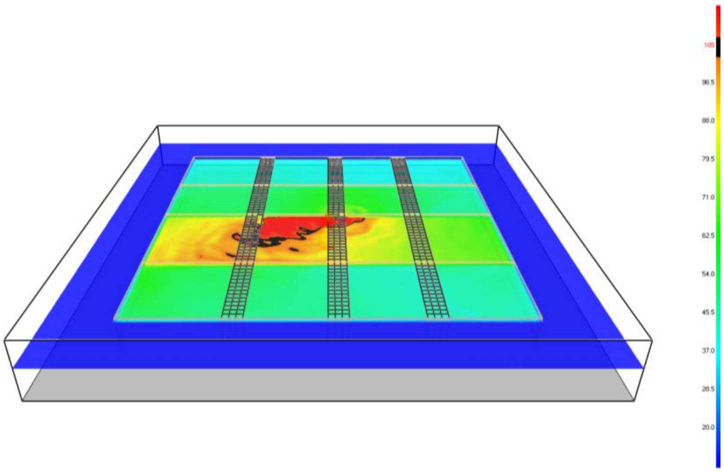
(b)

(c)

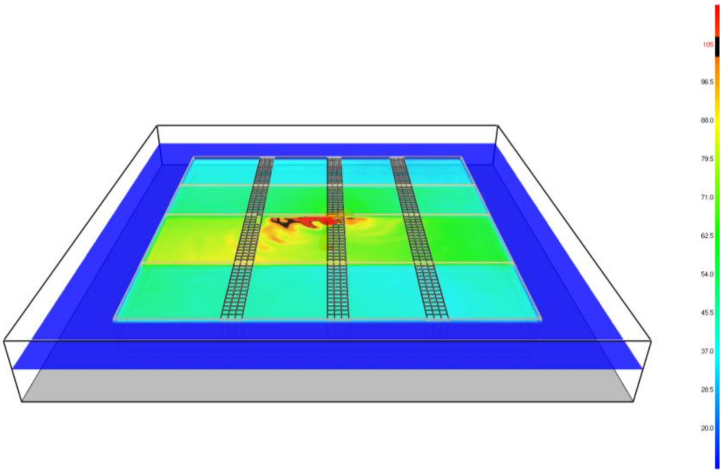
Figure 49: Visual representation of soot density at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.



(a)



(b)

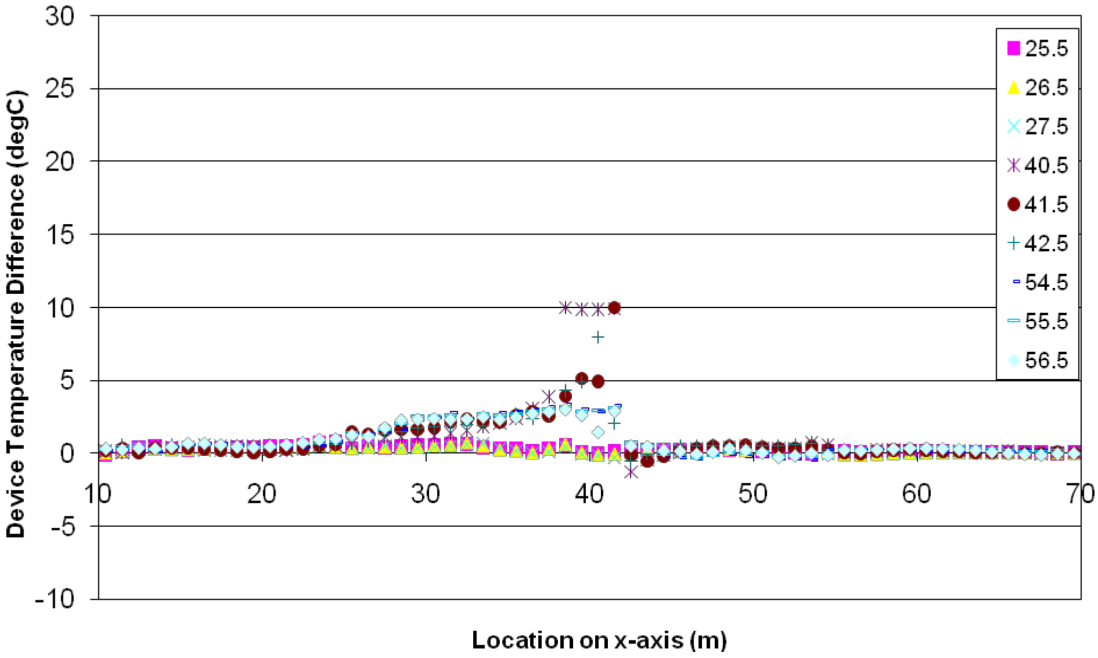


(c)

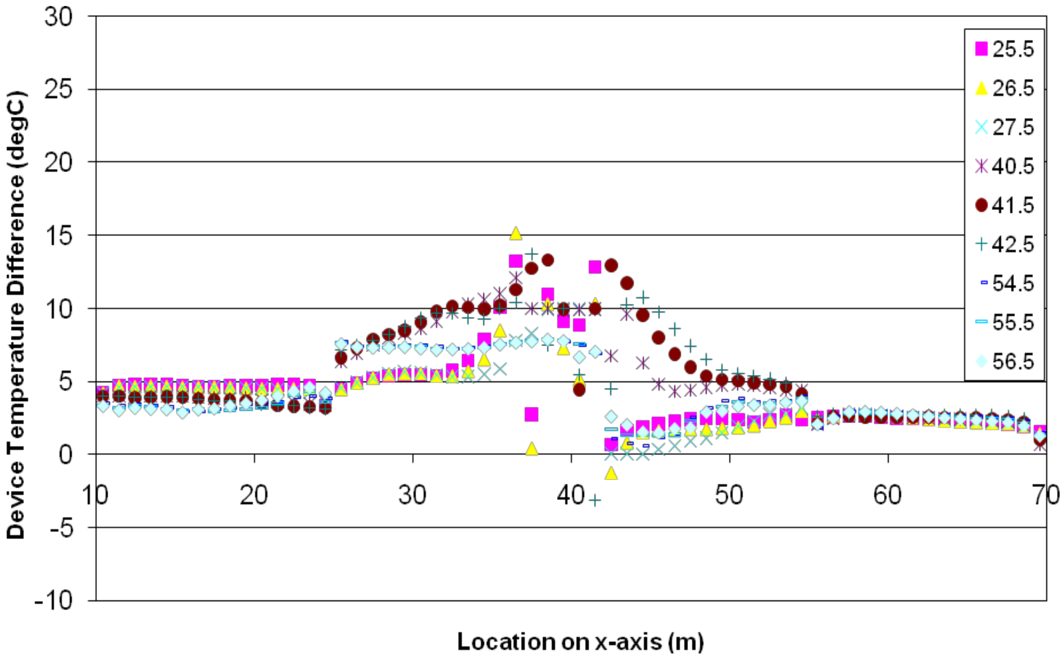
Figure 50: Gas temperatures (ºC) at 5.5 m above floor level, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s. Note that the maximum temperature on this scale is significantly less than for Scenario 1 or Scenario 2. Further note that the comparison should be noted, and not the temperature values as these are expected to be lower than expected.

A.3.3 Sensitivity: Effective Activation Temperature = 100°C

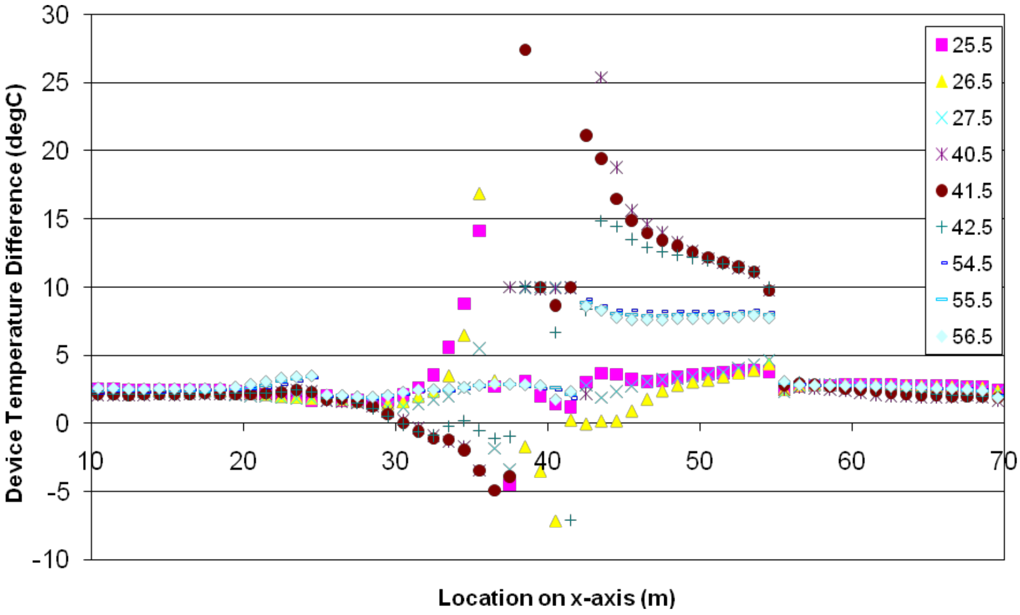
Results are presented as the difference between the results for the base case (as presented in Appendix A.3.2) minus the results for this case.



(a)



(b)



(c)

Figure 51: Difference in device temperatures (ºC) between the base case and the case with an effective activation temperature of 100ºC at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s. The series show the location on the y-axis (m).

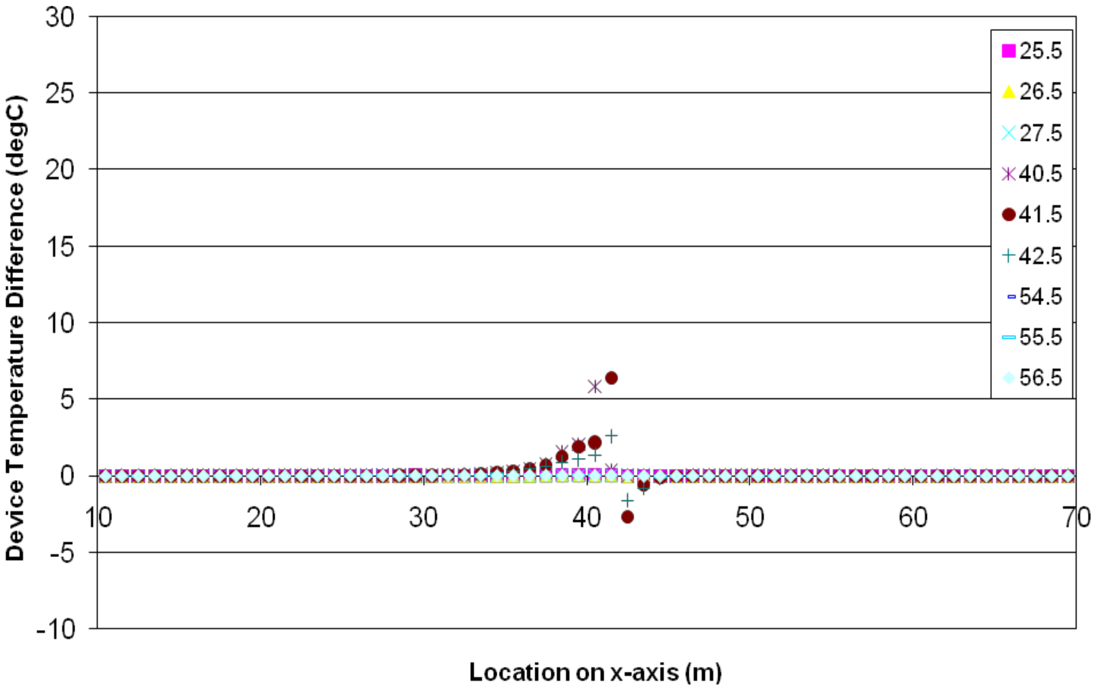
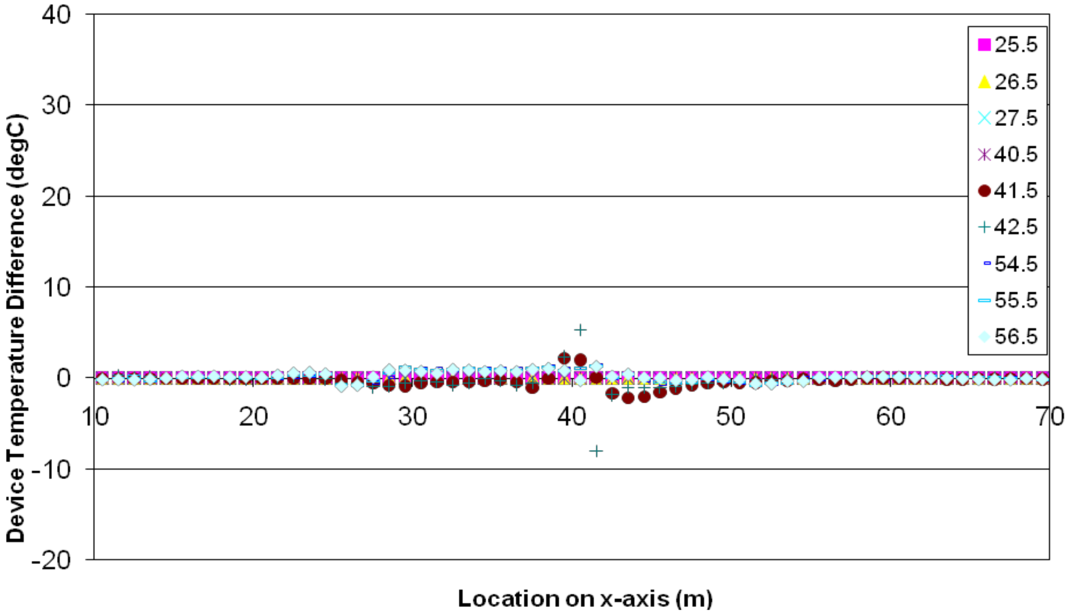
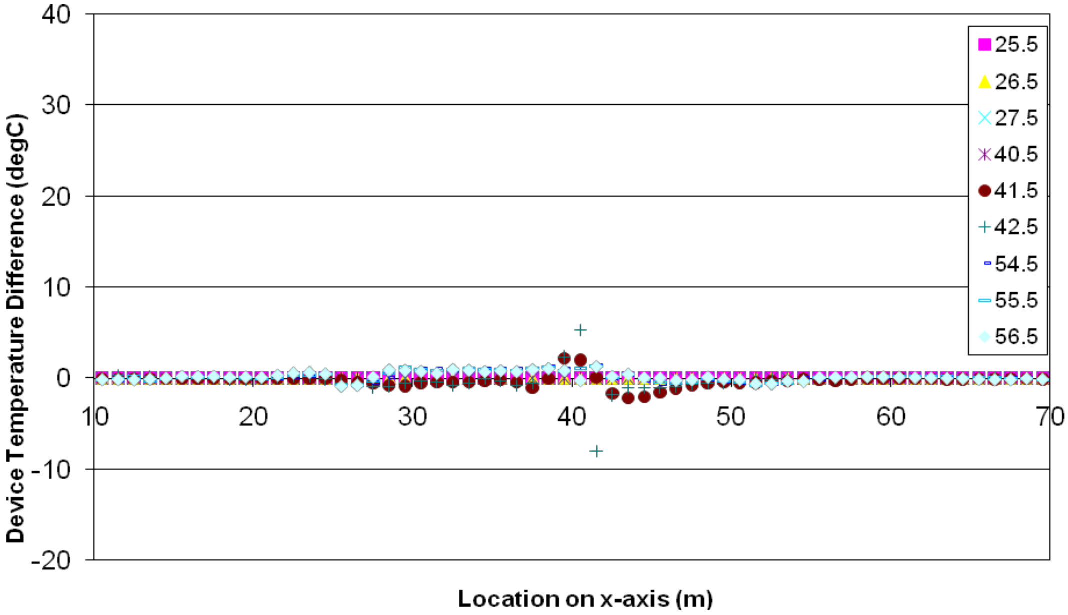


Figure 52: Difference in device temperatures (ºC) between the base case and the case with an effective activation temperature of 100ºC at t = 30 s. The series show the location on the y-axis (m).

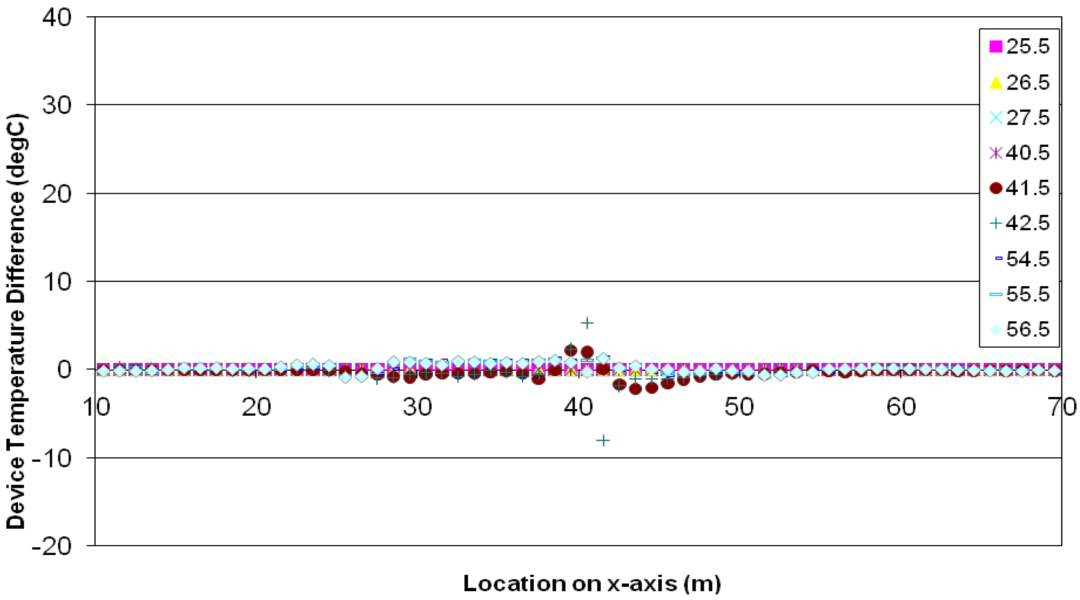
A.3.4 Sensitivity: Effective RTI = 119



(a)



(b)



(c)

Figure 53: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 119 at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s. The series show the location on the y-axis (m).

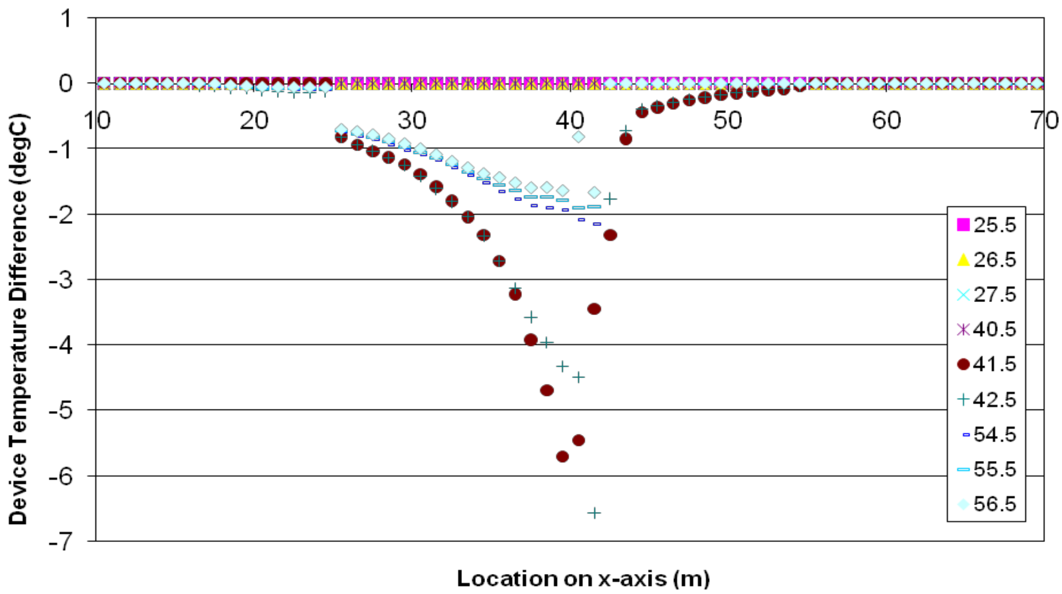
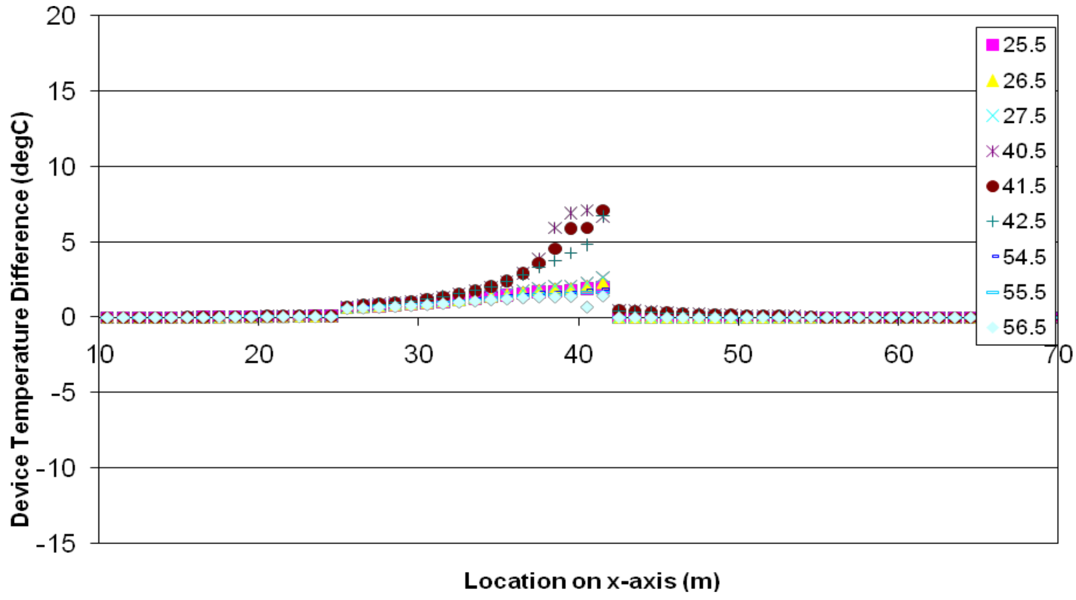
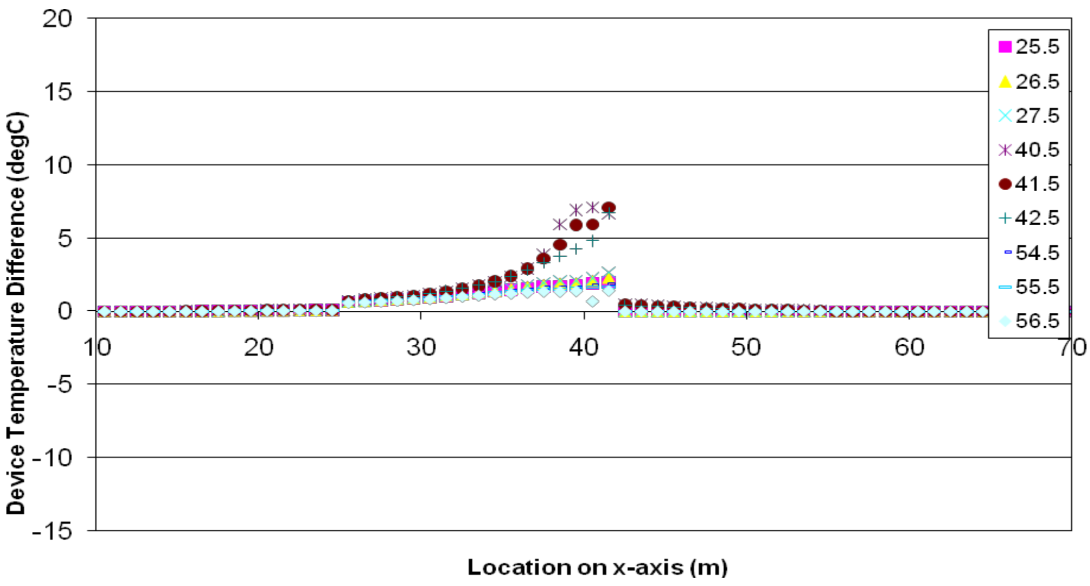


Figure 54: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 119 at t = 30 s. The series show the location on the y-axis (m).

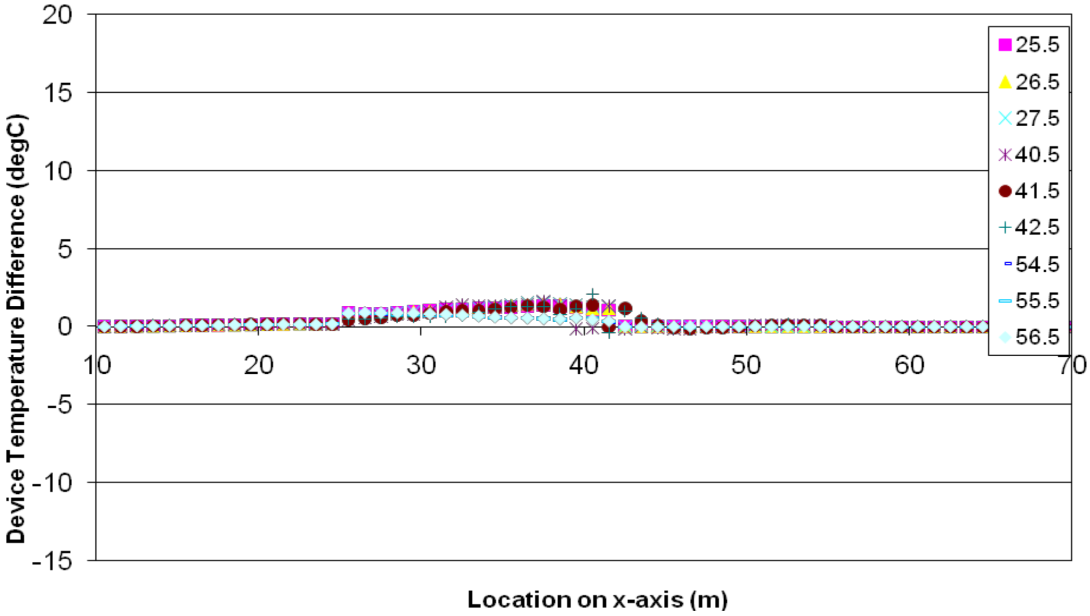
A.3.5 Sensitivity: Effective RTI = 145



(a)



(b)



(c)

Figure 55: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 145 at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s. The series show the location on the y-axis (m).

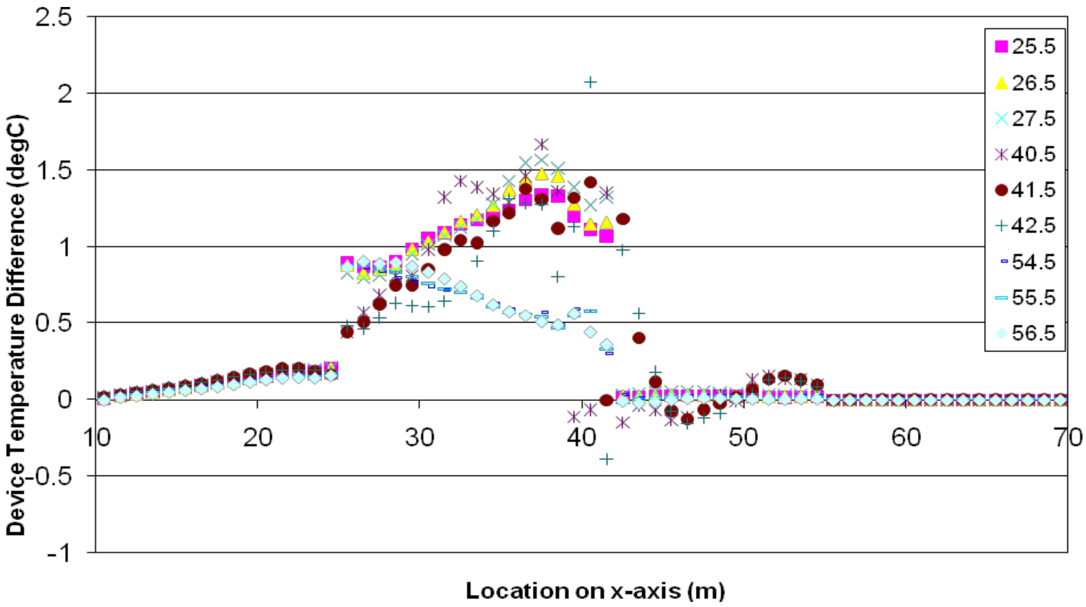
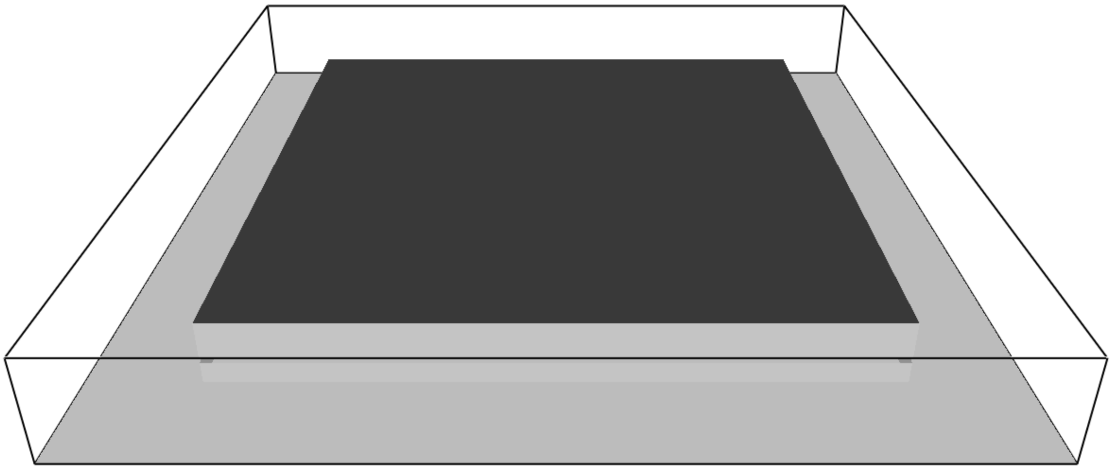
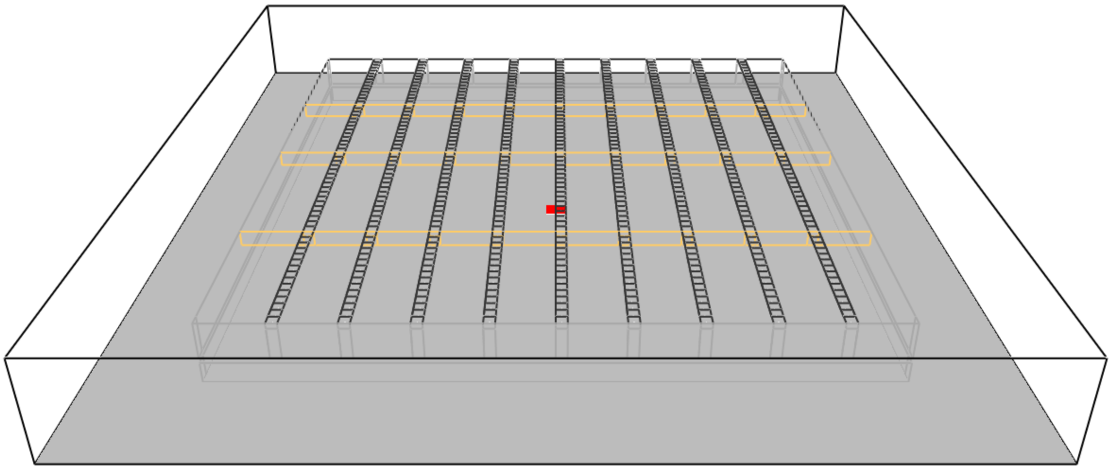


Figure 56: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 145 at t = 30 s. The series show the location on the y-axis (m).

A.3.6 Sensitivity: Location – Single Rows of Vent Material

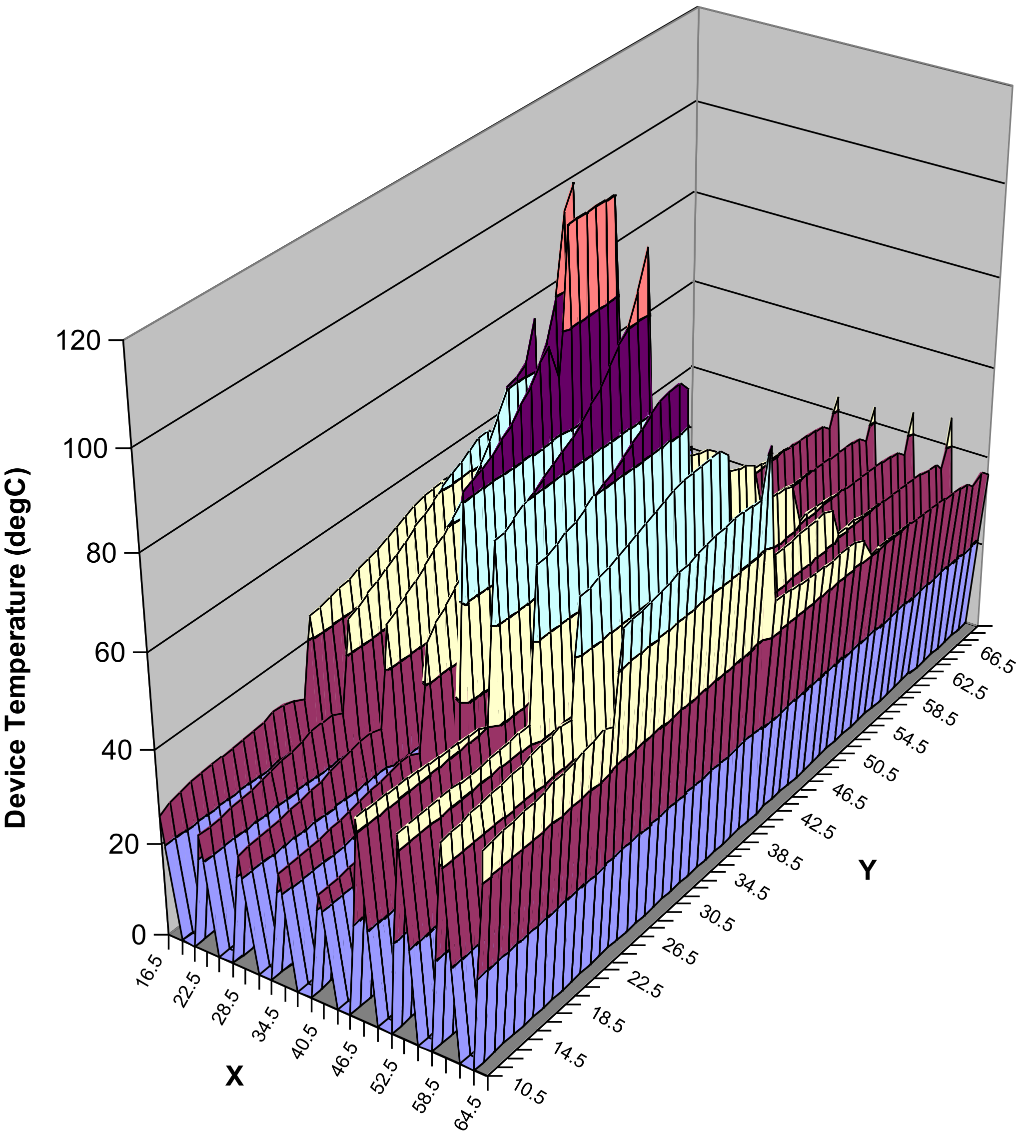


(a)



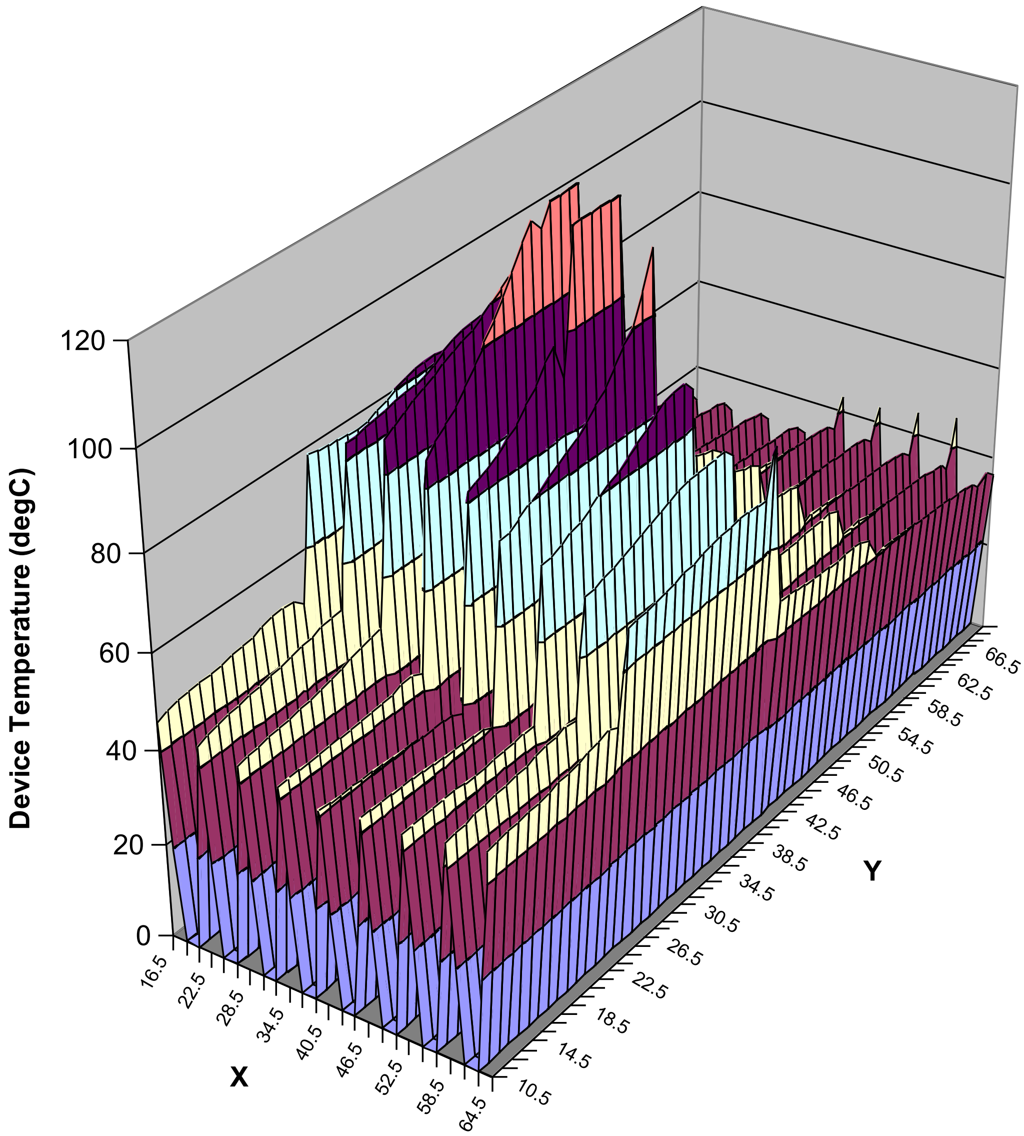
(b)

Figure 57: Visual representation of the geometry for the scenario, with (a) solid blockages, and (b) the outline of blockages.

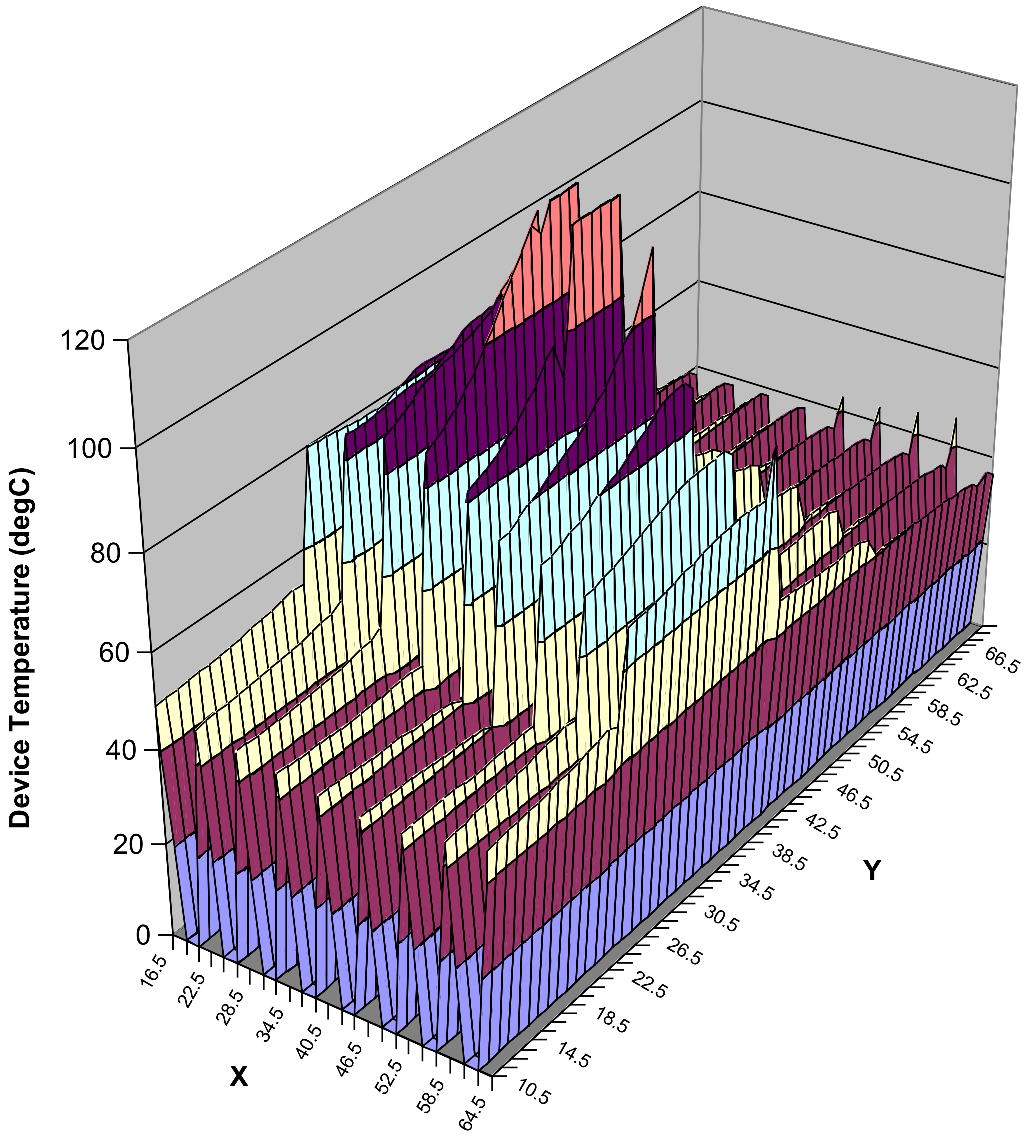


Device Temperature (degC)
120
100
80
60
40
20
0
X
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
Y
10.5
14.5
18.5
22.5
26.5
30.5
34.5
38.5
42.5
46.5
50.5
54.5
58.5
62.5
66.5

(a)

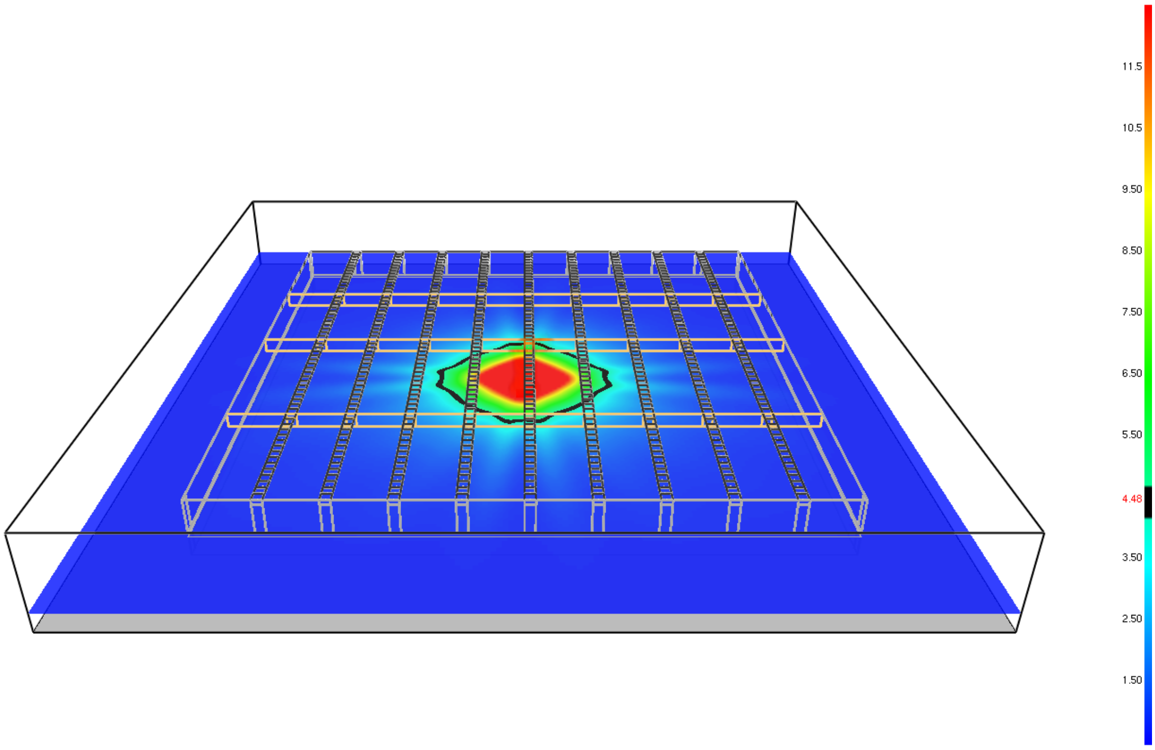

120
100
80
60
40
20
0
Device Temperature (degC)
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
X
10.5
14.5
18.5
22.5
26.5
30.5
34.5
38.5
42.5
46.5
50.5
54.5
58.5
62.5
66.5
Y

(b)

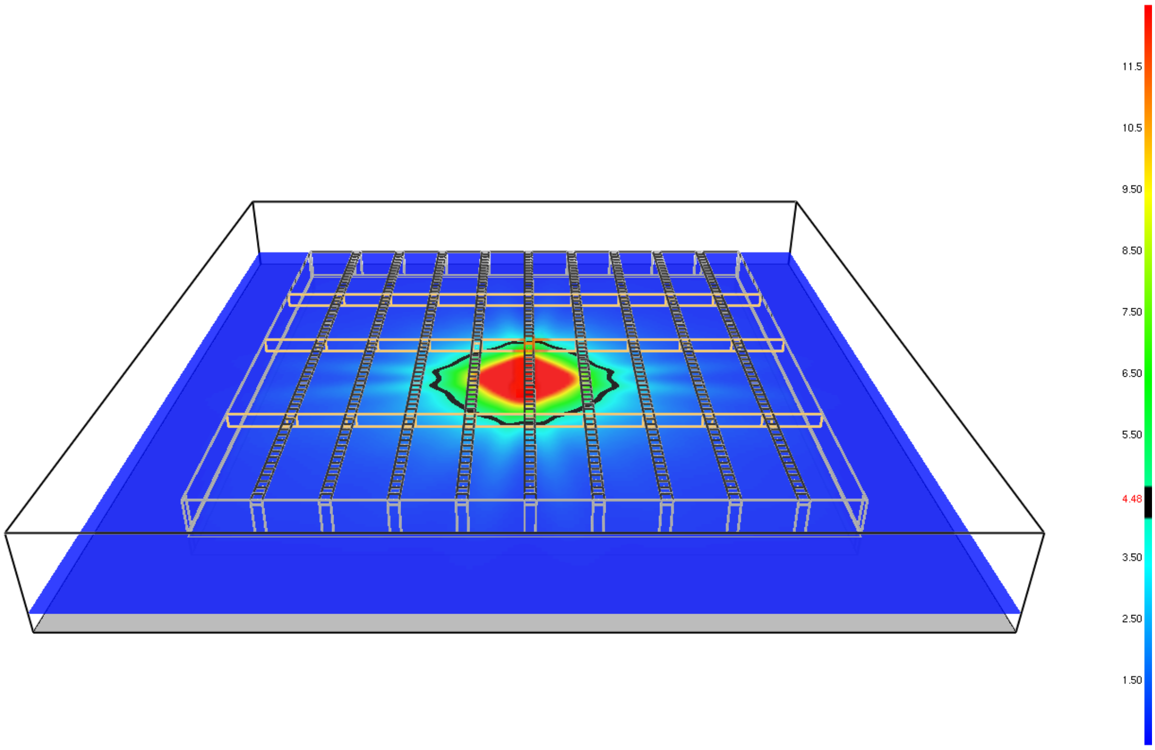


(c)

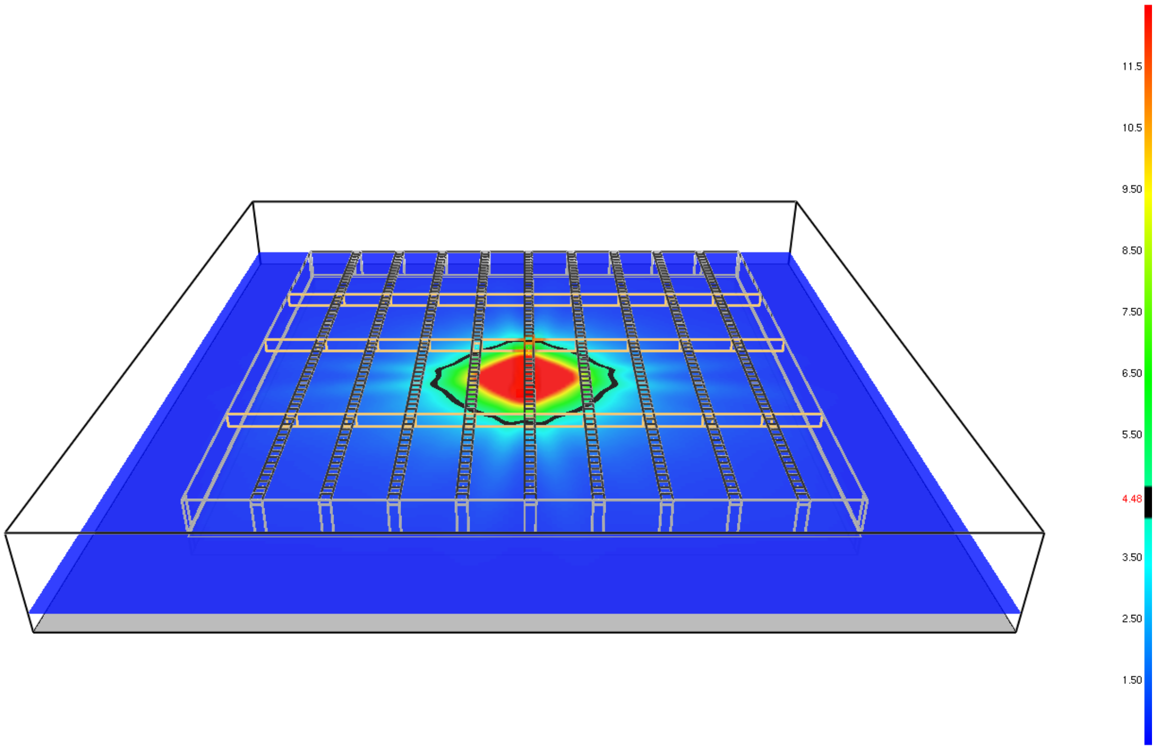
Figure 58: Device temperatures (ºC), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.


11.5
10.5
9.50
8.50
7.50
6.50
5.50
4.48
3.50
2.50
1.50

(a)


11.5
10.5
9.50
8.50
7.50
6.50
5.50
4.48
3.50
2.50
1.50

(b)



(c)

Figure 59: Radiant intensity (kW/m²) at 2 m above the floor height, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

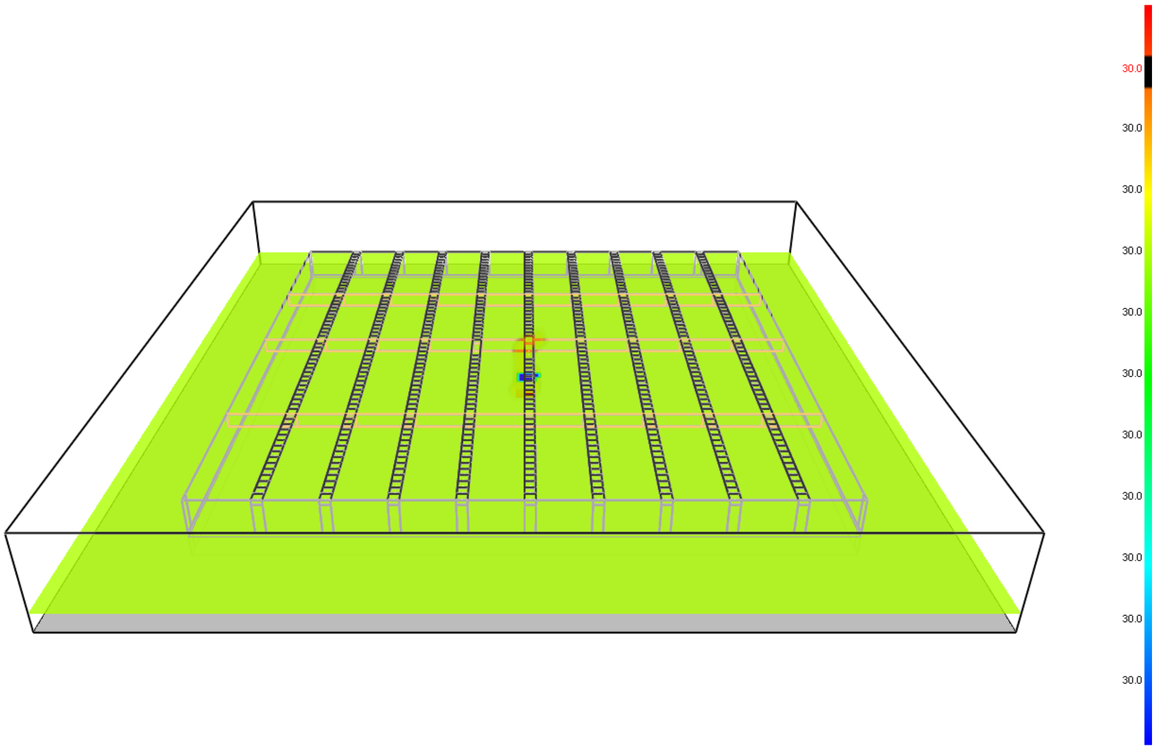
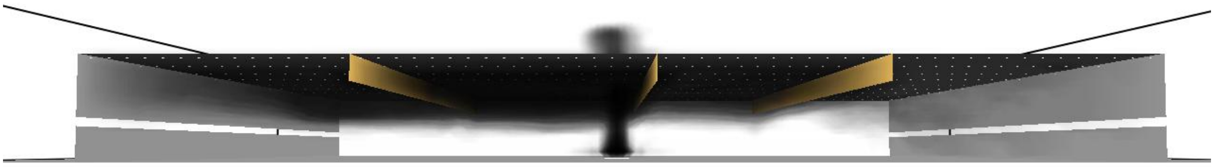
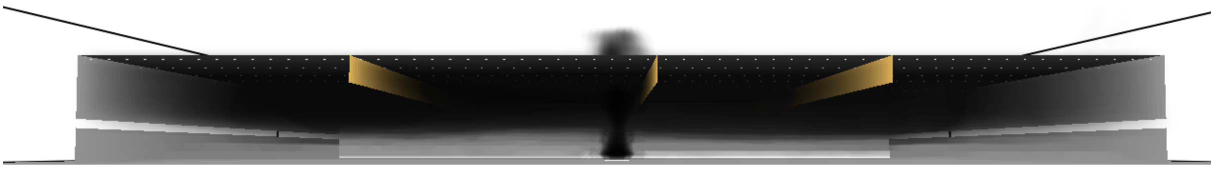


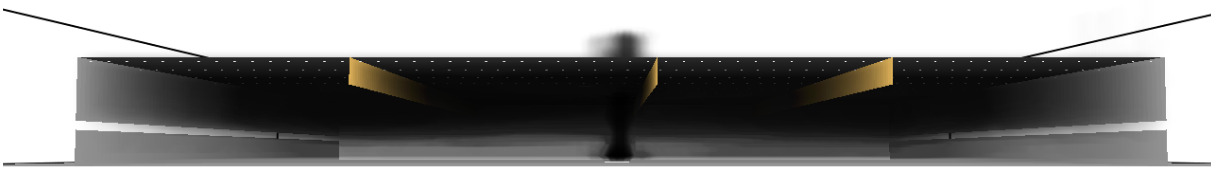
Figure 60: Visibility (m) at 2 m above floor height, at t = 1,000 s.



(a)

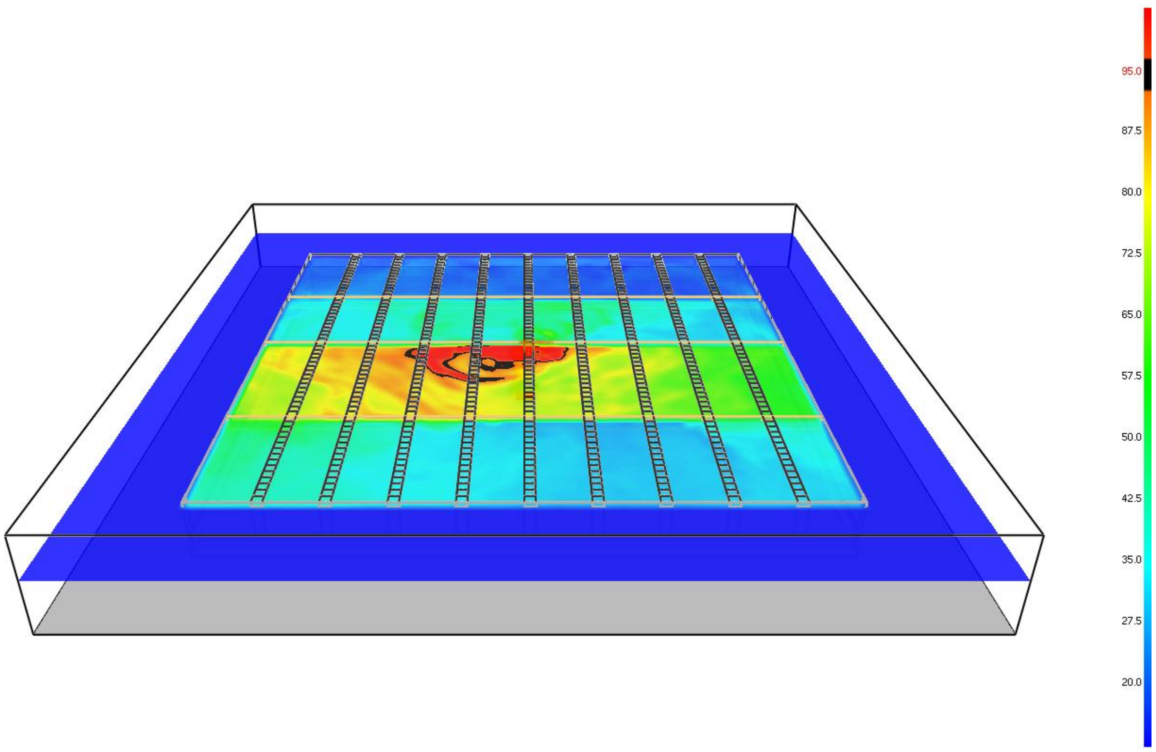


(b)

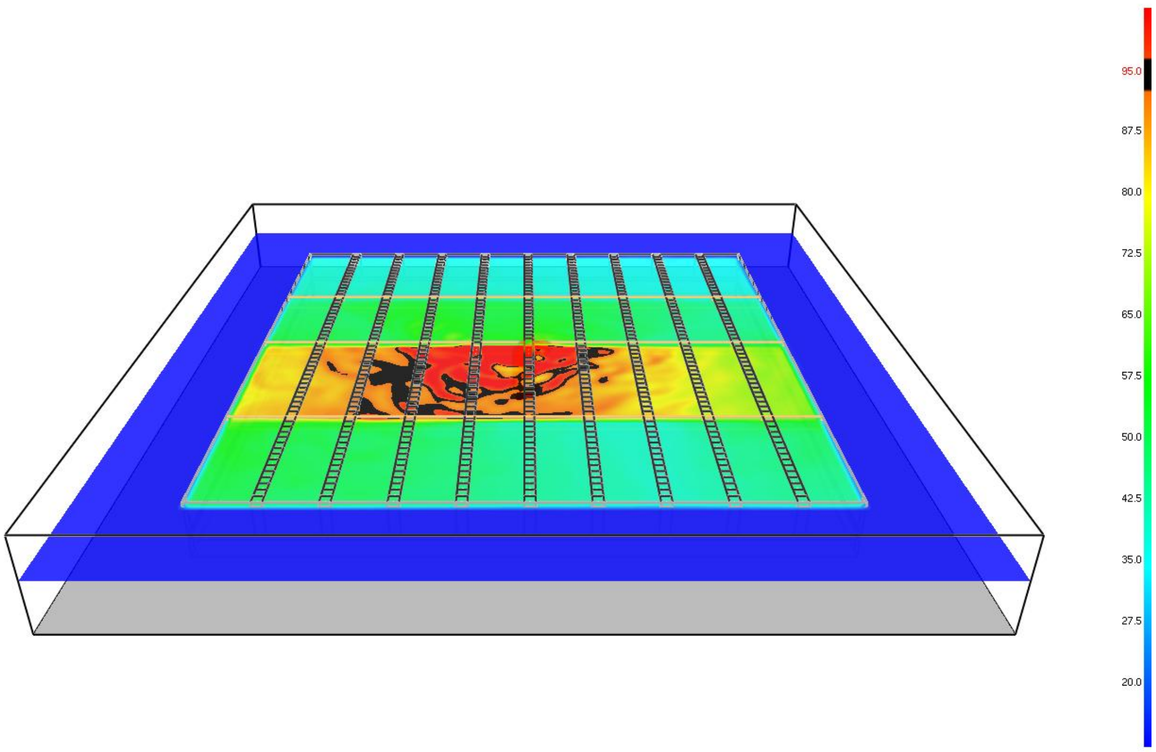


(c)

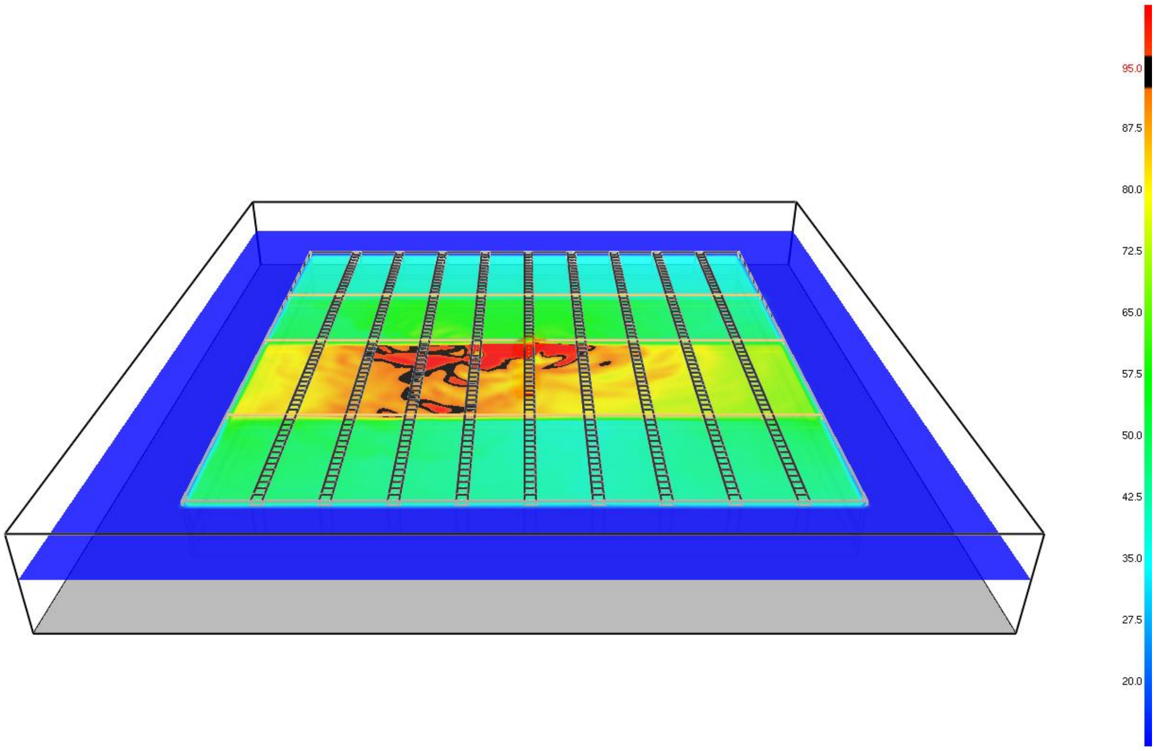
Figure 61: Visual representation of the soot density at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.


95.0
87.5
80.0
72.5
65.0
57.5
50.0
42.5
35.0
27.5
20.0

(a)


95.0
87.5
80.0
72.5
65.0
57.5
50.0
42.5
35.0
27.5
20.0

(b)

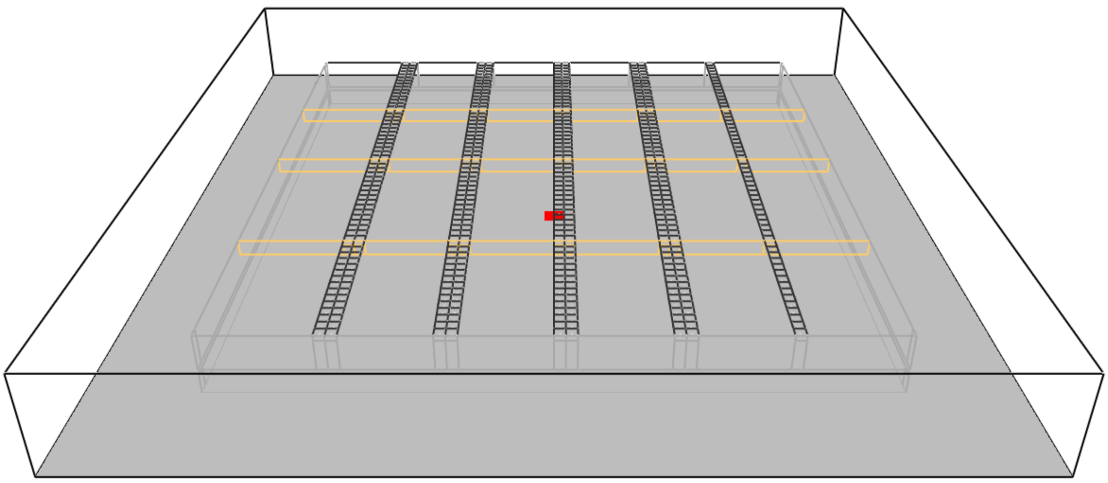


(c)

Figure 62: Gas temperatures (ºC) at 5.5 m above floor height, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000s. Note that the maximum temperature on this scale is less than for Scenario 3: Base Case. Moreover the comparison should be noted, and not the temperature values as these are expected to be lower than expected.

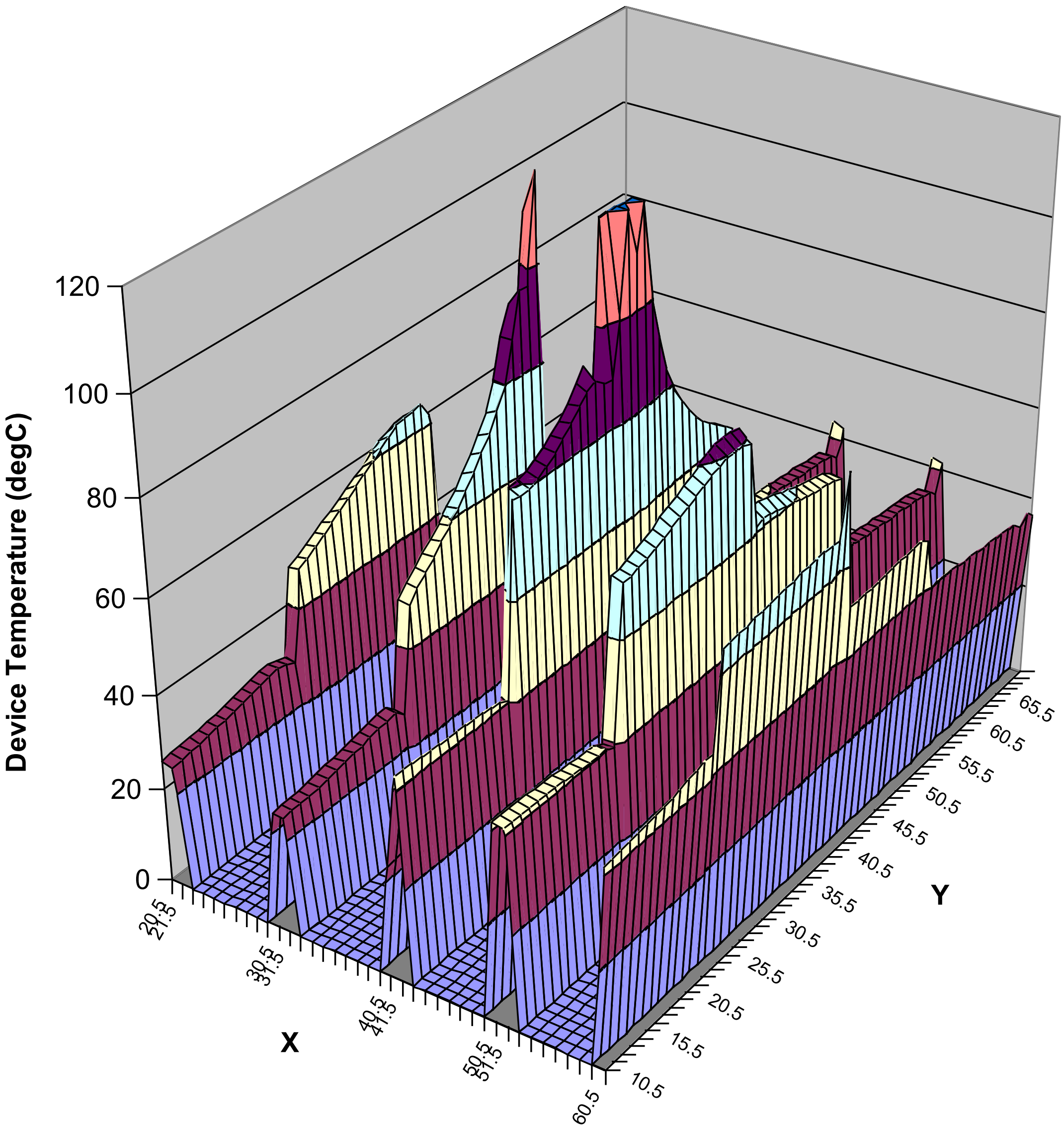
A.3.7 Sensitivity: Location – Double Rows of Vent Material

(a)



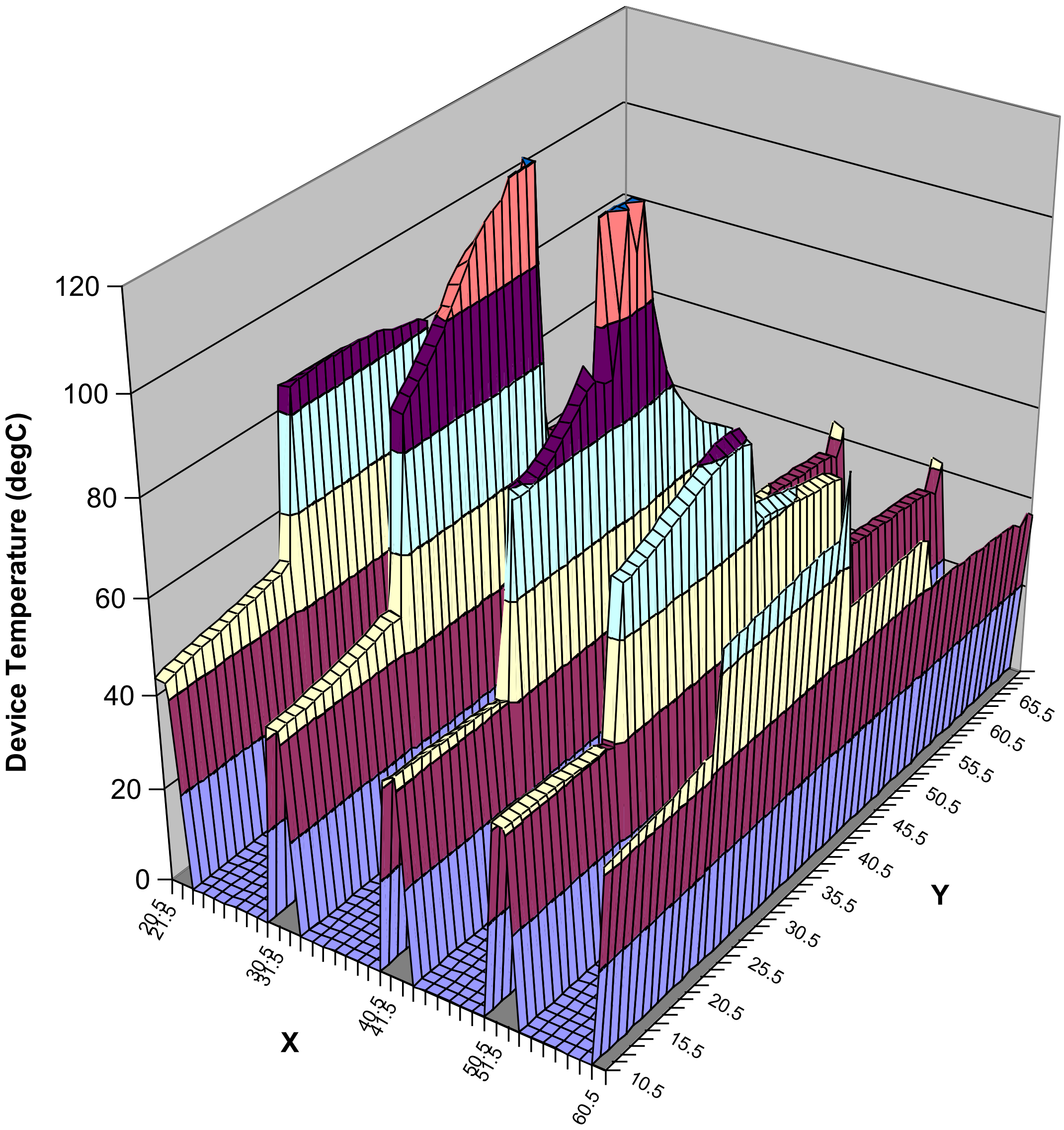
(b)

Figure 63: Visual representation of the geometry for the scenario, with (a) solid blockages, and (b) the outline of blockages.

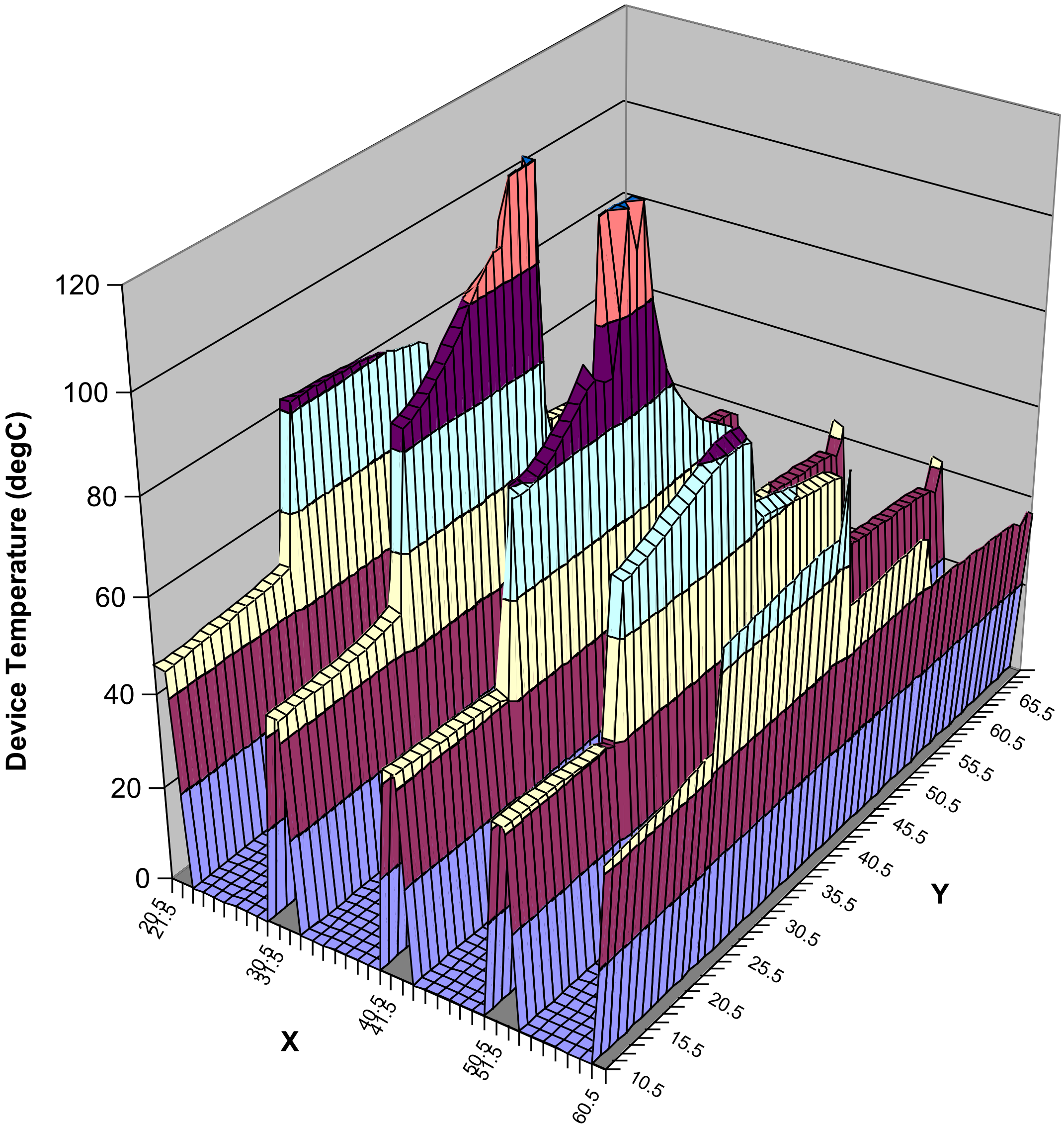


Device Temperature (degC)
120
100
80
60
40
20
0
X
Y
20.5
21.5
30.5
31.5
40.5
41.5
50.5
51.5
60.5
10.5
15.5
20.5
25.5
30.5
35.5
40.5
45.5
50.5
55.5
60.5
65.5

(a)

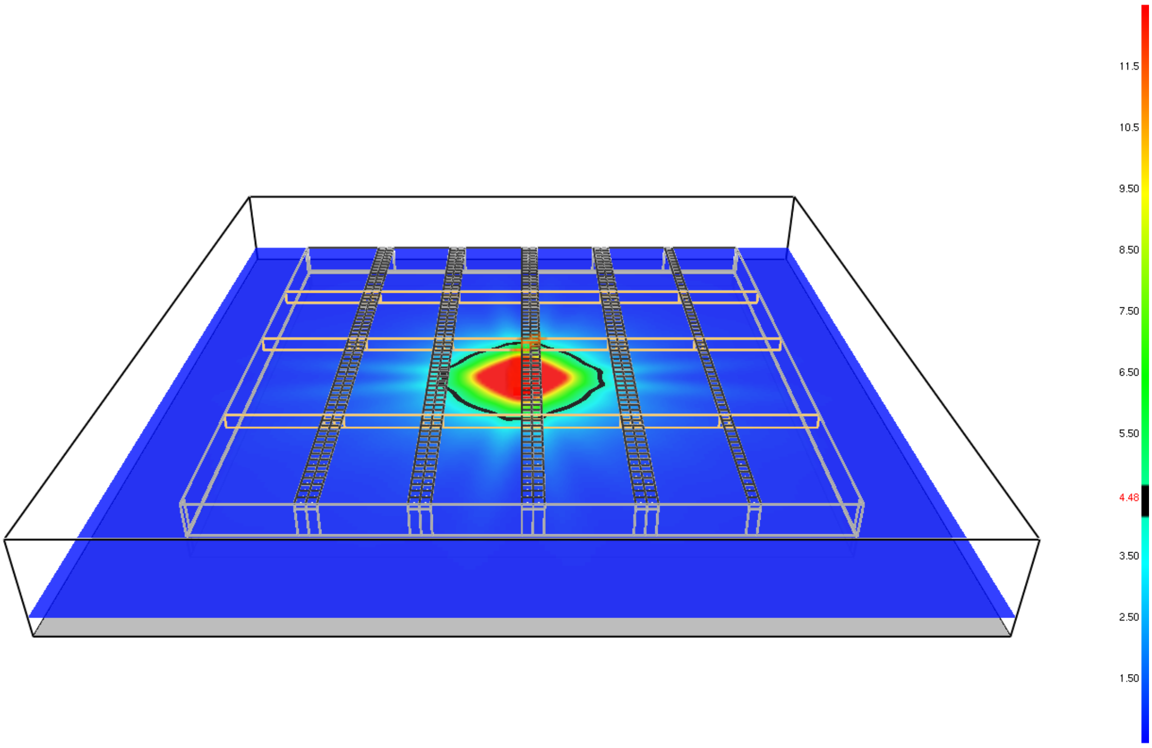

Device Temperature (degC)
120
100
80
60
40
20
0
X
20.5
21.5
30.5
31.5
40.5
41.5
50.5
51.5
60.5
Y
10.5
15.5
20.5
25.5
30.5
35.5
40.5
45.5
50.5
55.5
60.5
65.5

(b)

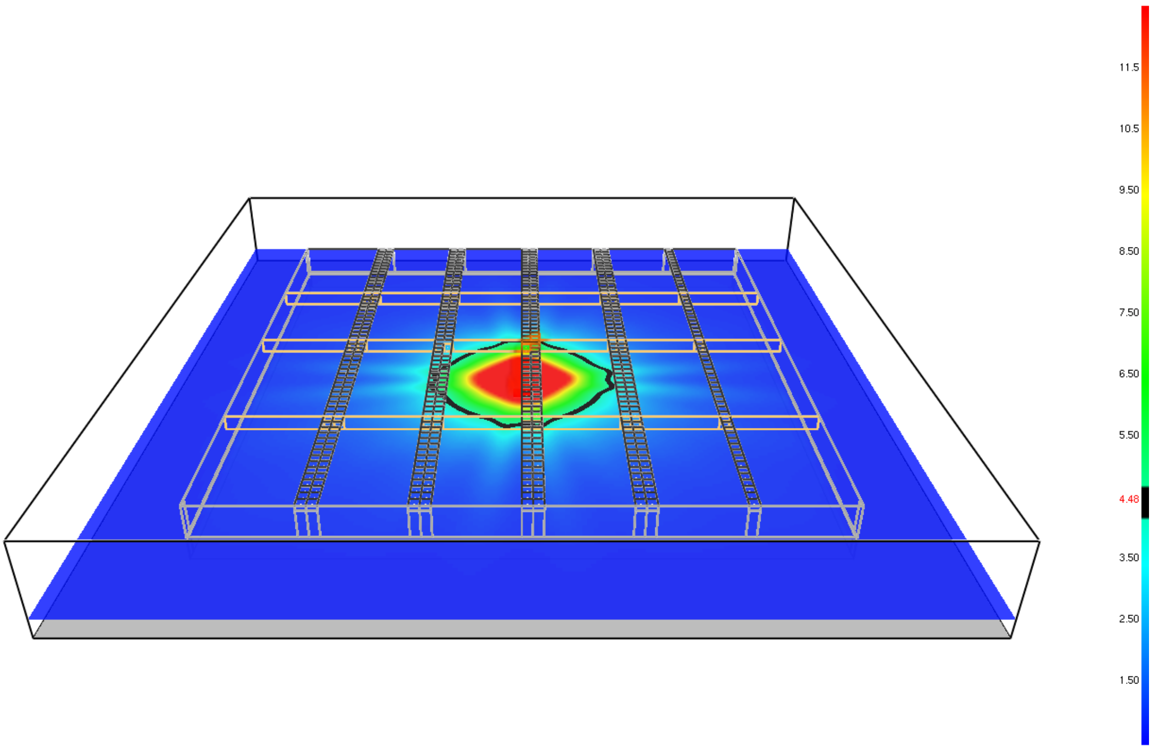


(c)

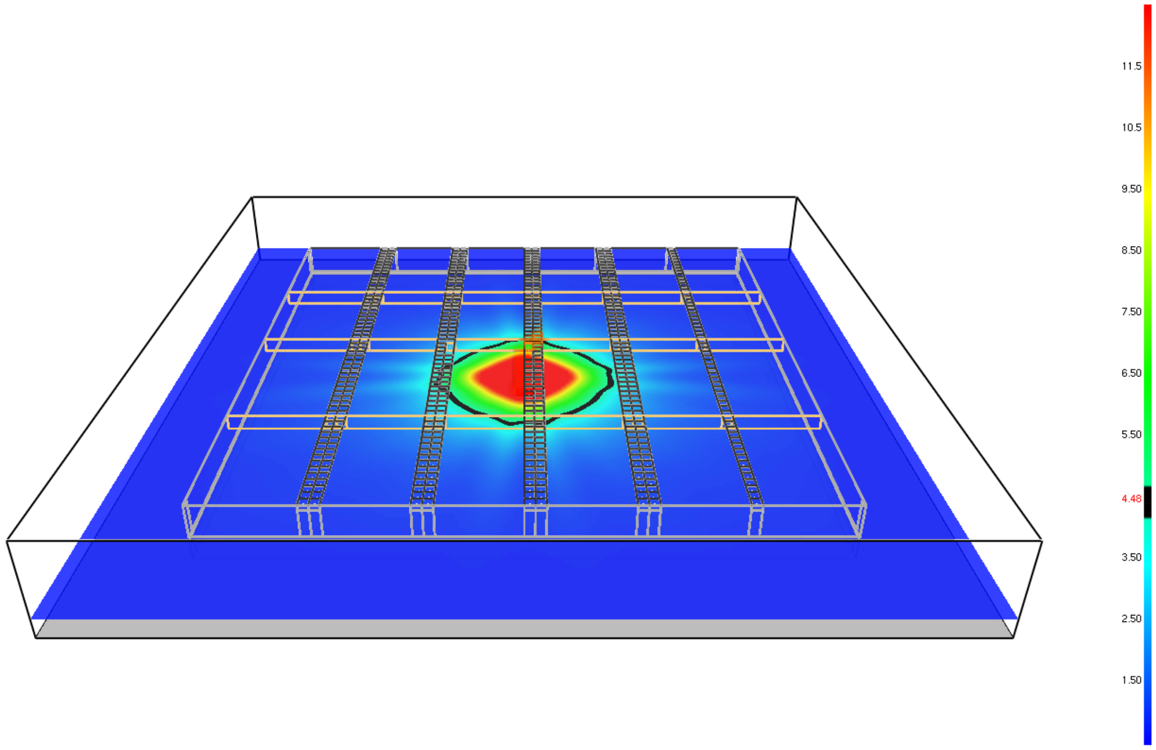
Figure 64: Device temperatures (ºC), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.


11.5
10.5
9.50
8.50
7.50
6.50
5.50
4.48
3.50
2.50
1.50

(a)


11.5
10.5
9.50
8.50
7.50
6.50
5.50
4.48
3.50
2.50
1.50

(b)



(c)

Figure 65: Radiant intensity (kW/m²) at 2 m above floor height, at (a) t = 100 s, (b) t = 500 s, and t = 1,000 s.

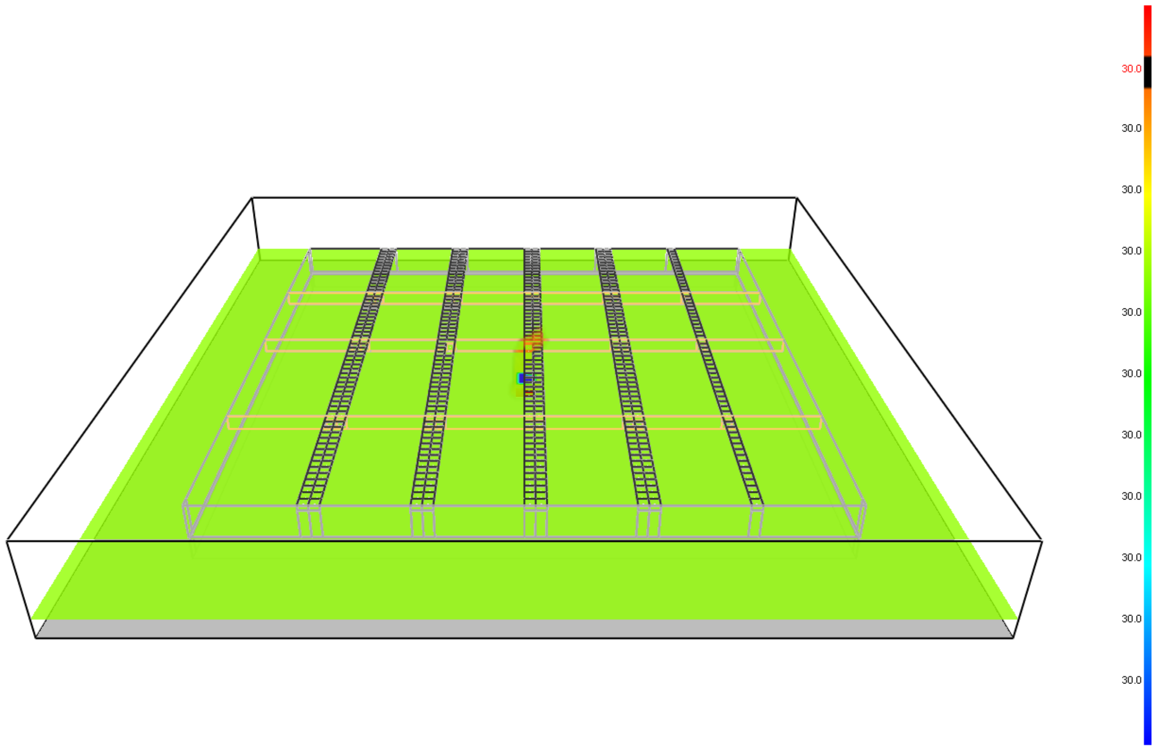
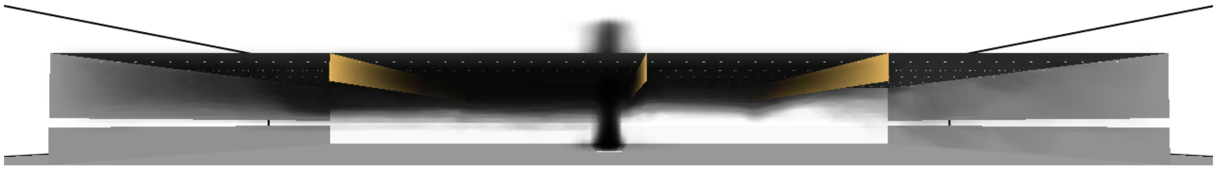
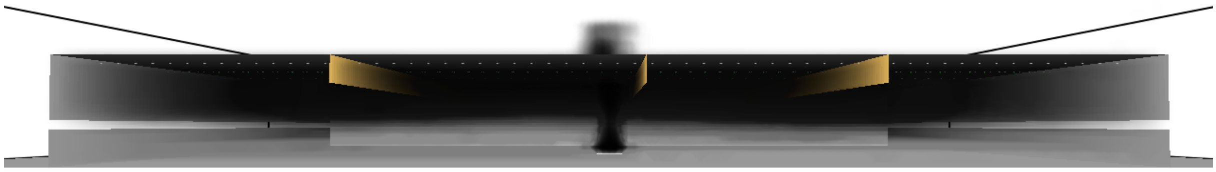


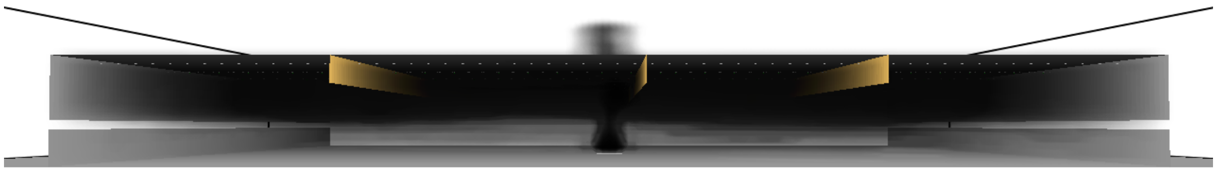
Figure 66: Visibility (m) at 2 m above floor height, t = 1,000 s.



(a)

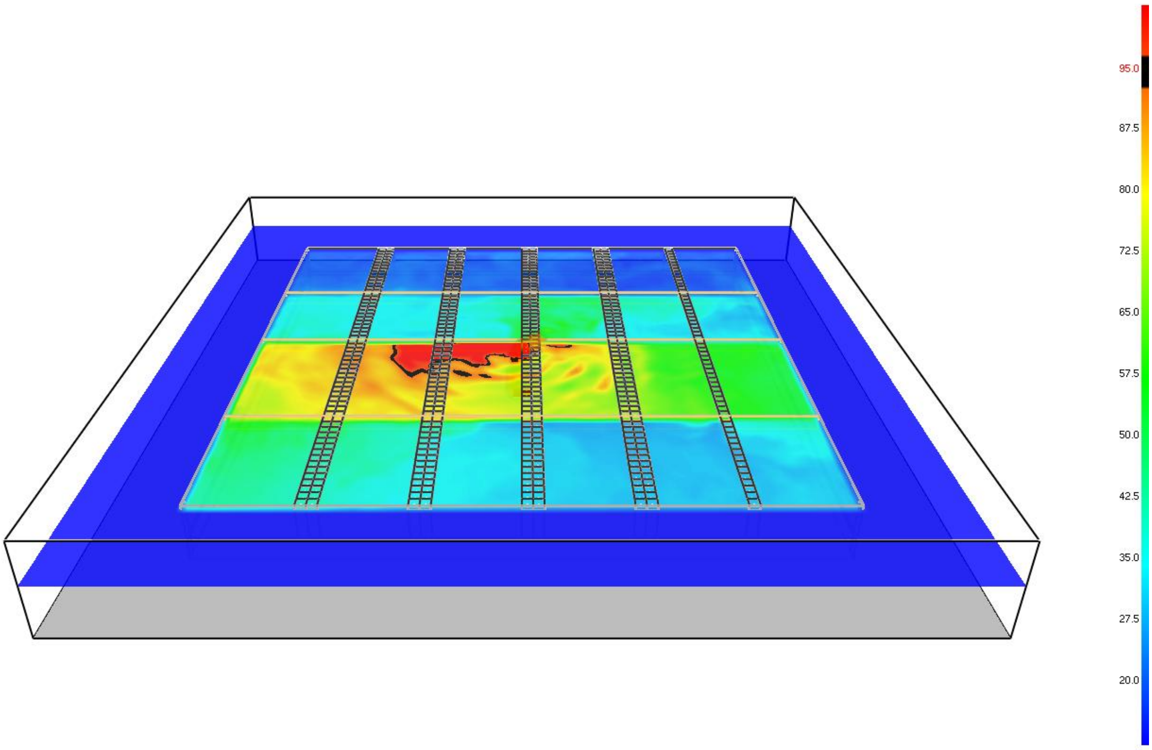


(b)

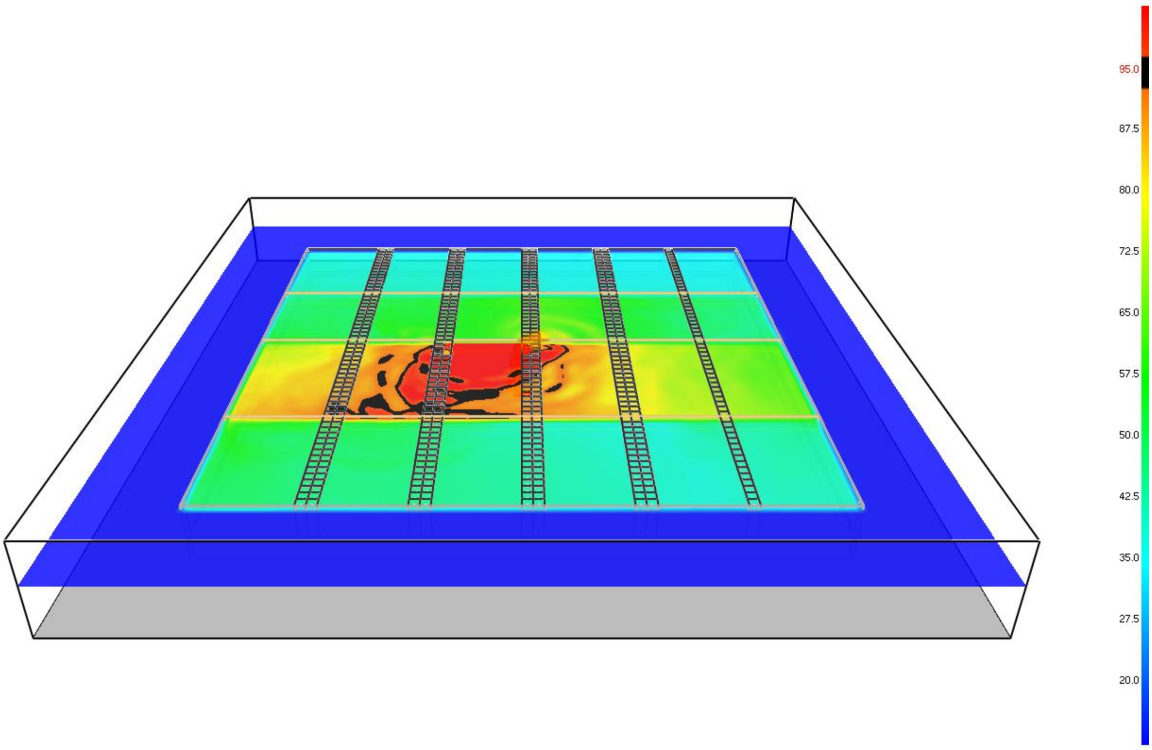


(c)

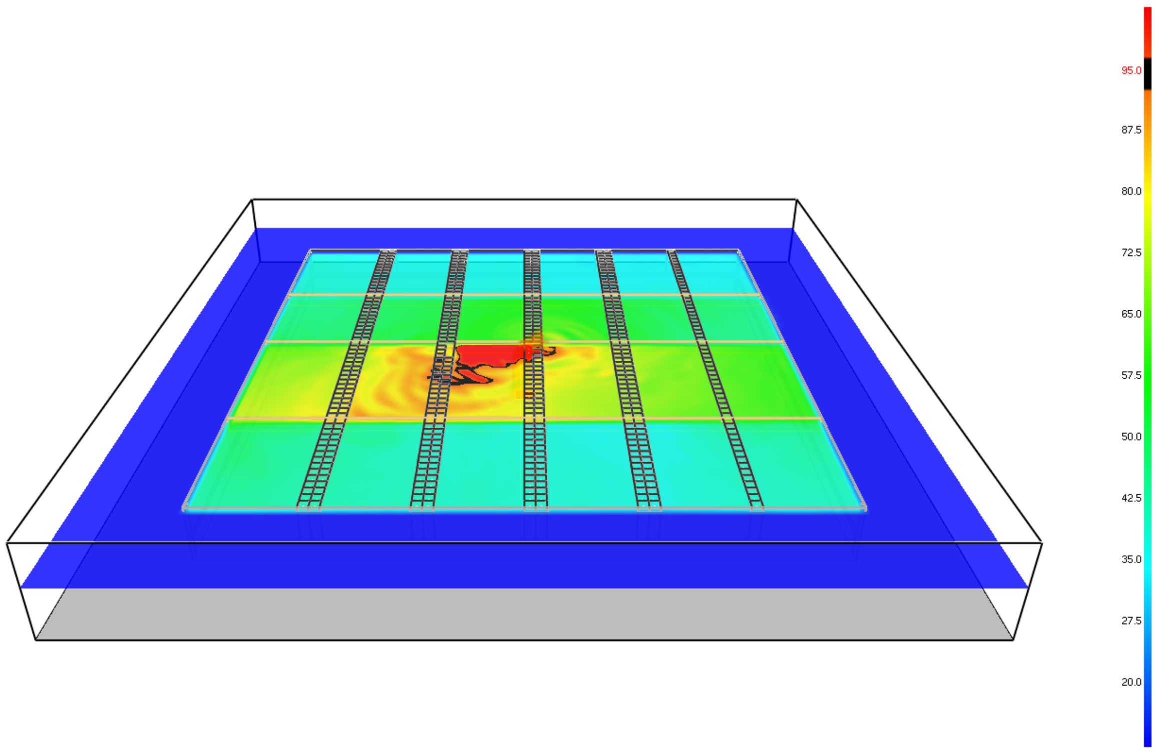
Figure 67: Visual representation of soot density at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.


95.0
87.5
80.0
72.5
65.0
57.5
50.0
42.5
35.0
27.5
20.0

(a)


95.0
87.5
80.0
72.5
65.0
57.5
50.0
42.5
35.0
27.5
20.0

(b)



(c)

Figure 68: Gas temperatures (ºC) at 5.5 m above floor height, at (a) t = 100 s, (b) t = 500 s,, and (c) t = 1,000 s. Note that the maximum temperature on this scale is less than for Scenario 3: Base Case. Moreover the comparison should be noted, and not the temperature values as these are expected to be lower than expected.

A.4 Scenario 4: Four Smoke Reservoirs and Simultaneous Activation of 68ºC Fire Venting in each Smoke Reservoir and Vent Area of 3% Reservoir Floor Area

A.4.1 Input

```
&HEAD CHID='warehouse_01', TITLE='Generic Warehouse - all vents in each smoke reservoir opens on activation of any detector in the same reservoir' /

&MISC RESTART=.FALSE., DTCORE=10, DATABASE_DIRECTORY='C: \nist\fds\database4\' /
&MISC SURF_DEFAULT='CONCRETE', REACTION='PROPANE'/

&PDIM XBAR0=0, YBAR0=0, ZBAR=0, XBAR=80, YBAR=80, ZBAR=10 /
&GRID IBAR=160, JBAR=160, KBAR=20 /

&TIME TWFIN=1000/

/open computational boundaries
&VENT CB='XBAR0', SURF_ID='OPEN' /
&VENT CB='XBAR', SURF_ID='OPEN' /
&VENT CB='YBAR0', SURF_ID='OPEN' /
&VENT CB='YBAR', SURF_ID='OPEN' /
&VENT CB='ZBAR', SURF_ID='OPEN' /

/walls of warehouse
&OBST XB=10,70,10,10.1,0,6, SURF_ID='CONCRETE'/
&OBST XB=10,70,69.9,70,0,6, SURF_ID='CONCRETE'/
&OBST XB=10,10.1,10,70,0,6, SURF_ID='CONCRETE'/
&OBST XB=69.9,70,10,70,0,6, SURF_ID='CONCRETE'/

/low-level permanently-open replacement-air vents 2x15% of floor area (based on AS 2665: 2001)
&HOLE XB=10,70,9,11,2,2.375/
&HOLE XB=10,70,69,71,2,2.375/
&HOLE XB=9,11,10,70,2,2.375/
&HOLE XB=69,71,10,70,2,2.375/

/flat roof
&OBST XB=10,70,10,70,6,6.05, SURF_ID='SHEET METAL'/

/fire
&SURF ID='FIRE_01', HRRPUA=2000, TAU_Q=-1.0/
&VENT XB=39,41,39,41,0,0, SURF_ID='FIRE_01', VENT_COLOR='RED'/

/smoke reservoirs
&OBST XB=10,70,24.9,25.1,4.5,6.1, SURF_ID='INERT' /
&OBST XB=10,70,41.9,42.1,4.5,6.1, SURF_ID='INERT' /
&OBST XB=10,70,54.9,55.1,4.5,6.1, SURF_ID='INERT' /

/heat detectors
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&HEAT XYZ=16.5,28.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det3'/
&HEAT XYZ=16.5,34.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det4'/
&HEAT XYZ=16.5,40.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det5'/
&HEAT XYZ=16.5,46.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det6'/
&HEAT XYZ=16.5,52.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det7'/
&HEAT XYZ=16.5,58.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det8'/
&HEAT XYZ=16.5,64.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det9'/

&HEAT XYZ=22.5,16.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det10'/
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&HEAT XYZ=22.5,28.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det12'/
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&HEAT XYZ=22.5,52.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det16'/
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&HEAT XYZ=22.5,64.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det18'/

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&HEAT XYZ=28.5,40.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det23'/
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&HEAT XYZ=64.5,64.5,5.8, RTI=132, ACTIVATION_TEMPERATURE=68, LABEL='det81'/

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&HOLE XB=40,41,22,23,5.5,6.5,HEAT_CREATE='det1'/
```

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&TAIL /makes
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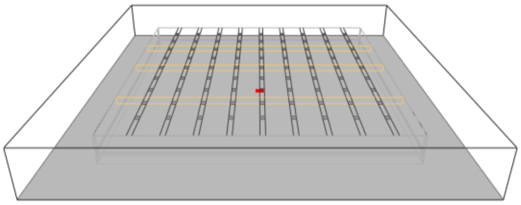
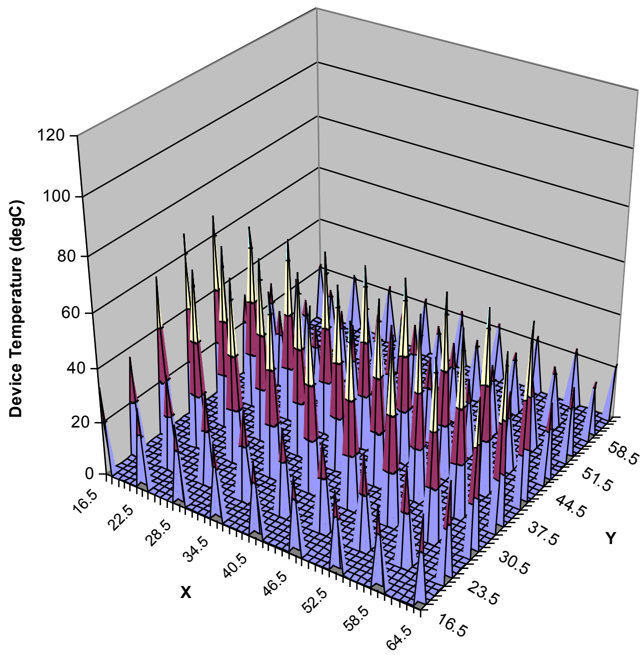
A.4.2 Results – Base Case

(a)

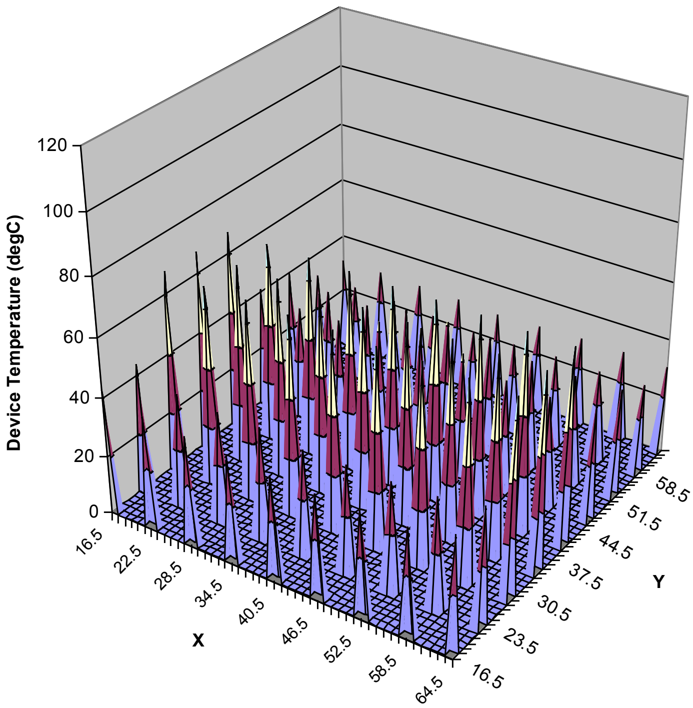


(b)

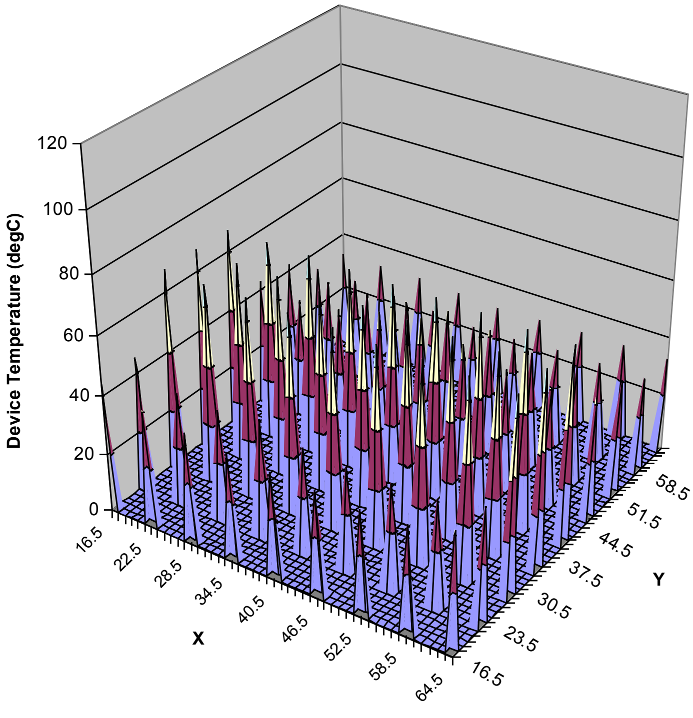
Figure 69: Indicative visual representation of the geometry for the scenario, with (a) solid blockages, and (b) the outline of blockages.


Device Temperature (degC)
120
100
80
60
40
20
0
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
X
58.5
51.5
44.5
37.5
30.5
23.5
16.5
Y

(a)


Device Temperature (degC)
120
100
80
60
40
20
0
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
X
58.5
51.5
44.5
37.5
30.5
23.5
16.5
Y

(b)



(c)

Figure 70: Device temperatures (°C), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1000 s

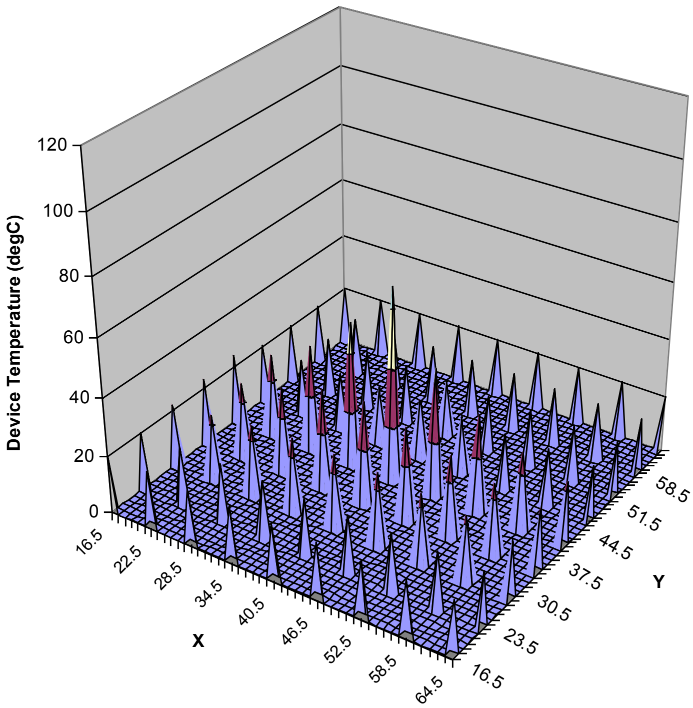
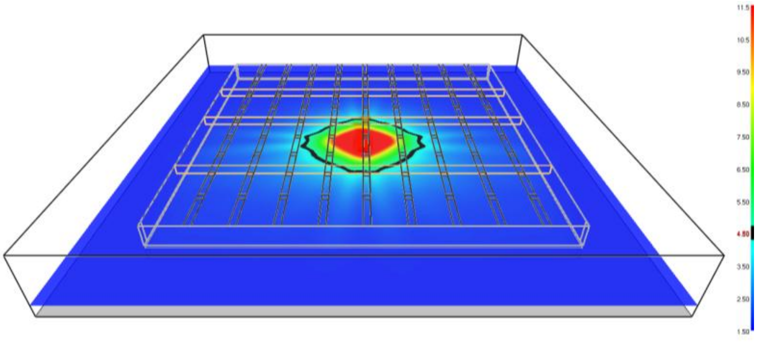
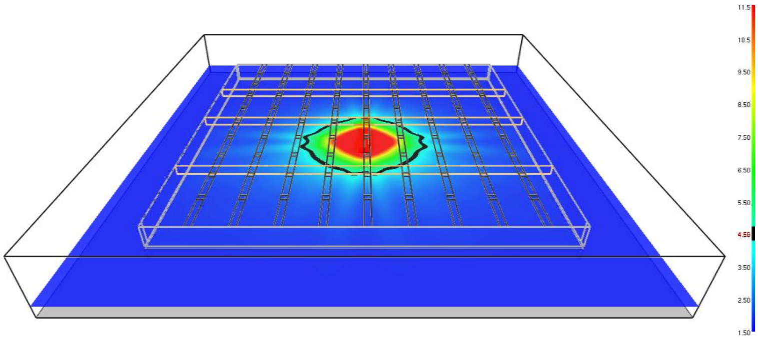


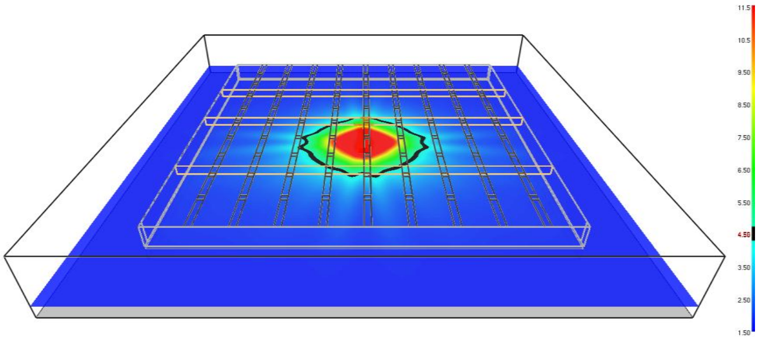
Figure 71: Device temperatures (°C), at t = 20 s



(a)



(b)



(c)

Figure 72: Radiant intensity (kW/m²) at 2 m above floor height, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

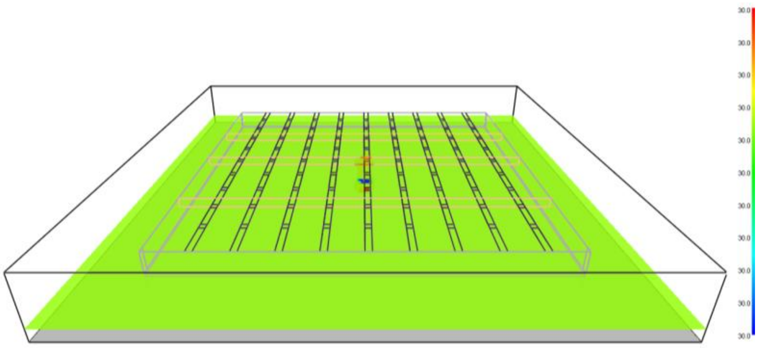
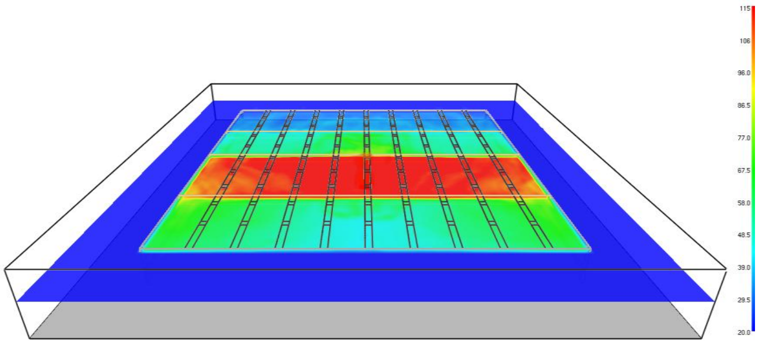
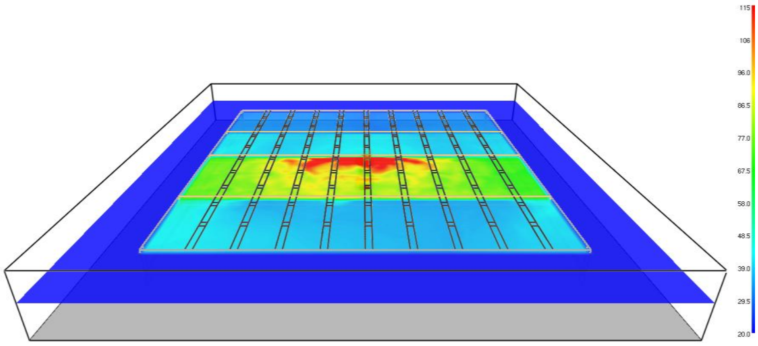


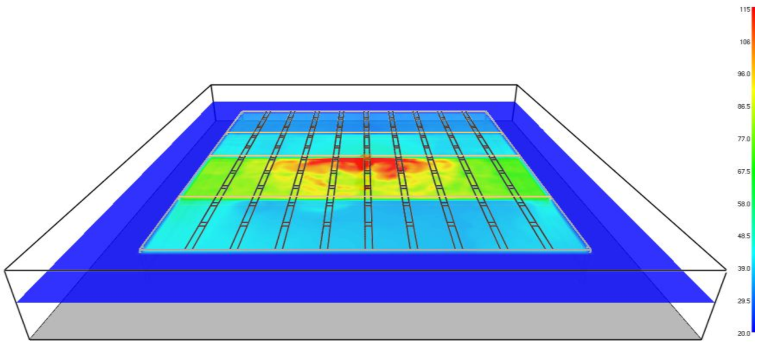
Figure 73: Visibility (m) at 2 m above floor height, at t = 1,000 s.



(a)



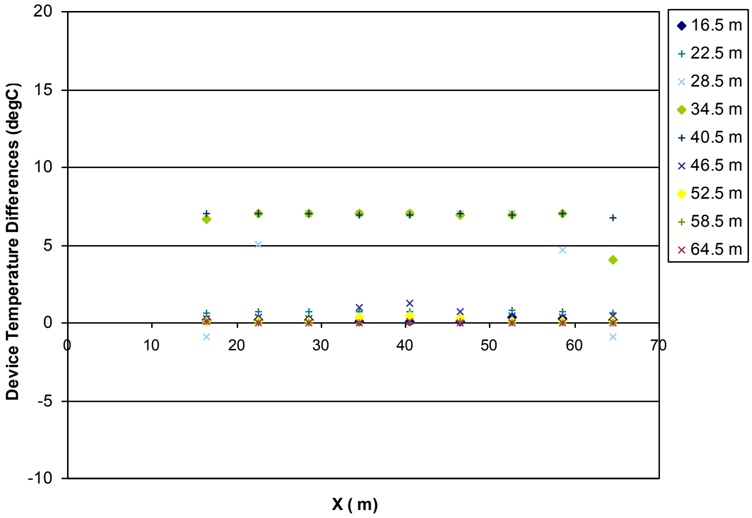
(b)



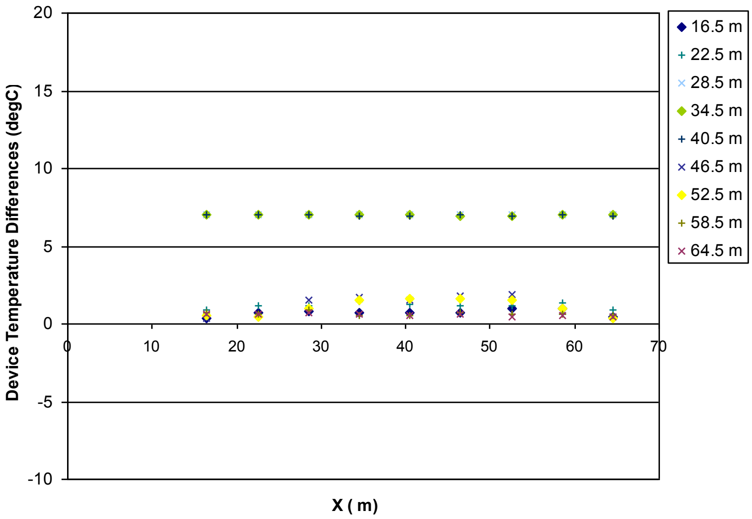
(c)

Figure 74: Gas temperatures (ºC) 0.5 m below ceiling, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

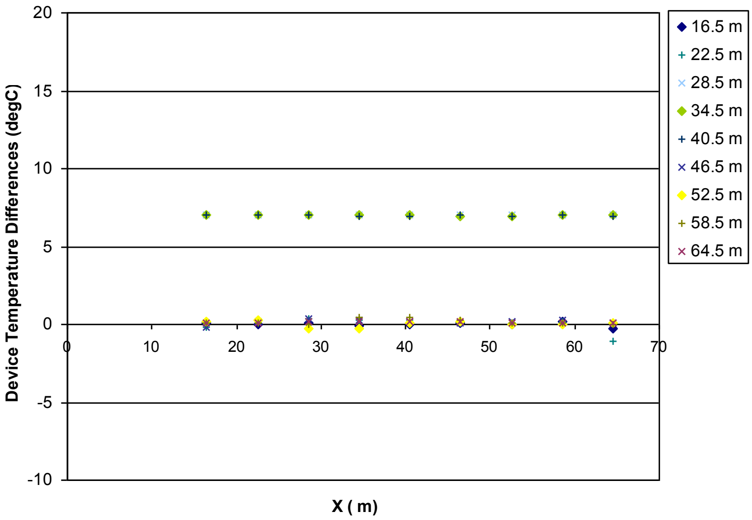
A.4.3 Sensitivity: Effective Activation Temperature = 68ºC - 10%



(a)



(b)



(c)

Figure 75: Difference in device temperatures (ºC) between the base case and the case with an effective activation temperature of 61ºC at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

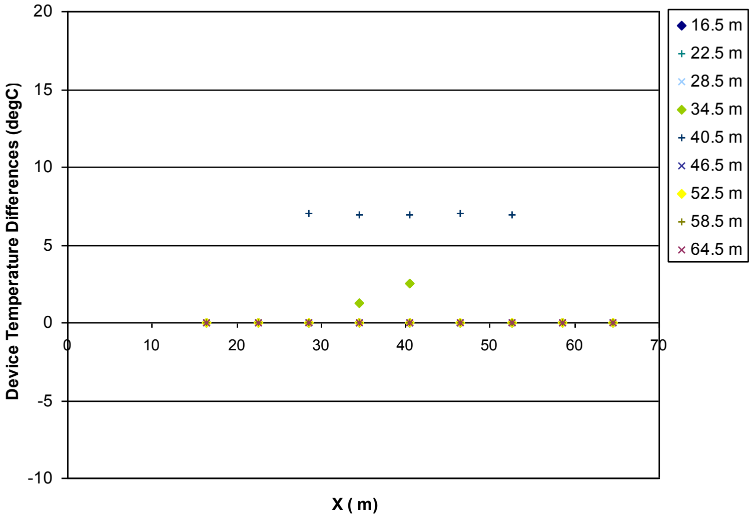
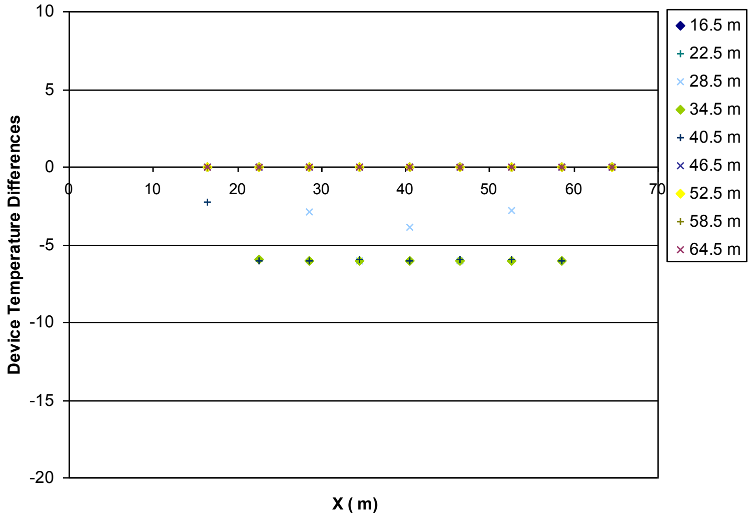
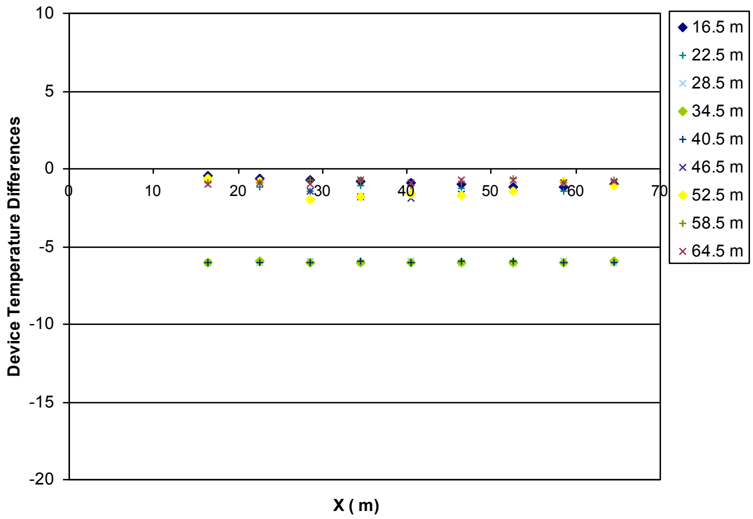


Figure 76: Difference in device temperatures (ºC) between the base case and the case with an effective activation temperature of 61ºC at t = 50 s.

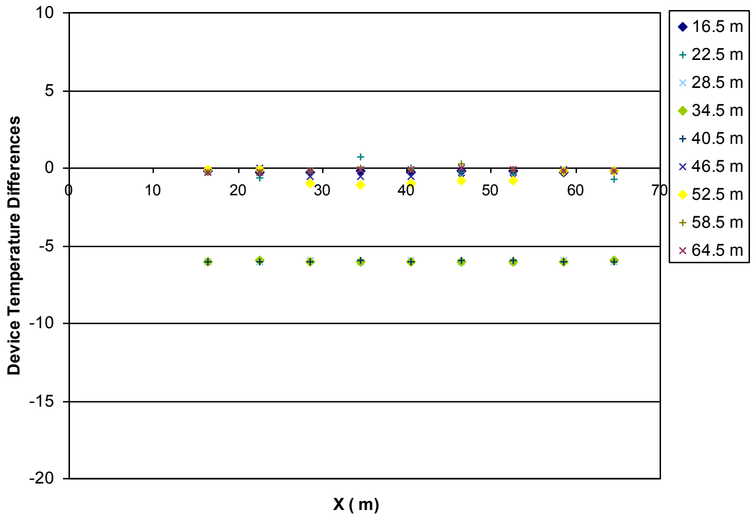
A.4.4 Sensitivity: Effective Activation Temperature = 68°C + 10%



(a)



(b)



(c)

Figure 77: Difference in device temperatures between the base case and the case with an effective activation temperature of 61ºC at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

A.4.5 Sensitivity: Effective RTI = 119

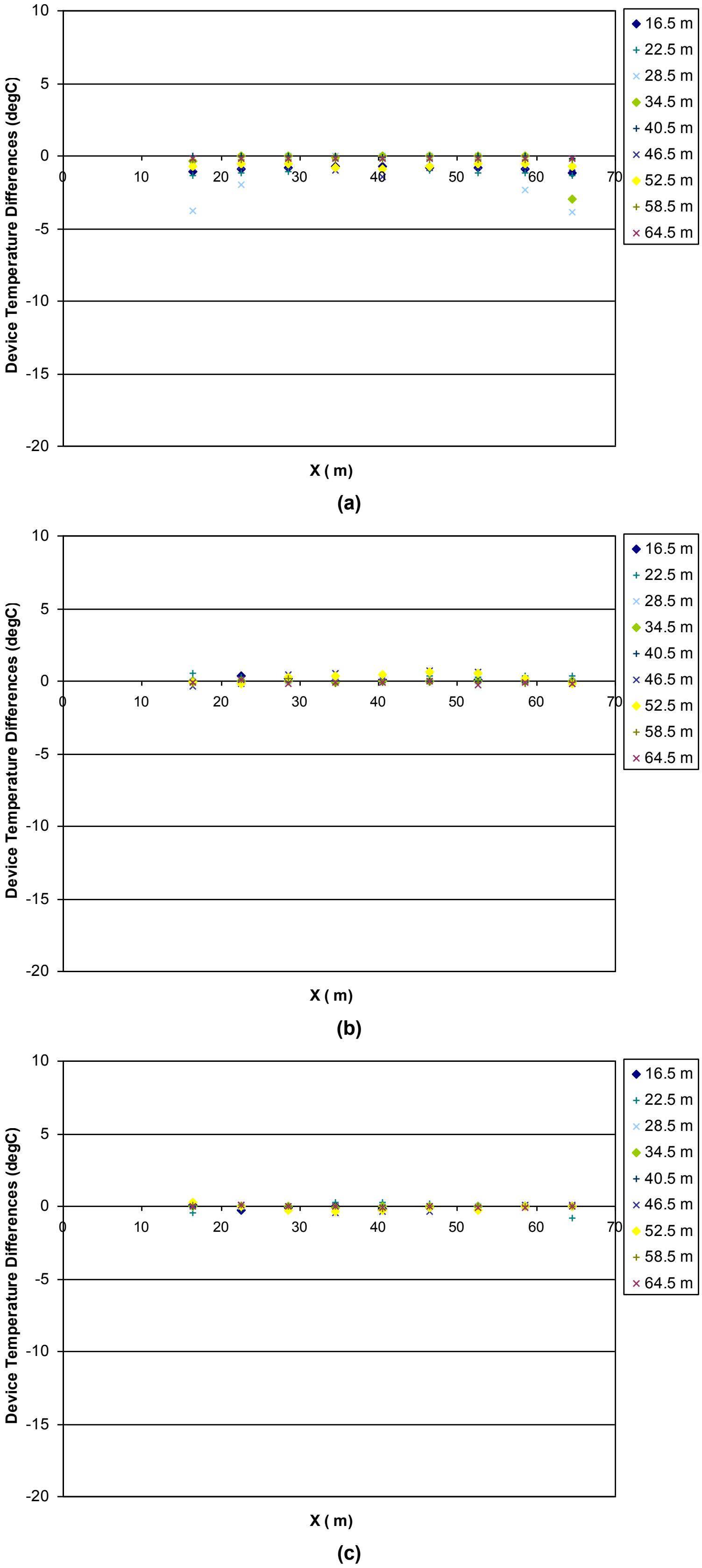
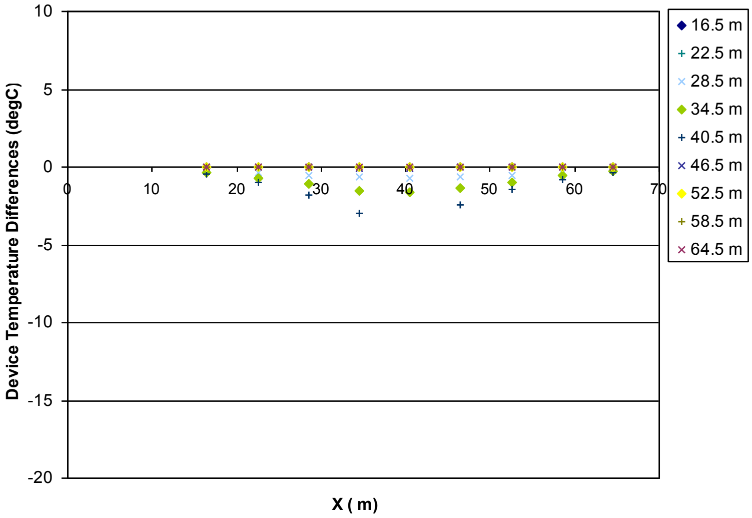
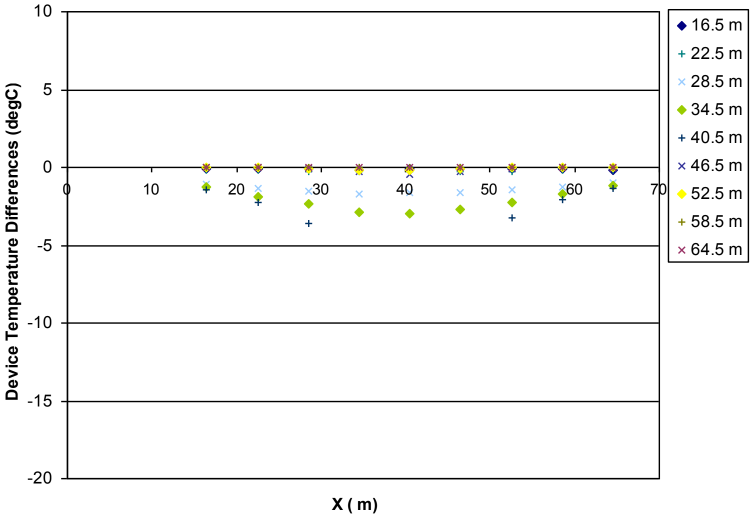


Figure 78: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 119 at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.



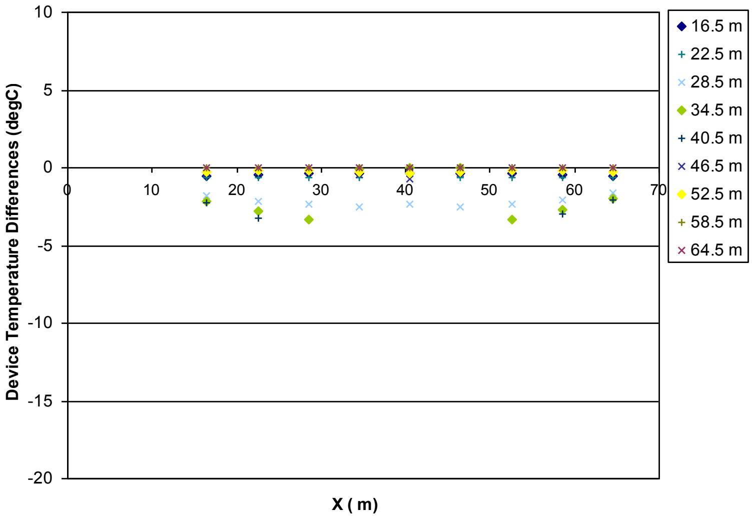
Device Temperature Differences (degC)
X (m)
16.5 m
22.5 m
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

(a)



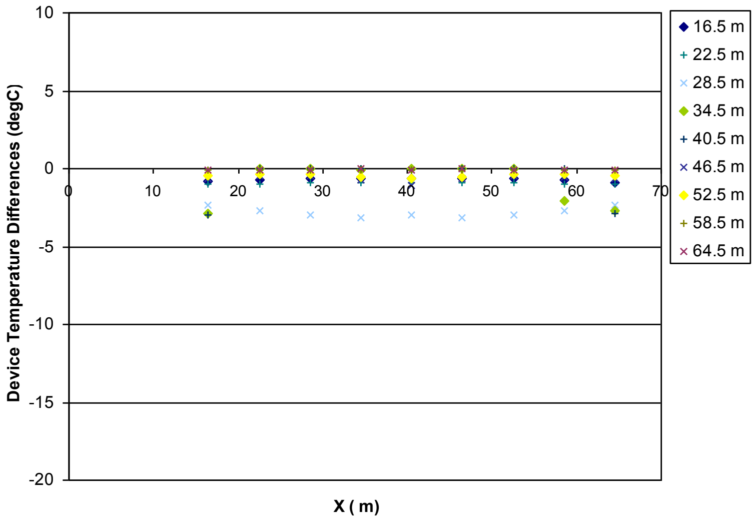
Device Temperature Differences (degC)
X (m)
16.5 m
22.5 m
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

(b)



Device Temperature Differences (degC)
X (m)
16.5 m
22.5 m
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

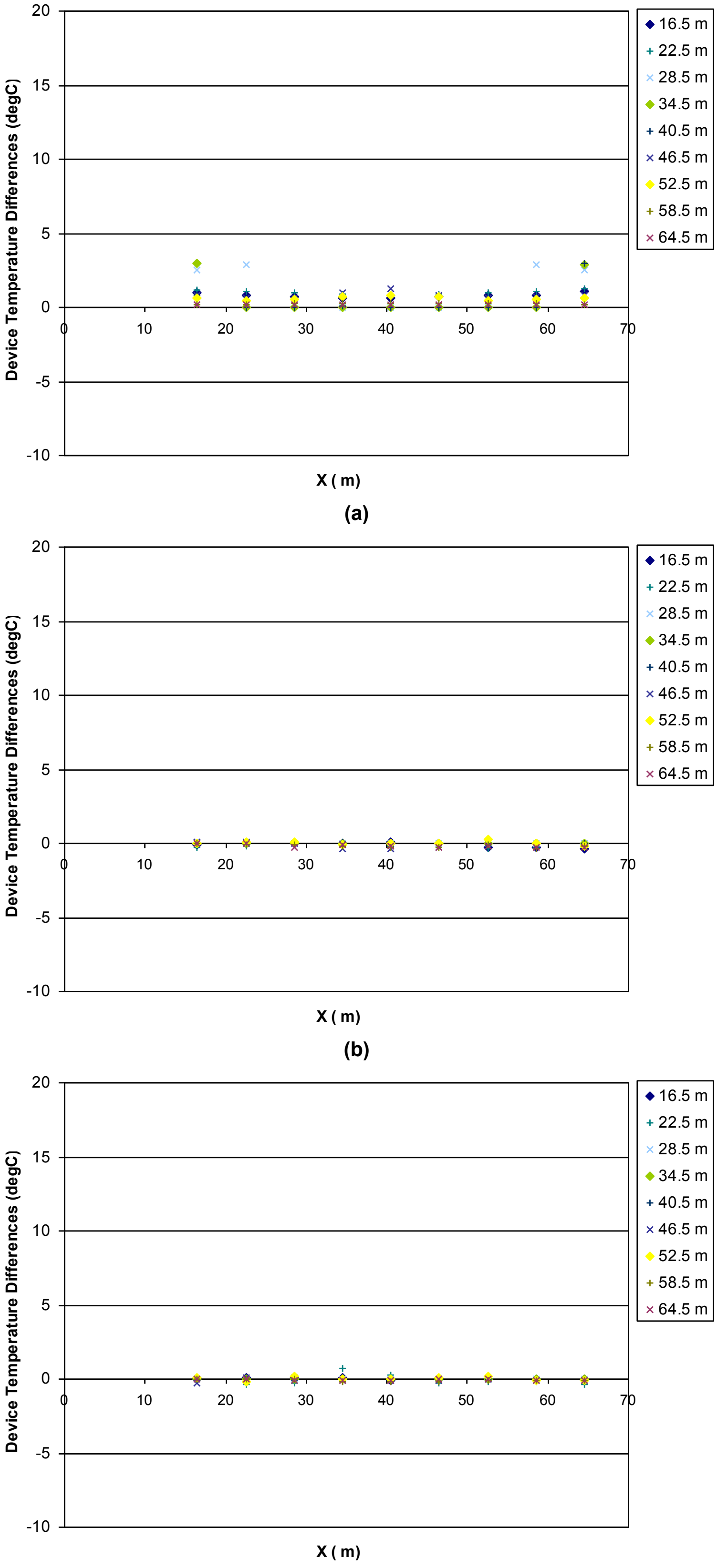
(c)



(d)

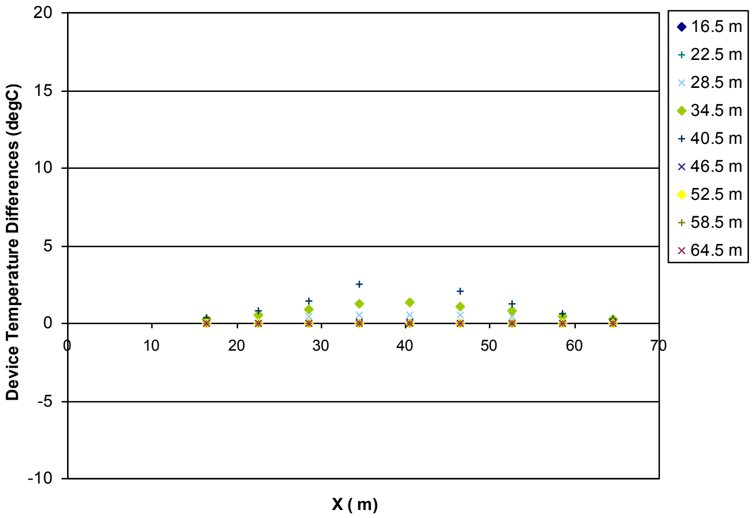
Figure 79: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 119 at (a) t = 20 s, (b) t = 40 s, (c) t = 60 s, and (d) t = 80 s.

A.4.6 Sensitivity: Effective RTI = 145

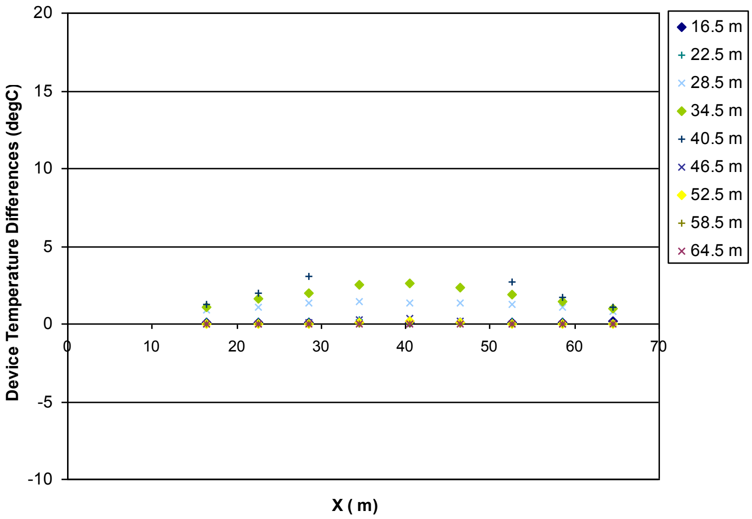


(c)

Figure 80: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 145 at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.


Device Temperature Differences (degC)
X (m)
16.5 m
22.5 m
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

(a)


Device Temperature Differences (degC)
X (m)
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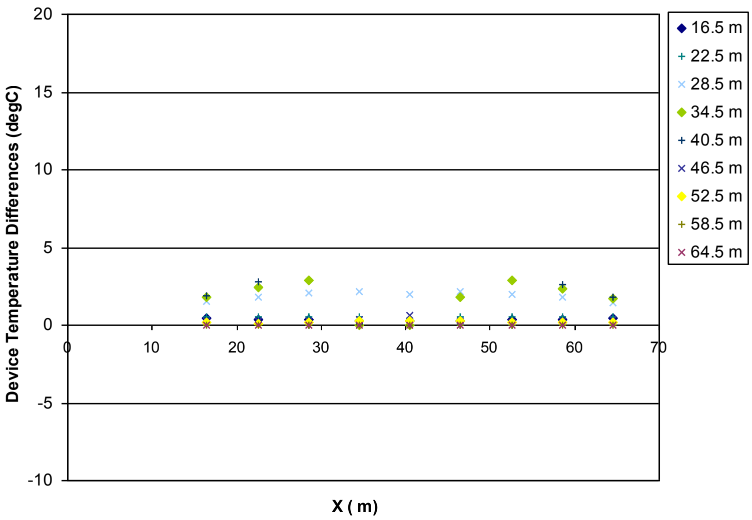
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

(b)


Device Temperature Differences (degC)
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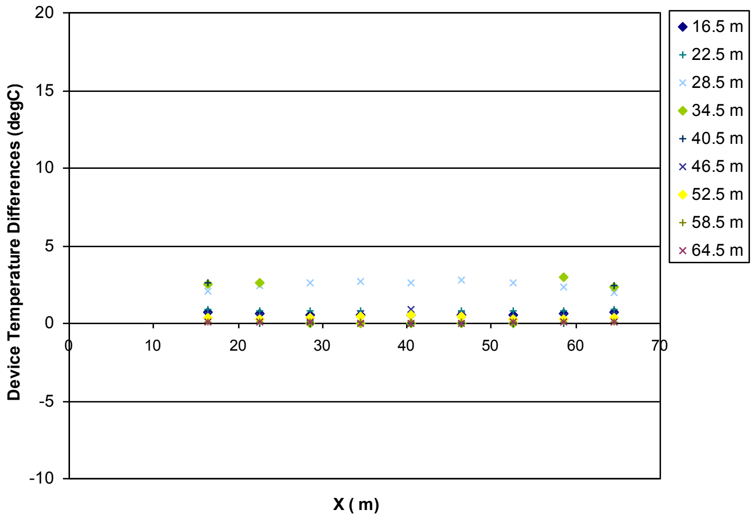
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

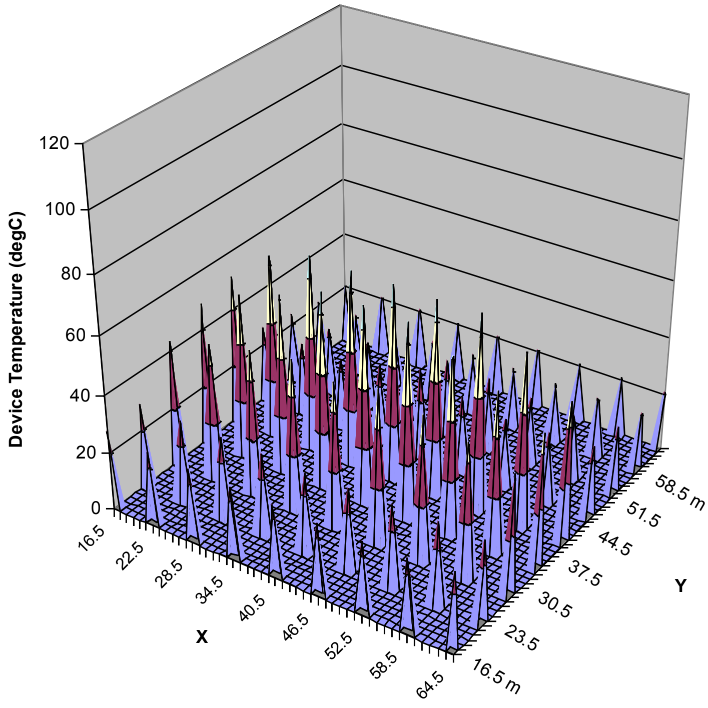
(c)



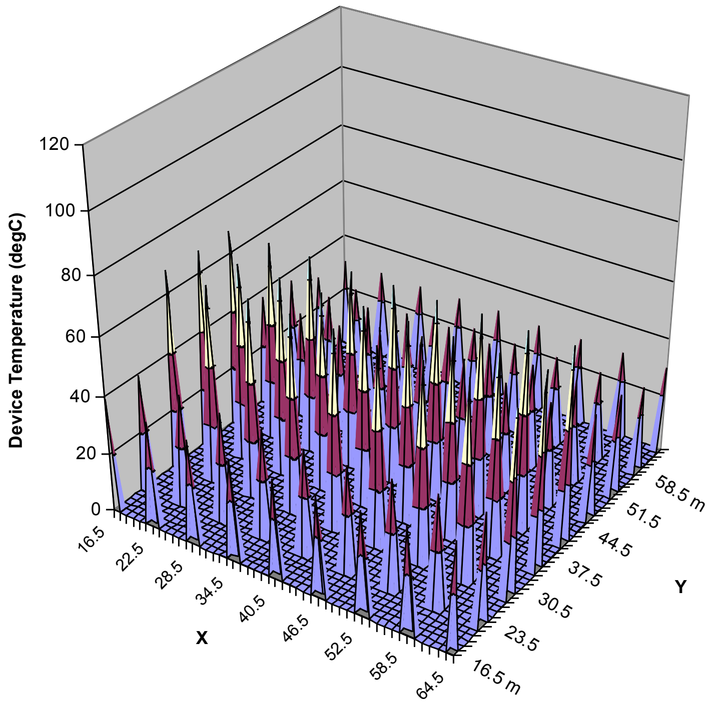
(d)

Figure 81: Difference in device temperatures (ºC) between the base case and the case with an effective RTI of 145, at (a) t = 20 s, (b) t = 40 s, (c) t = 60 s, and (d) t = 80 s.

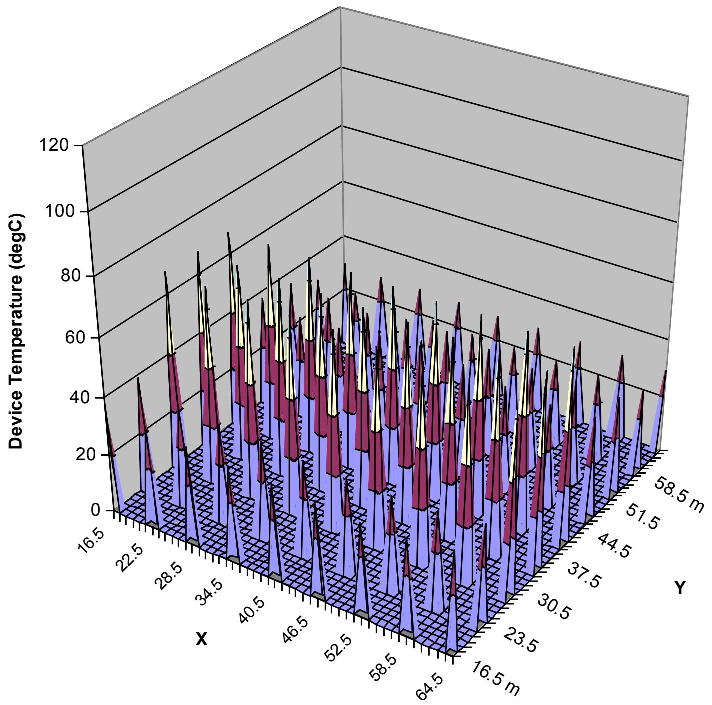
A.4.7 Sensitivity: Peak HRR = 5 MW



(a)



(b)



(c)

Figure 82: Device temperatures (°C), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

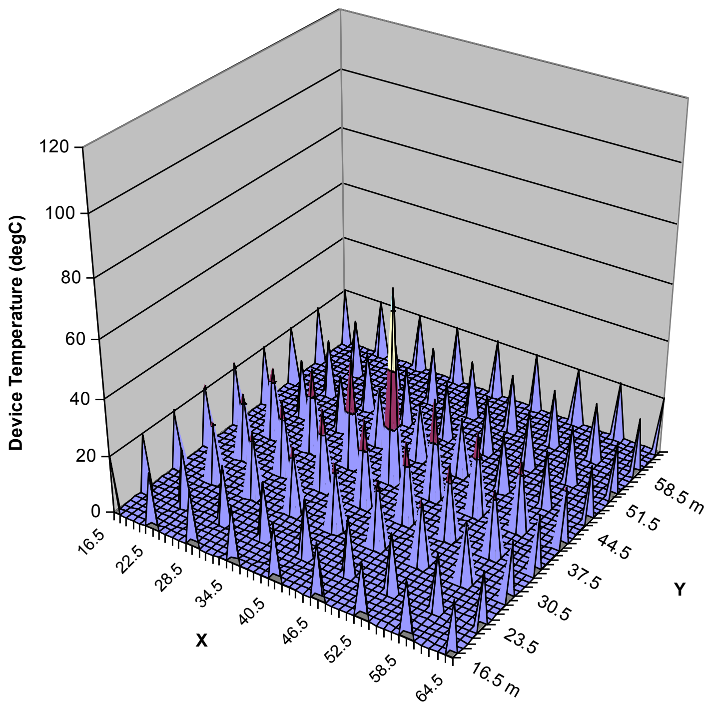


Figure 83: Device temperatures (°C), at t = 20 s.

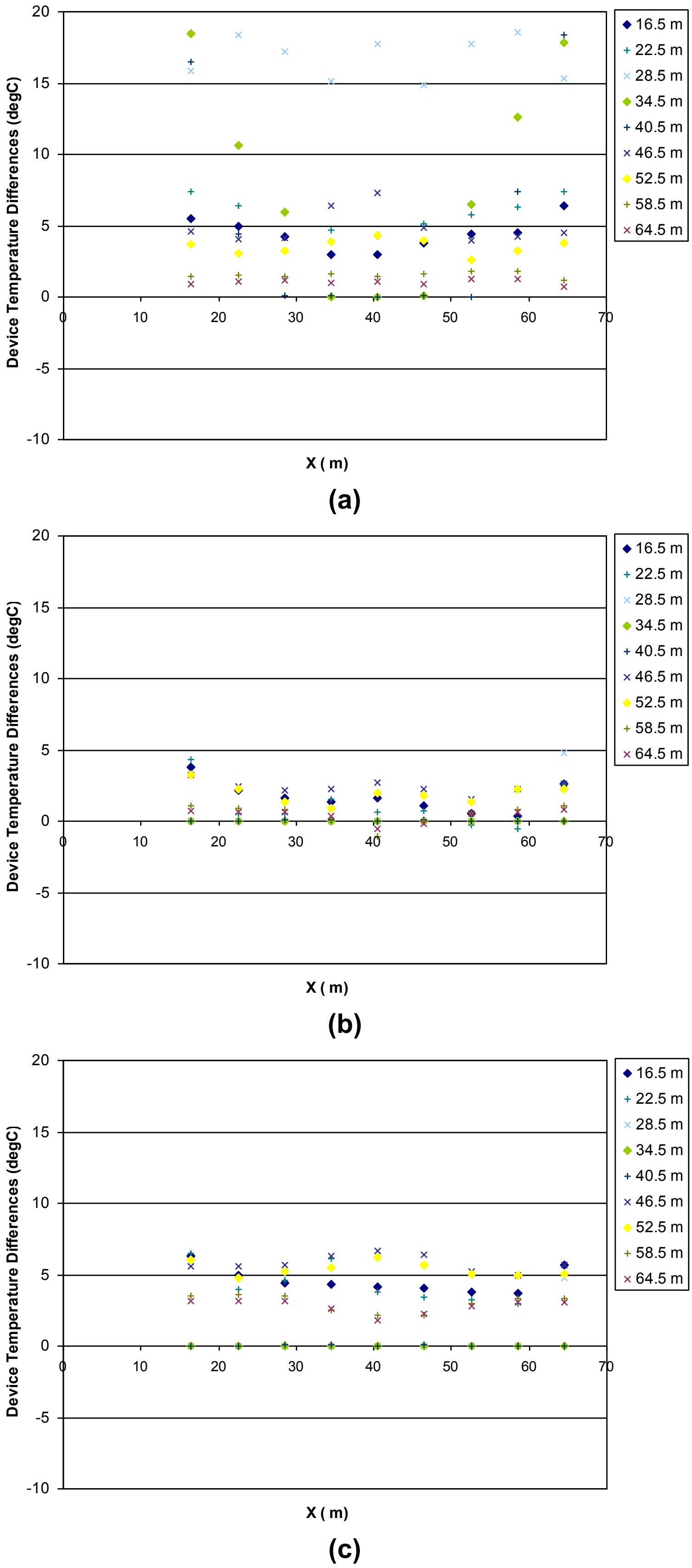
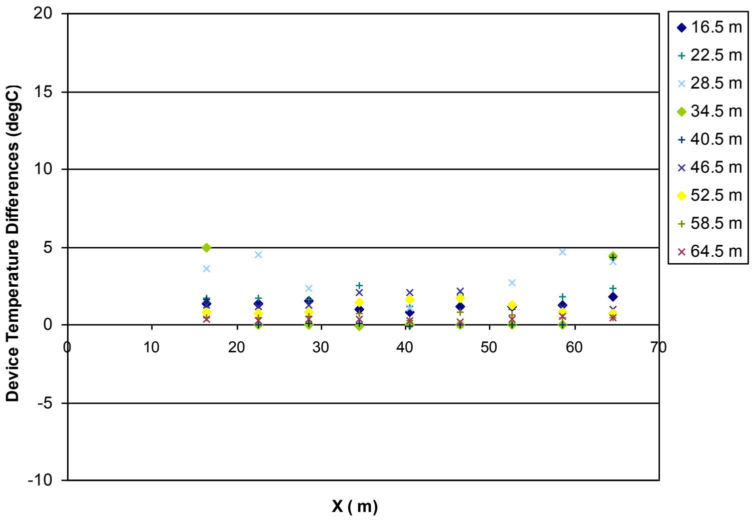
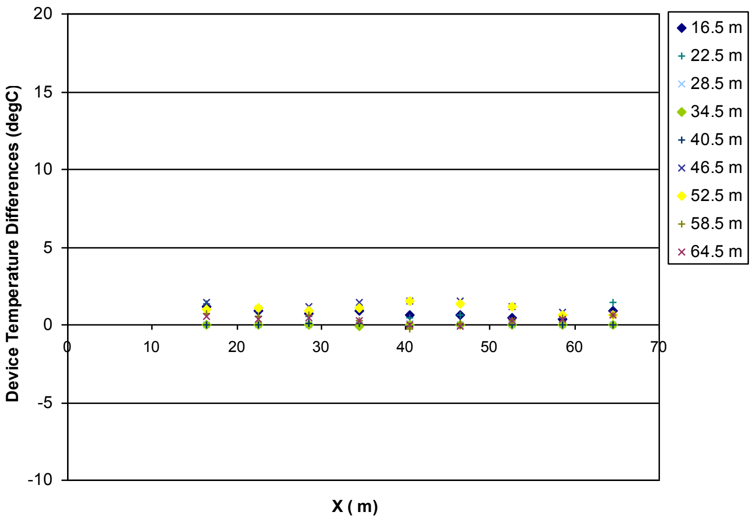


Figure 84: Difference in device temperatures (ºC) between the base case and the case with a peak HRR of 5 MW, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

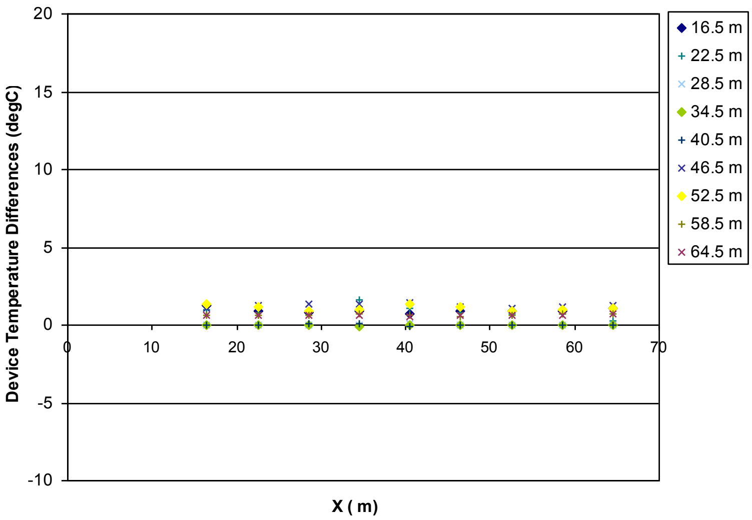
A.4.8 Sensitivity: Peak HRR = 8 MW – 10%



(a)



(b)



(c)

Figure 85: Difference in device temperatures (ºC) between the base case and the case with a peak HRR of 8 MW - 10%, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

A.4.9 Sensitivity: Peak HRR = 8 MW + 10%

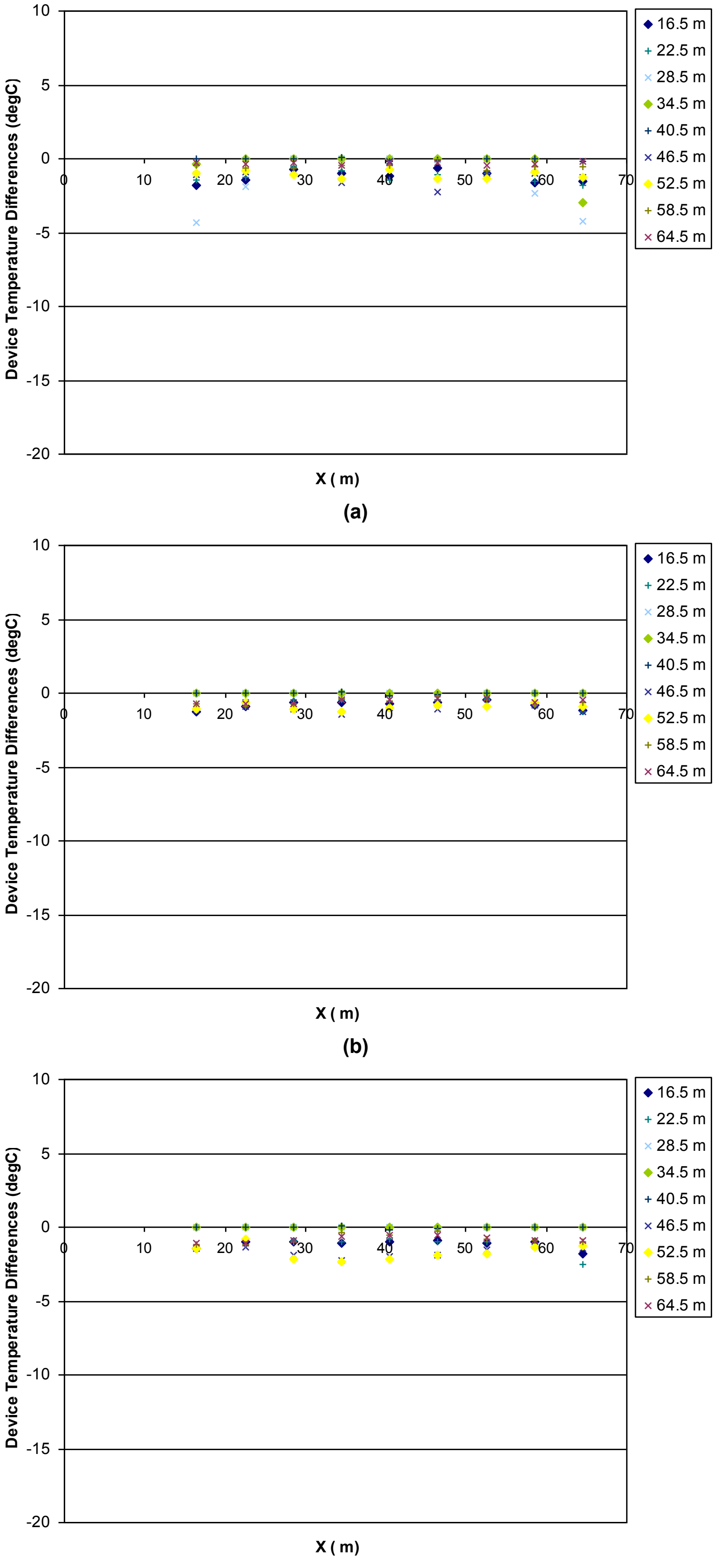
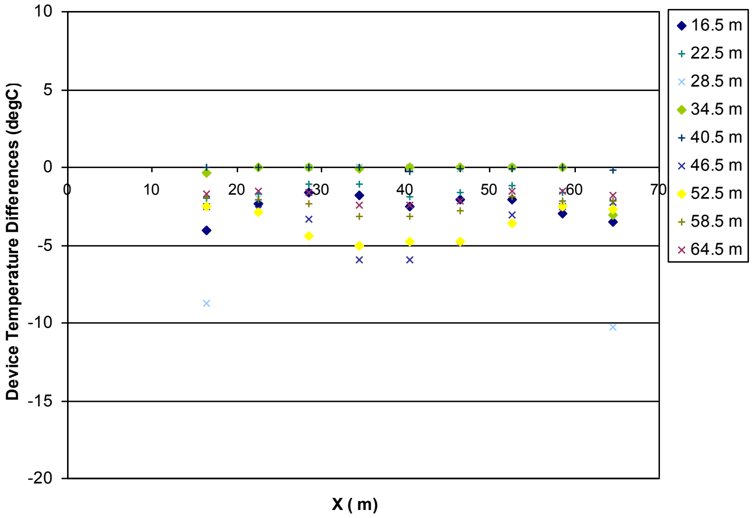
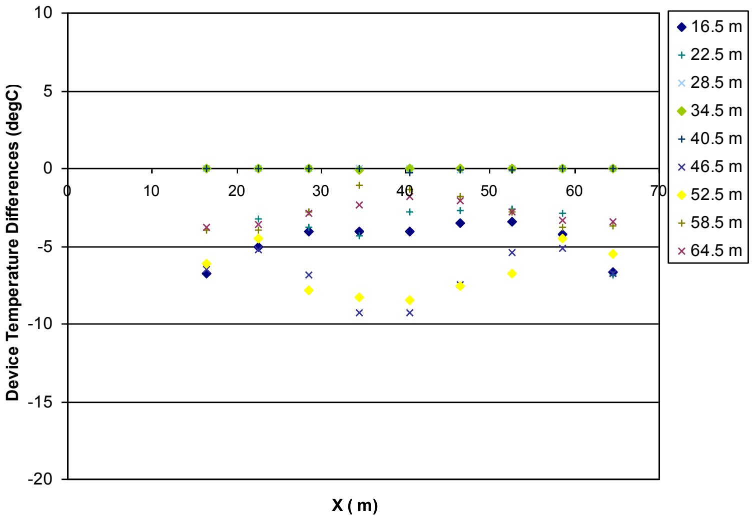


Figure 86: Difference in device temperatures (ºC) between the base case and the case with a peak HRR of 8 MW + 10%, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

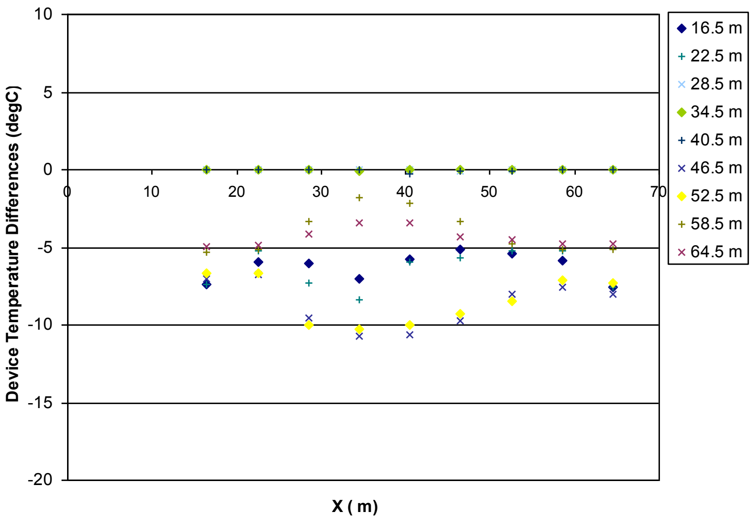
A.4.10 Sensitivity: Peak HRR = 12 MW



(a)



(b)



(c)

Figure 87: Difference in device temperatures (ºC) between the base case and the case with a peak HRR of 12 MW, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

A.4.11 Sensitivity: Wind Speed = 3 m/s

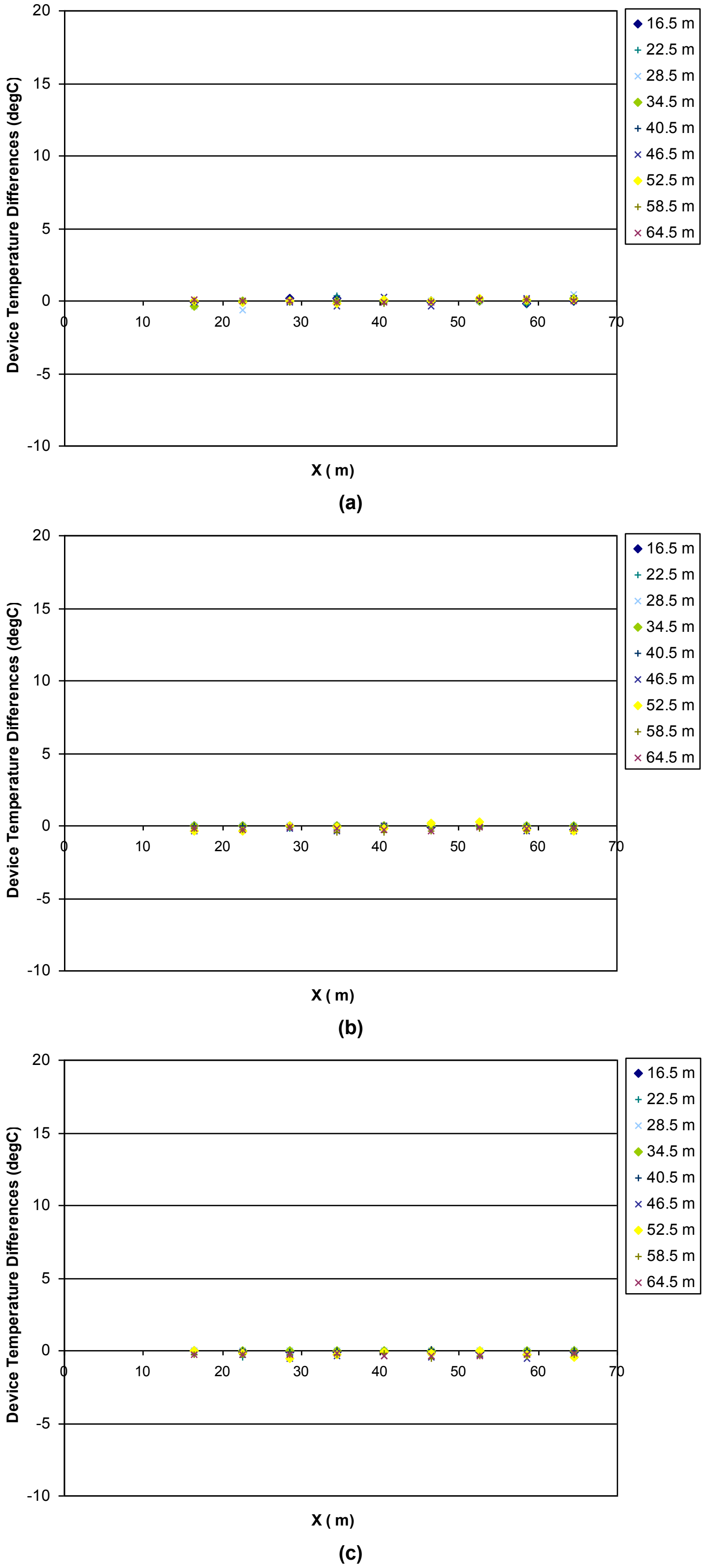
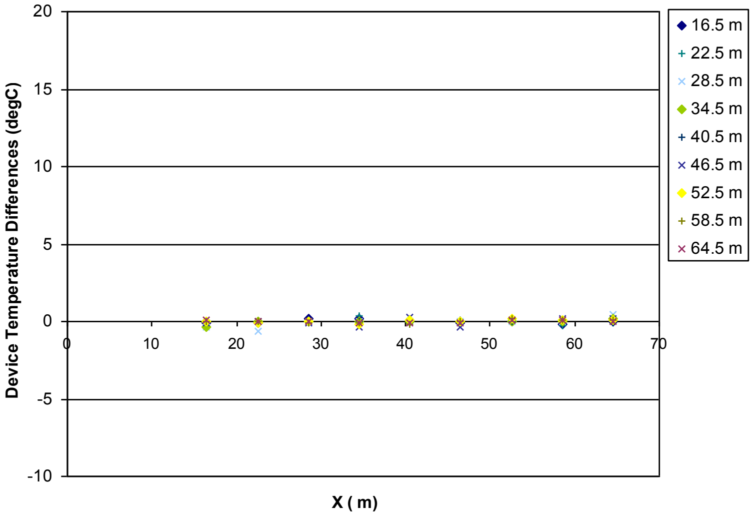
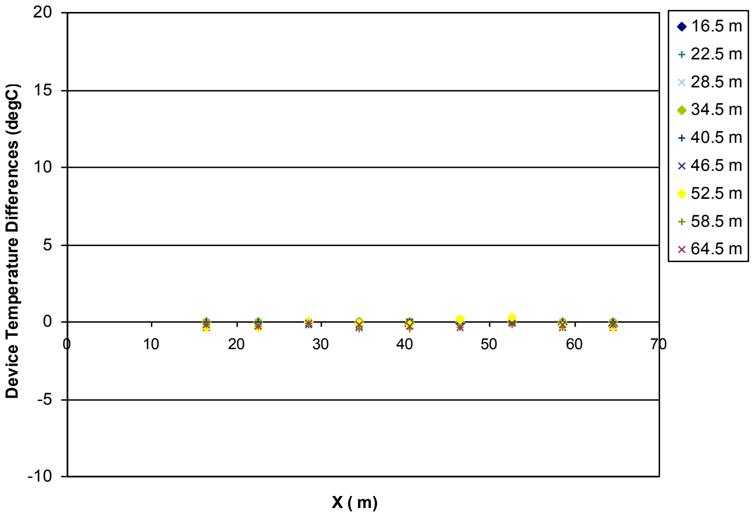


Figure 88: Difference in device temperatures (ºC) between the base case and the case with a wind speed of 3 m/s, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

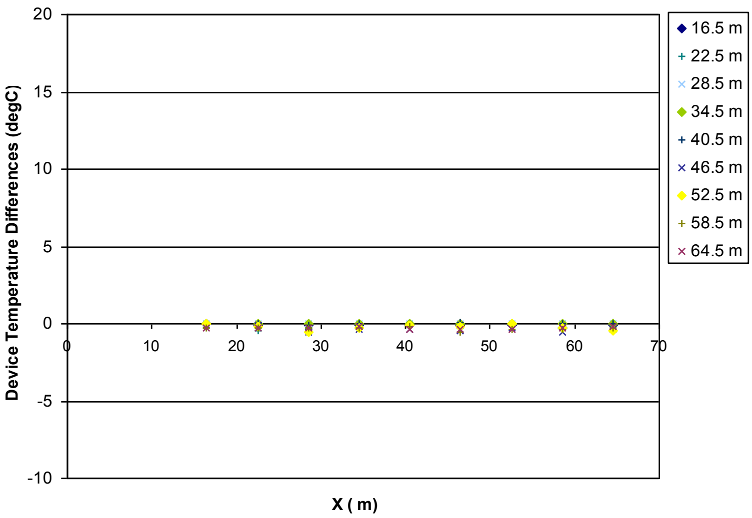
A.4.12 Sensitivity: Wind Speed = 5 m/s



(a)



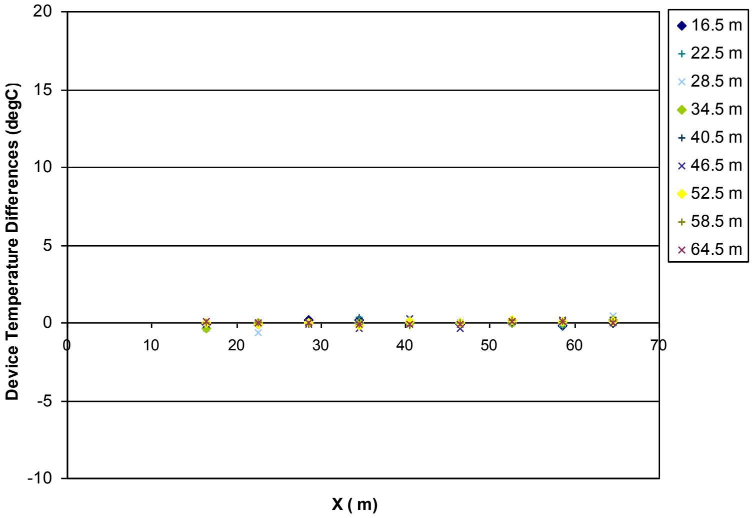
(b)



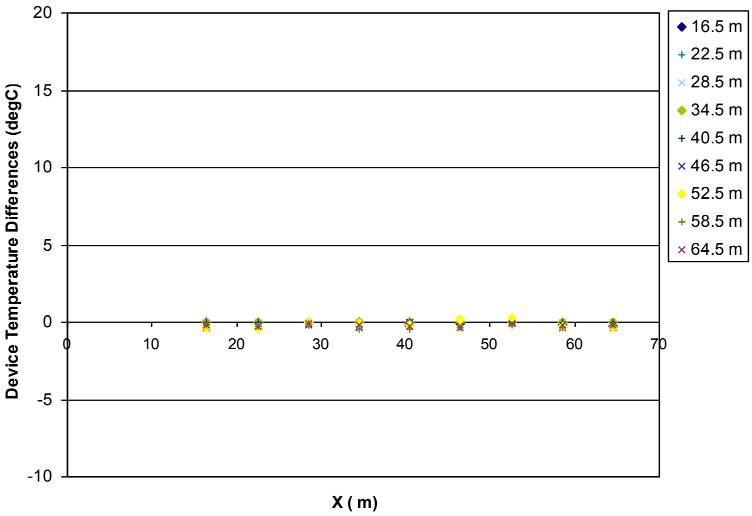
(c)

Figure 89: Differences between device temperatures for base case and wind speed of 5 m/s, at (a) t = 100 s, (b) t = 500 s, (c) t = 1,000 s.

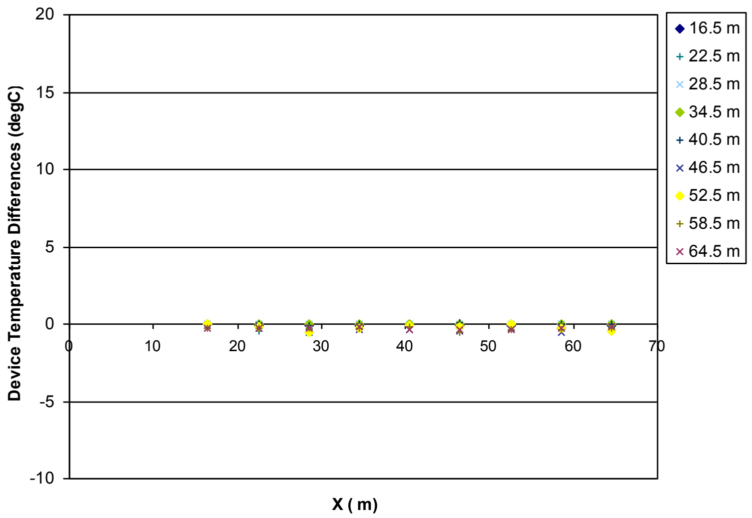
A.4.13 Sensitivity: Wind Speed = 10 m/s



(a)

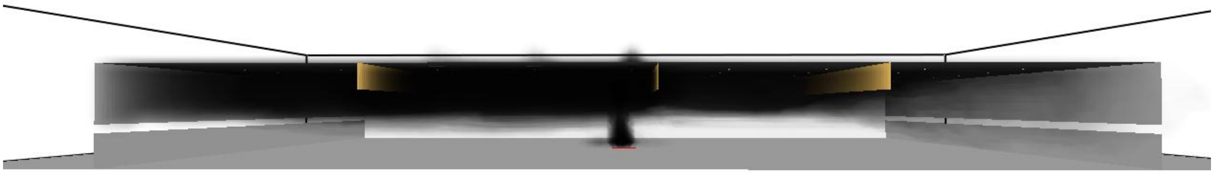


(b)



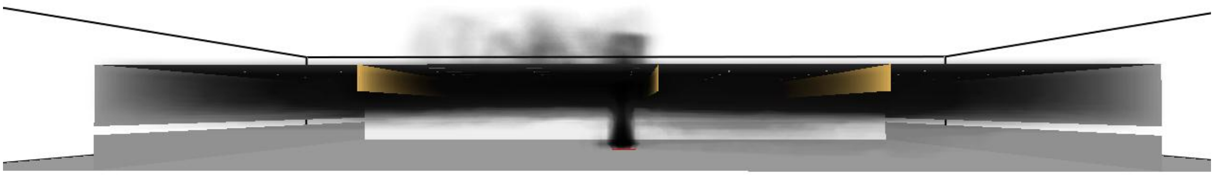
(c)

Figure 90: Difference in device temperatures (ºC) between the base case and the case with a wind speed of 3 m/s, at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.



(a)

(b)

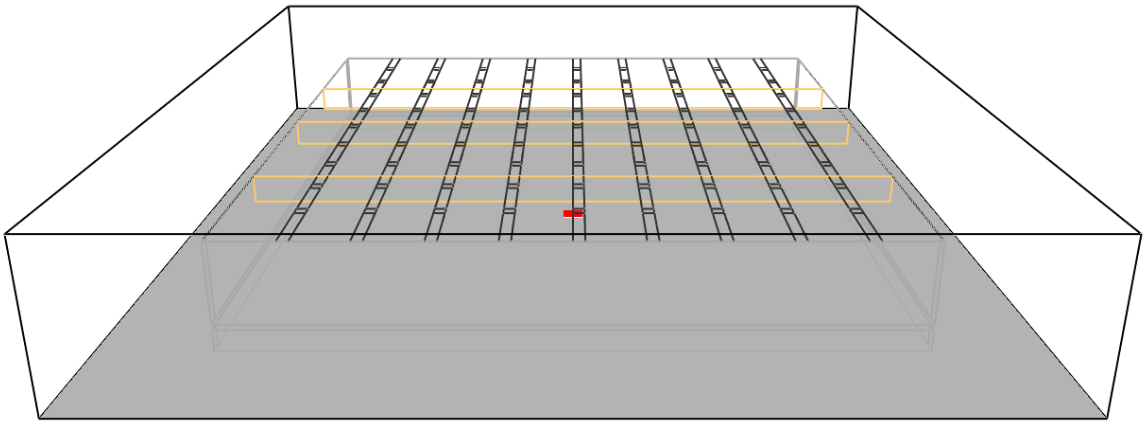


(c)

Figure 91: Visual representation of soot density at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

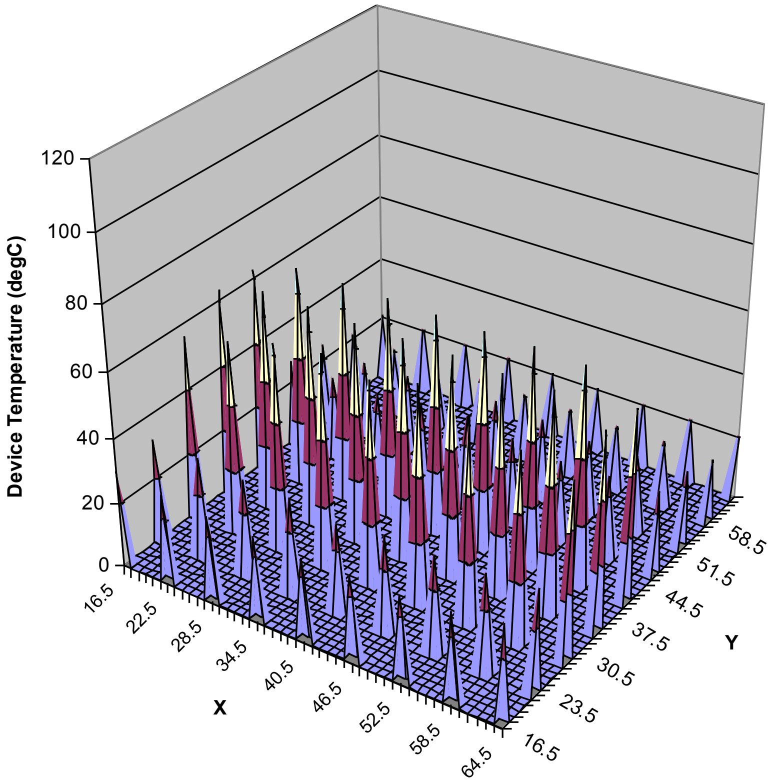
A.4.14 Sensitivity: Compartment Height = 10 m

(a)

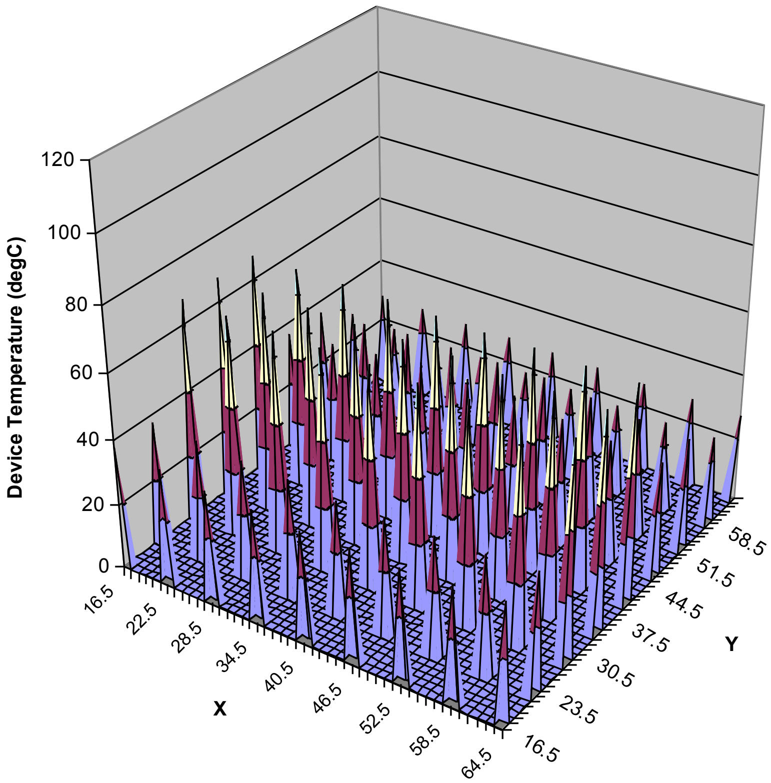


(b)

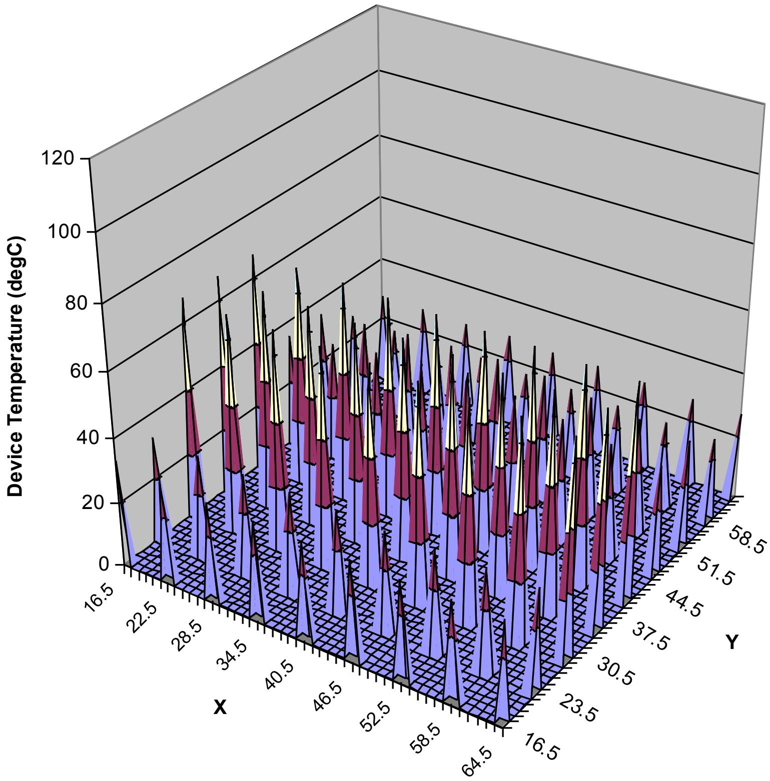
Figure 92: Visual representations of scenario geometry


Device Temperature (degC)
120
100
80
60
40
20
0
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
X
58.5
51.5
44.5
37.5
30.5
23.5
16.5
Y

(a)


Device Temperature (degC)
120
100
80
60
40
20
0
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
X
58.5
51.5
44.5
37.5
30.5
23.5
16.5
Y

(b)



(c)

Figure 93: Device temperatures (ºC), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

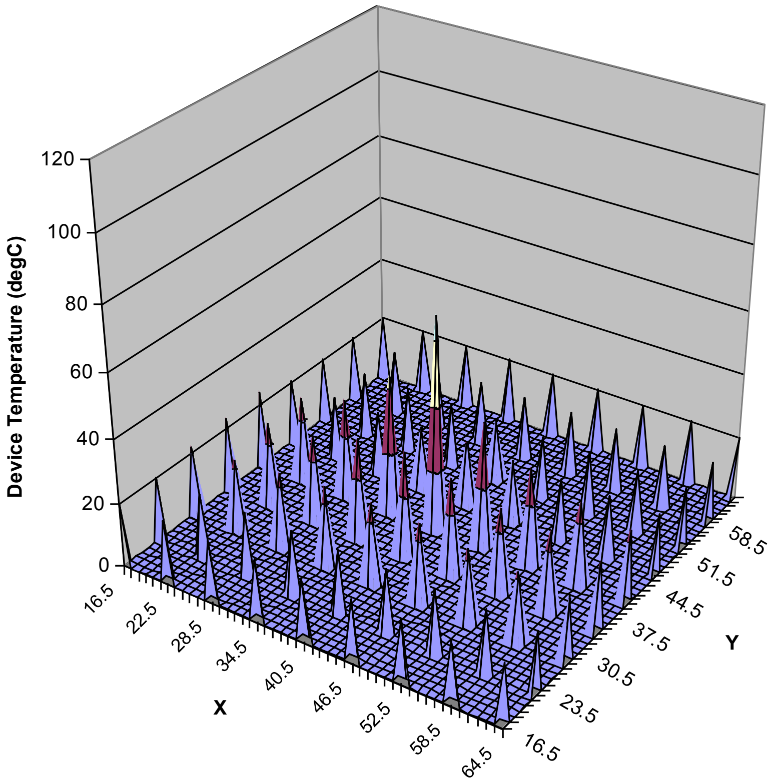
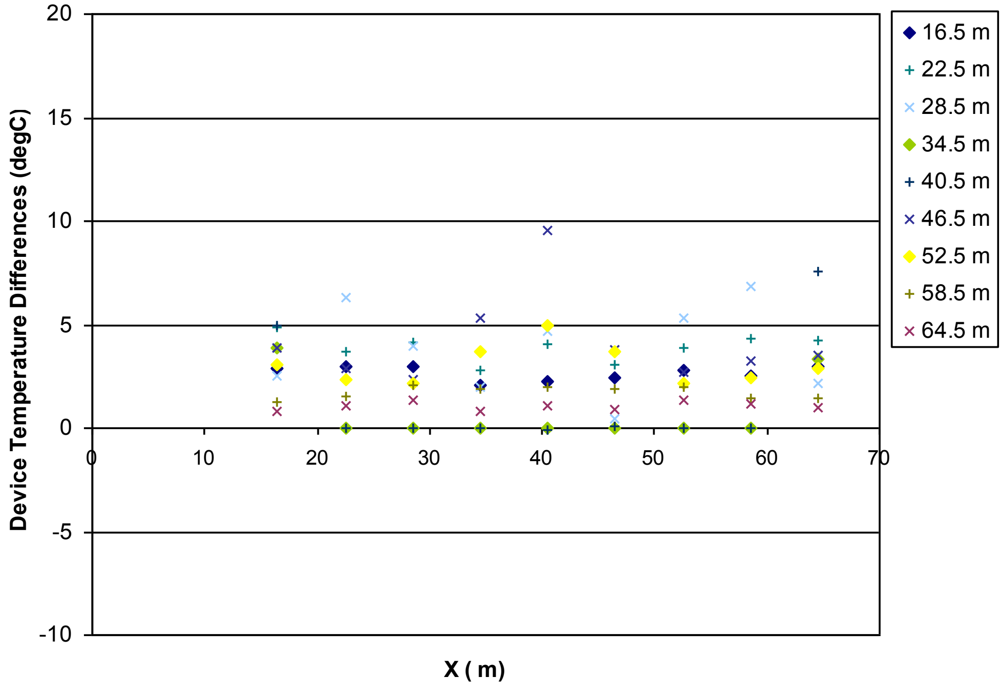
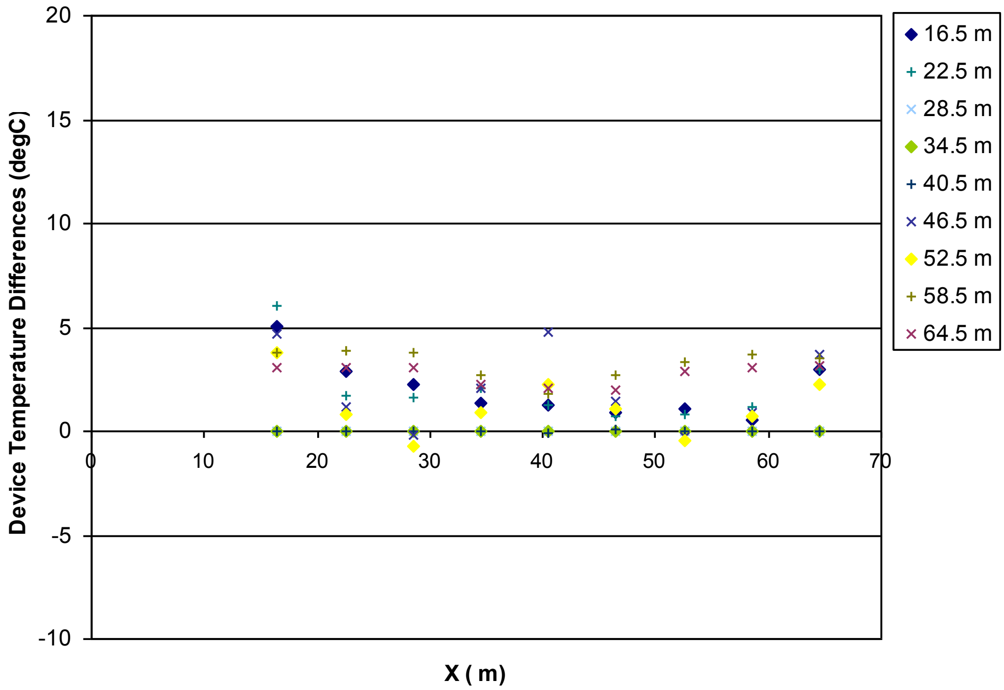


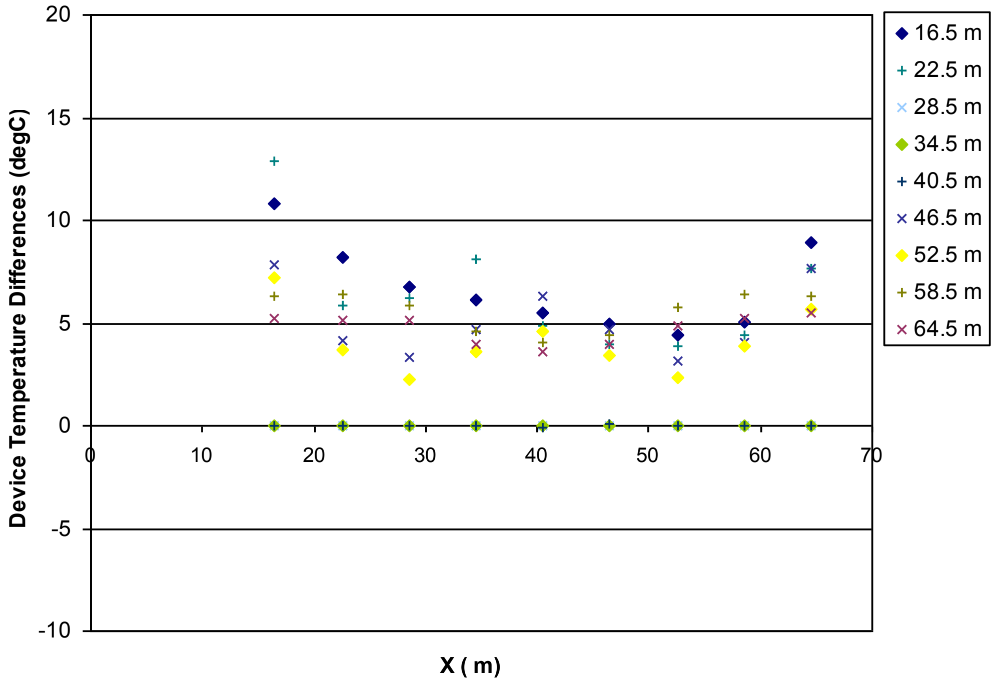
Figure 94: Device temperatures (ºC), at t = 20 s.


Device Temperature Differences (degC)
20
15
10
5
0
-5
-10
0
10
20
30
40
50
60
70
X (m)
16.5 m
22.5 m
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

(a)

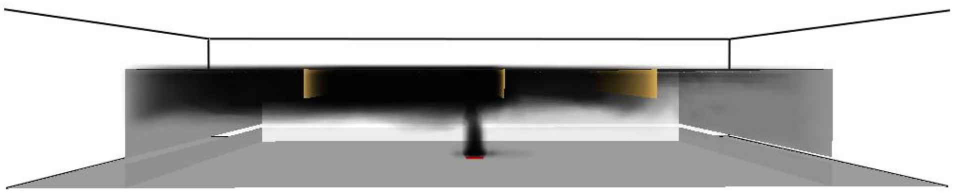

Device Temperature Differences (degC)
20
15
10
5
0
-5
-10
0
10
20
30
40
50
60
70
X (m)
16.5 m
22.5 m
28.5 m
34.5 m
40.5 m
46.5 m
52.5 m
58.5 m
64.5 m

(b)

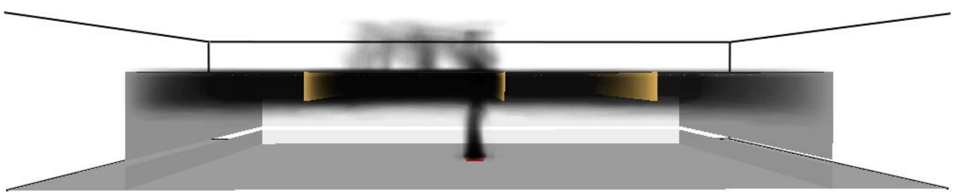


(c)

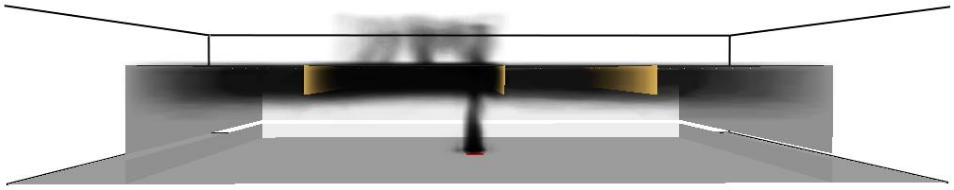
Figure 95: Device temperature differences (ºC) between the base case and 10 m compartment height at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.



(a)



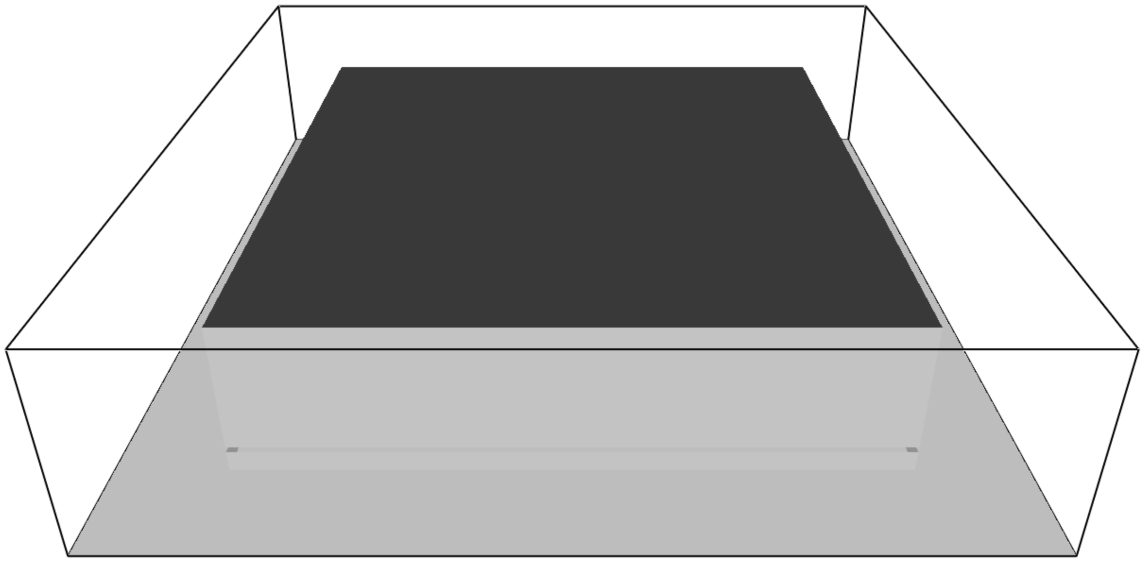
(b)



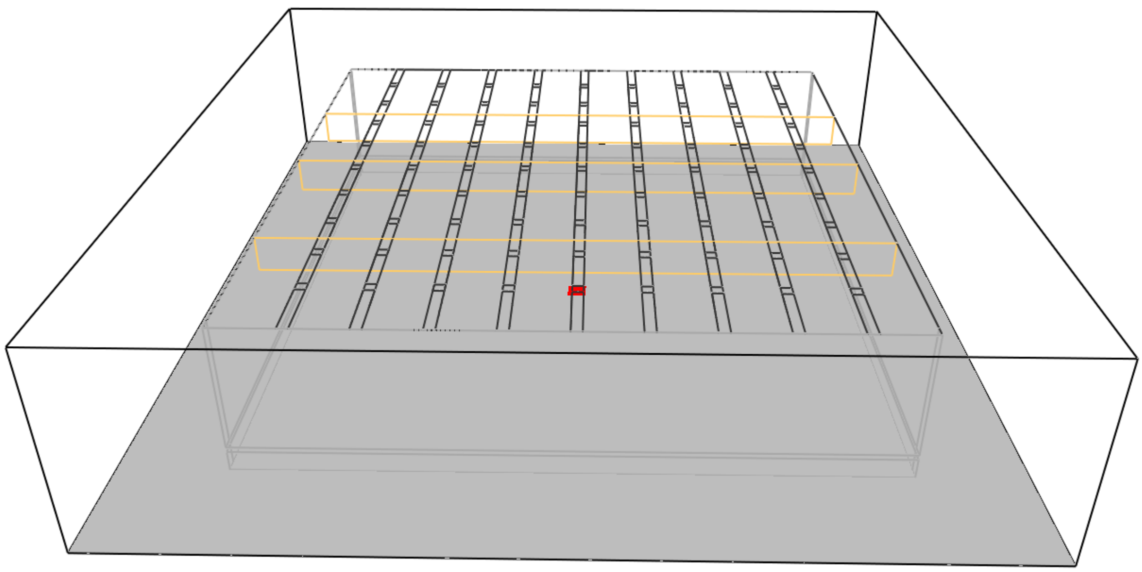
(c)

Figure 96: Visual representation of soot density at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000s.

A.4.15 Sensitivity: Compartment Height = 15 m

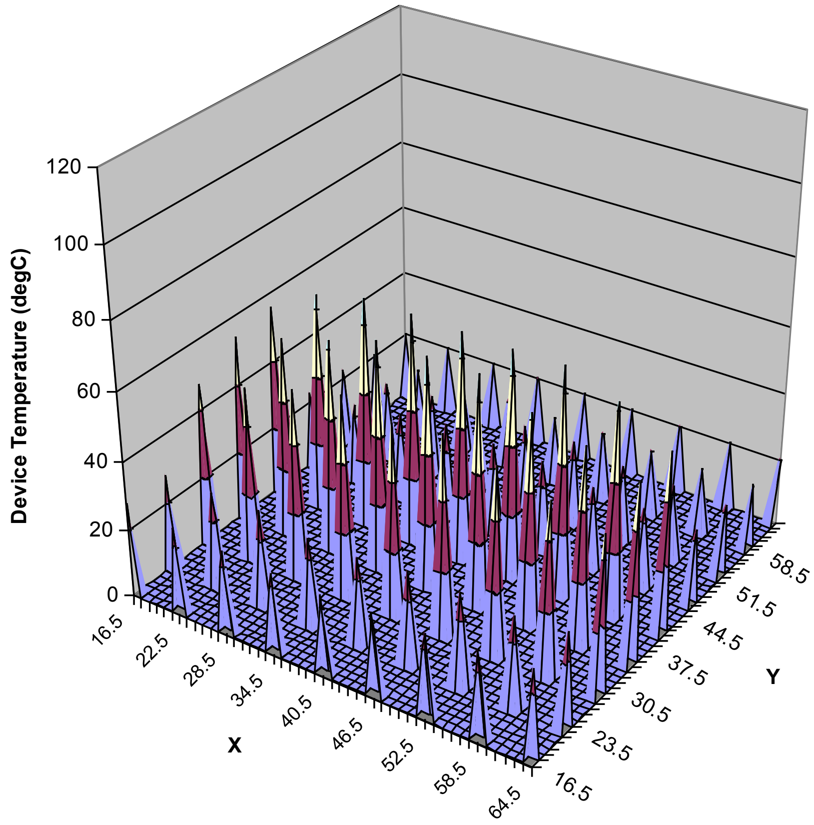


(a)

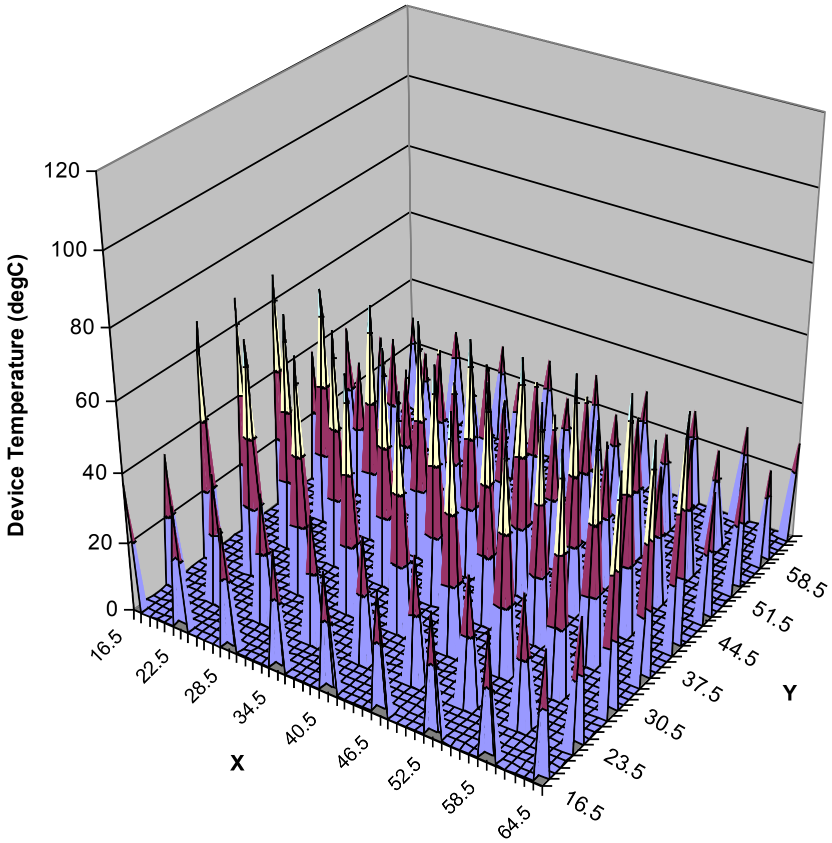


(b)

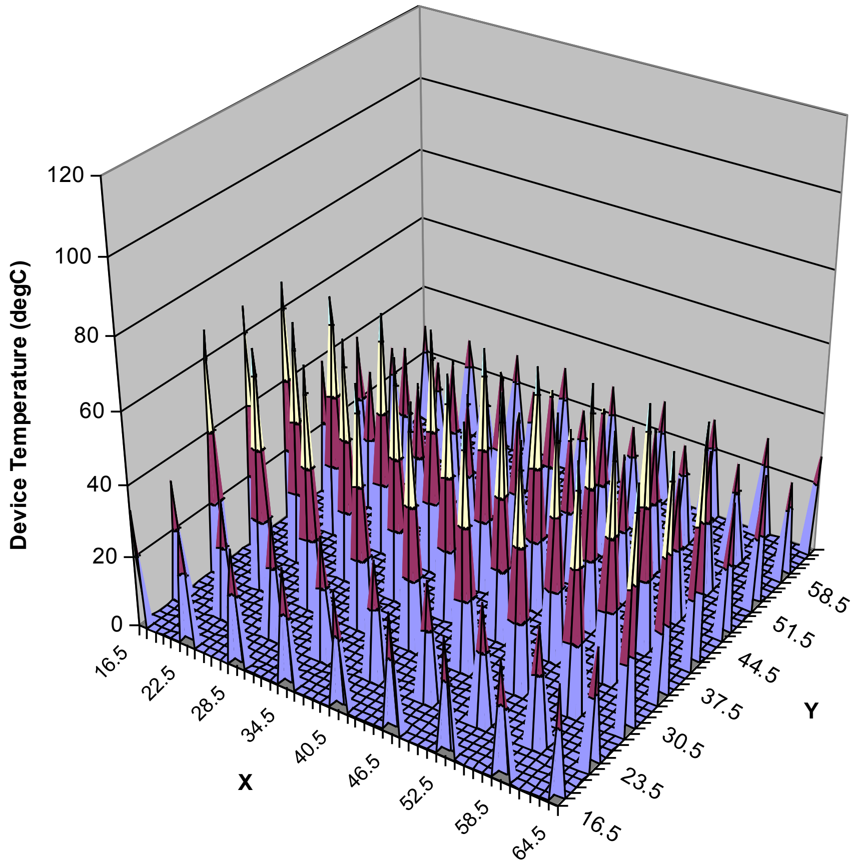
Figure 97: Visual representation of scenario geometry.


Device Temperature (degC)
120
100
80
60
40
20
0
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
X
16.5
23.5
30.5
37.5
44.5
51.5
58.5
Y

(a)


Device Temperature (degC)
120
100
80
60
40
20
0
16.5
22.5
28.5
34.5
40.5
46.5
52.5
58.5
64.5
X
16.5
23.5
30.5
37.5
44.5
51.5
58.5
Y

(b)



(c)

Figure 98: Device temperatures (ºC), at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000s

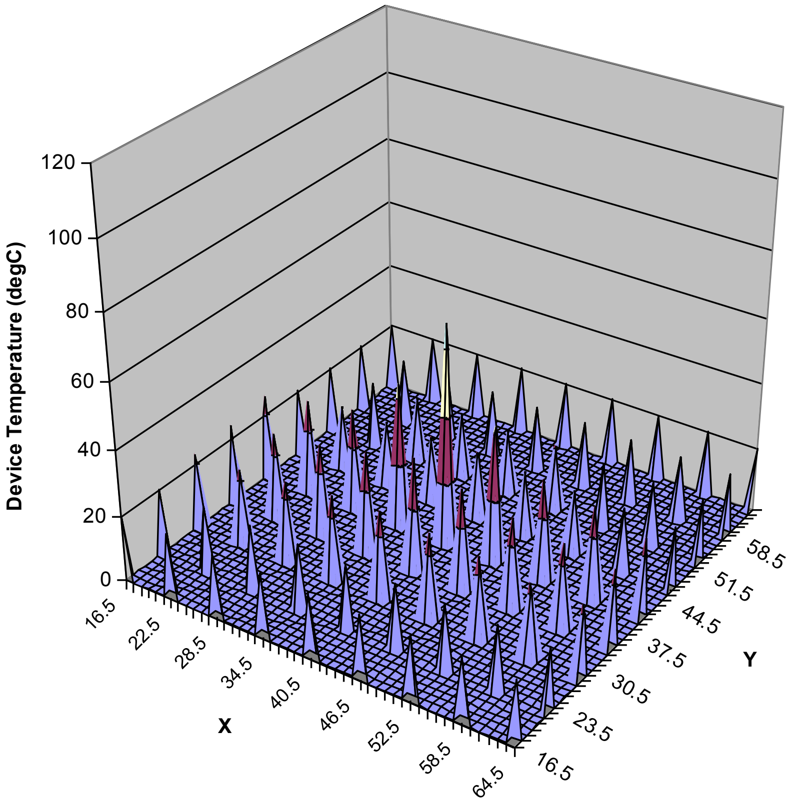
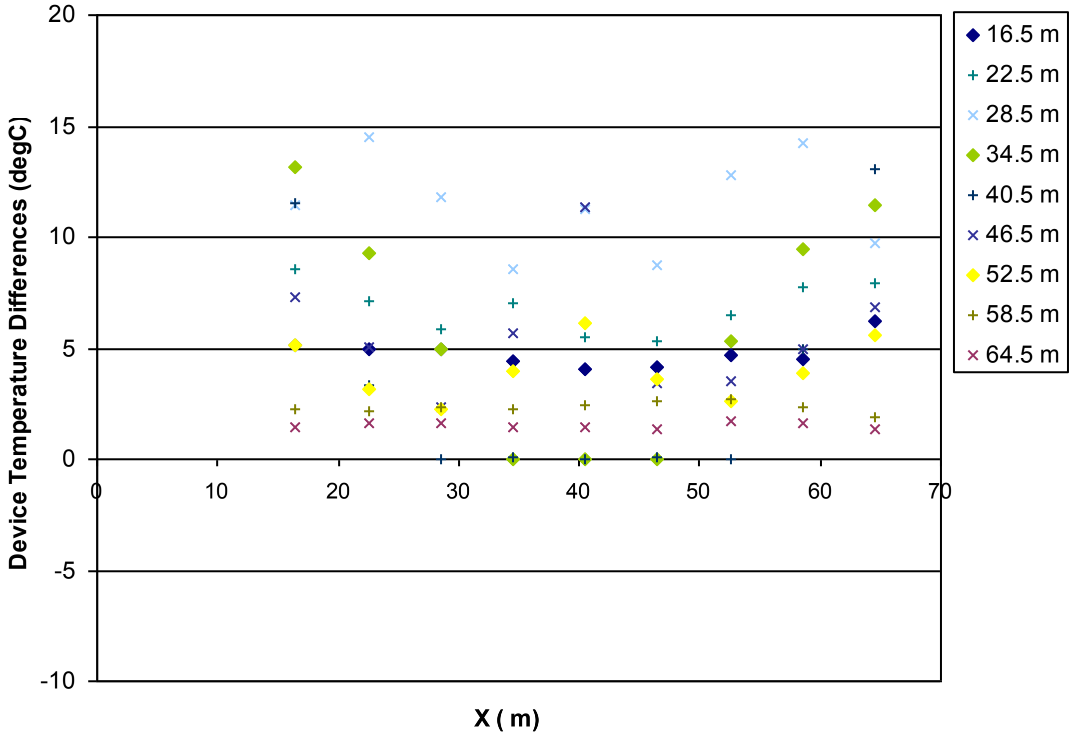
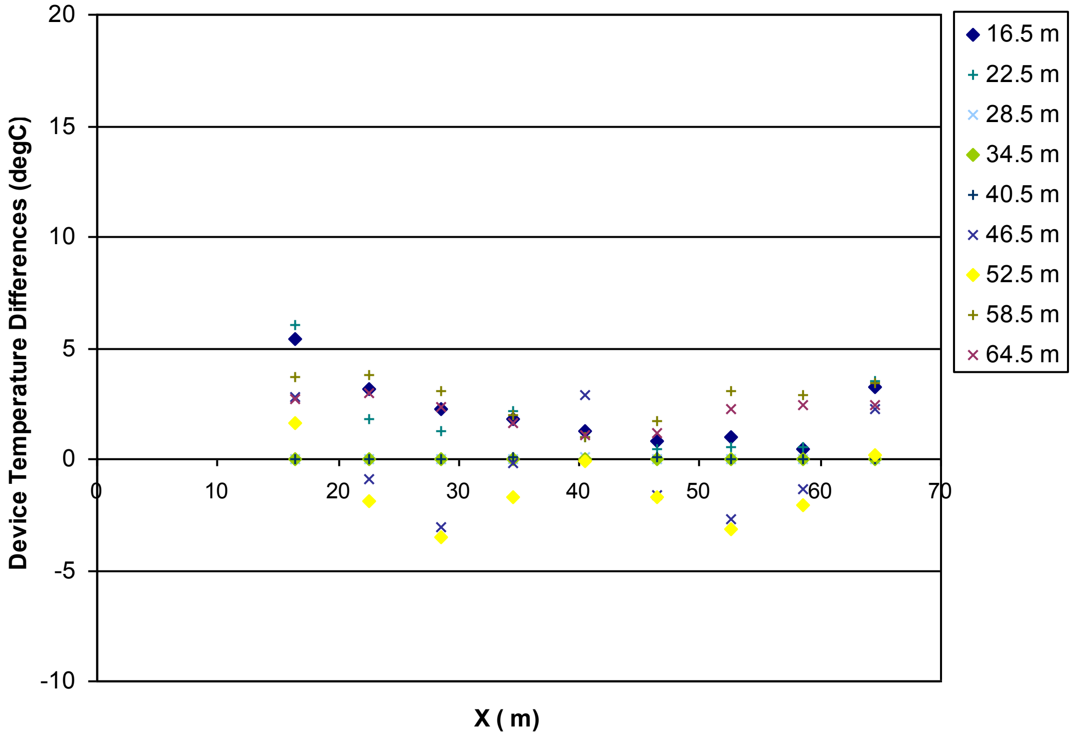


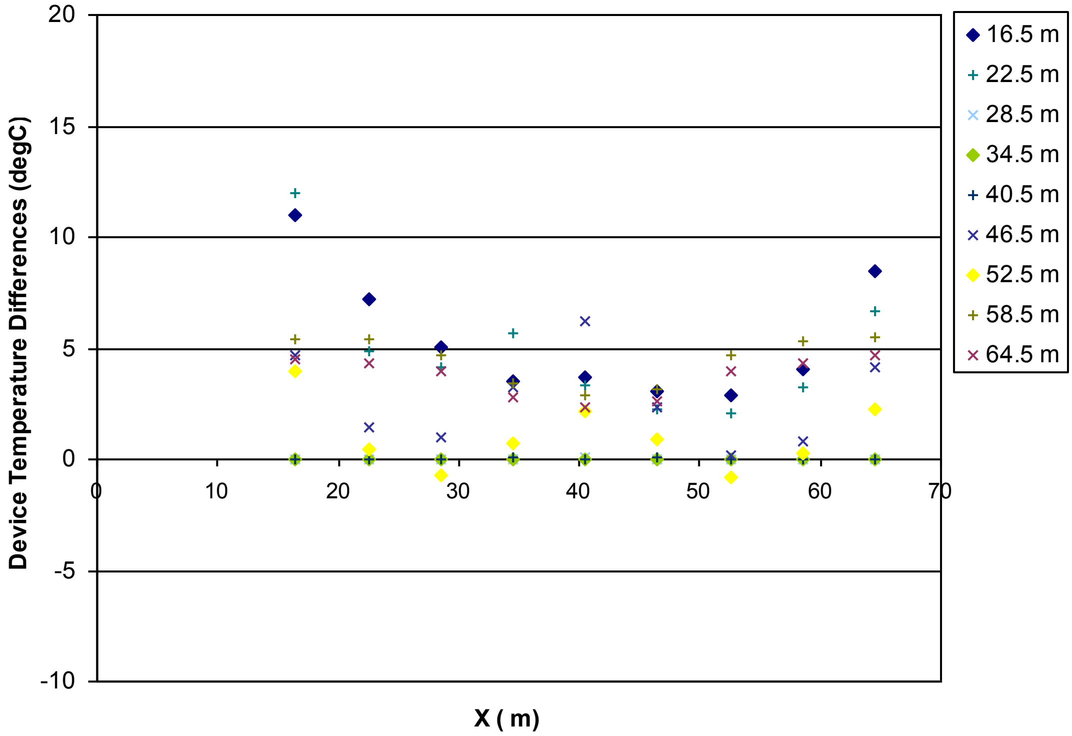
Figure 99: Device temperatures (ºC), at t = 25s



(a)

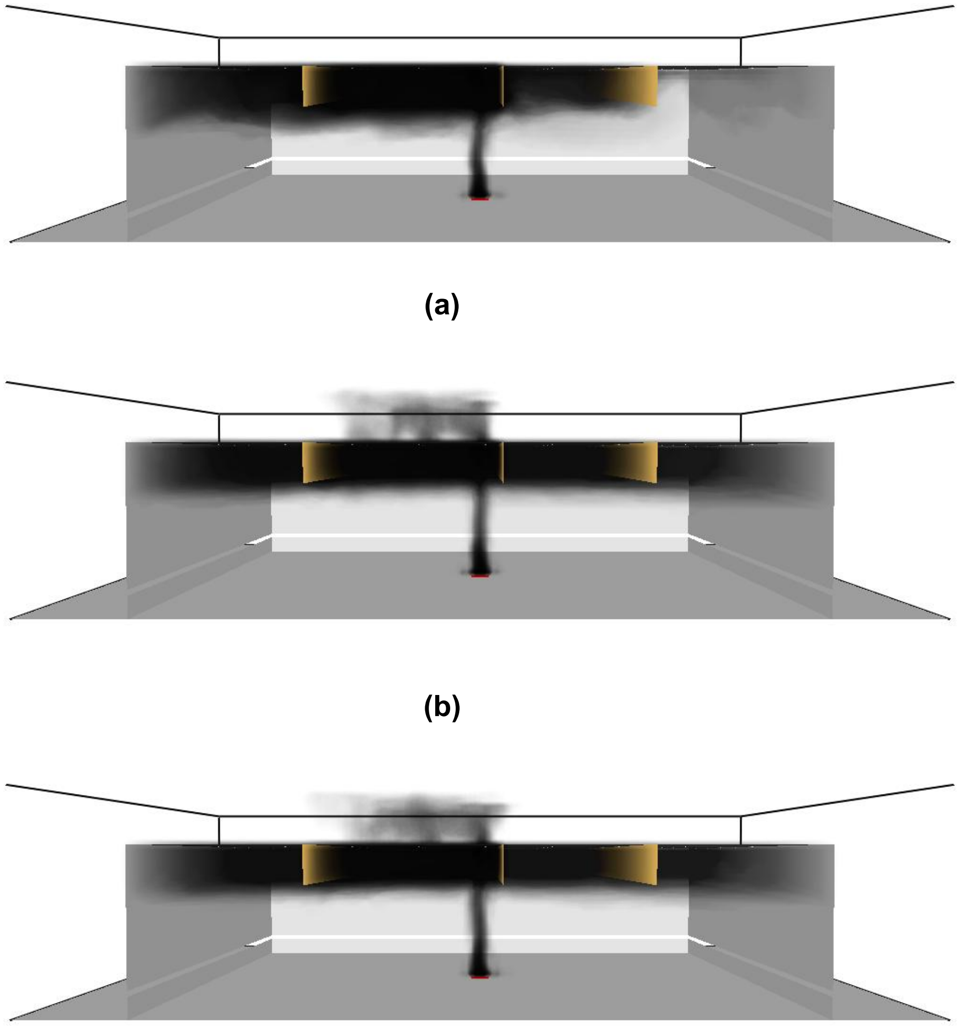


(b)



(c)

Figure 100: Difference between base case and 15 m compartment height device temperatures at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.



(a)

(b)

(c)

Figure 101: Visual representation of soot density at (a) t = 100 s, (b) t = 500 s, and (c) t = 1,000 s.

A.4.16 Sensitivity: Summary

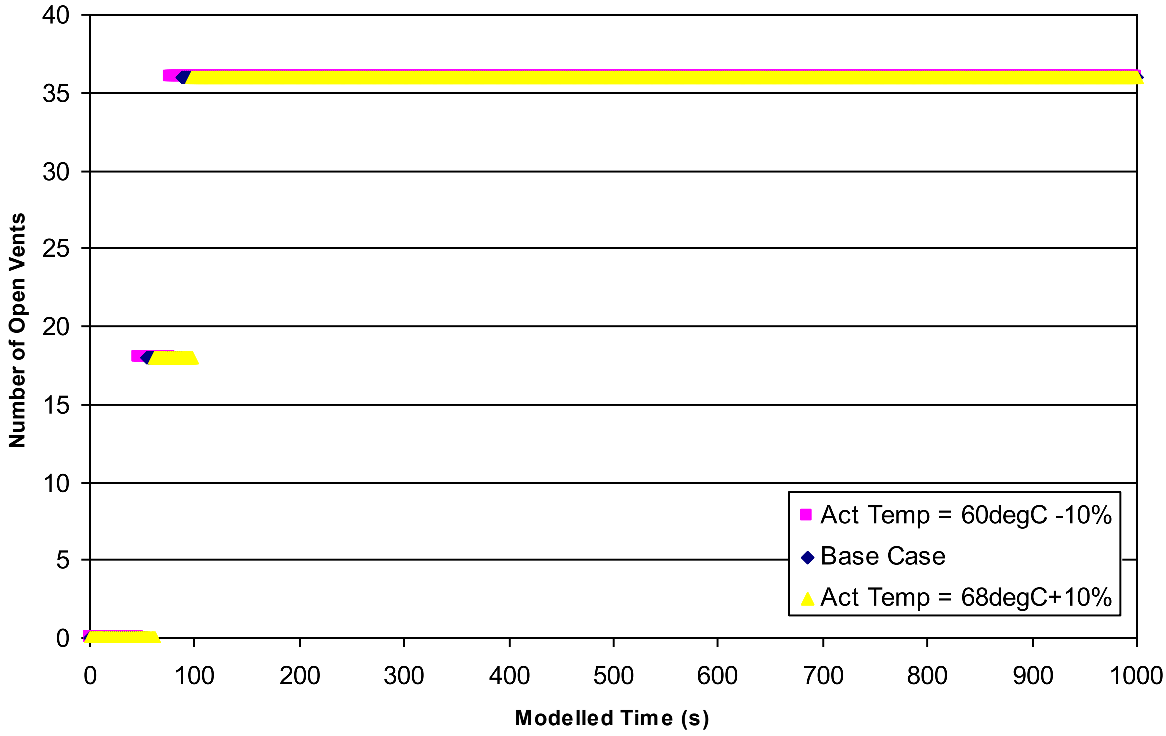


Figure 102: Number of open vents for various effective activation temperatures.

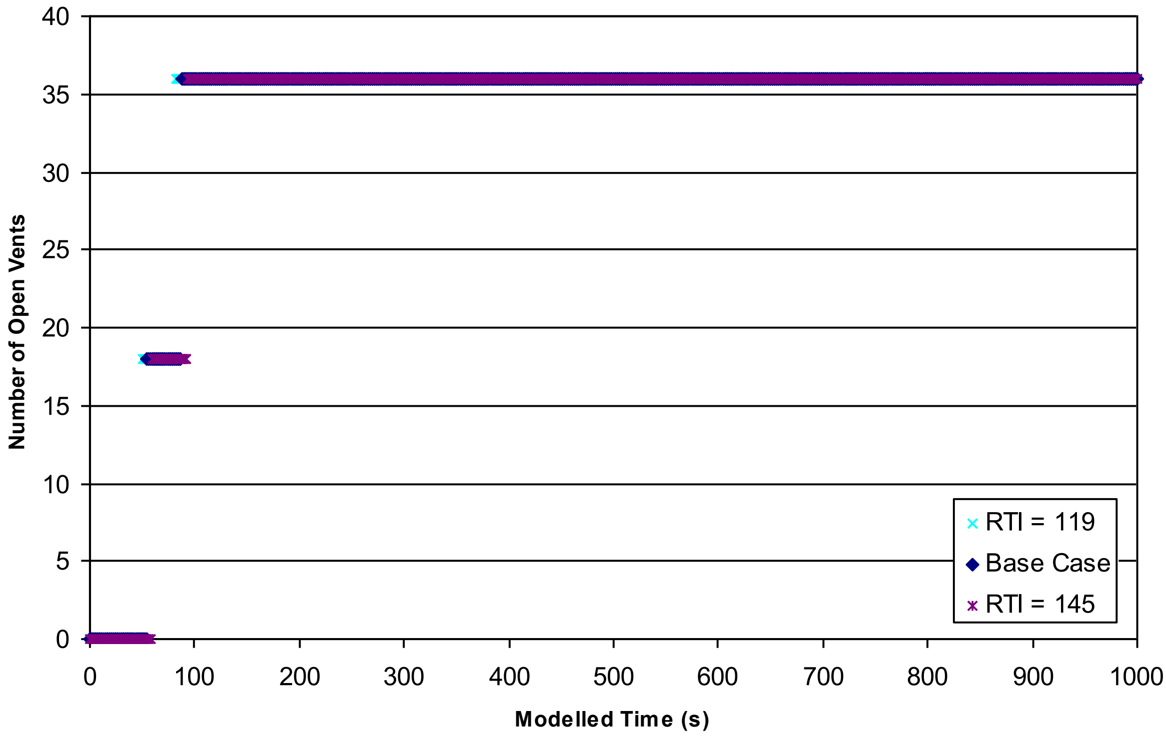


Figure 103: Number of open vents for various effective RTI values.

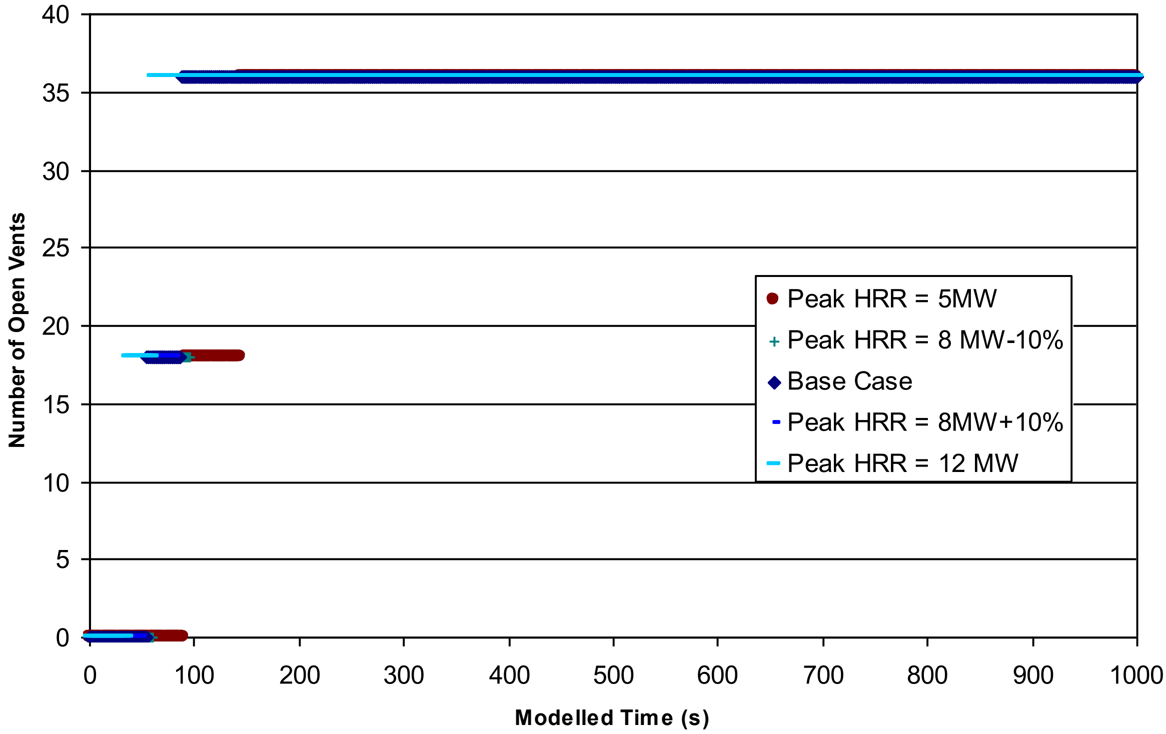


Figure 104: Number of open vents for various peak heat release rates.

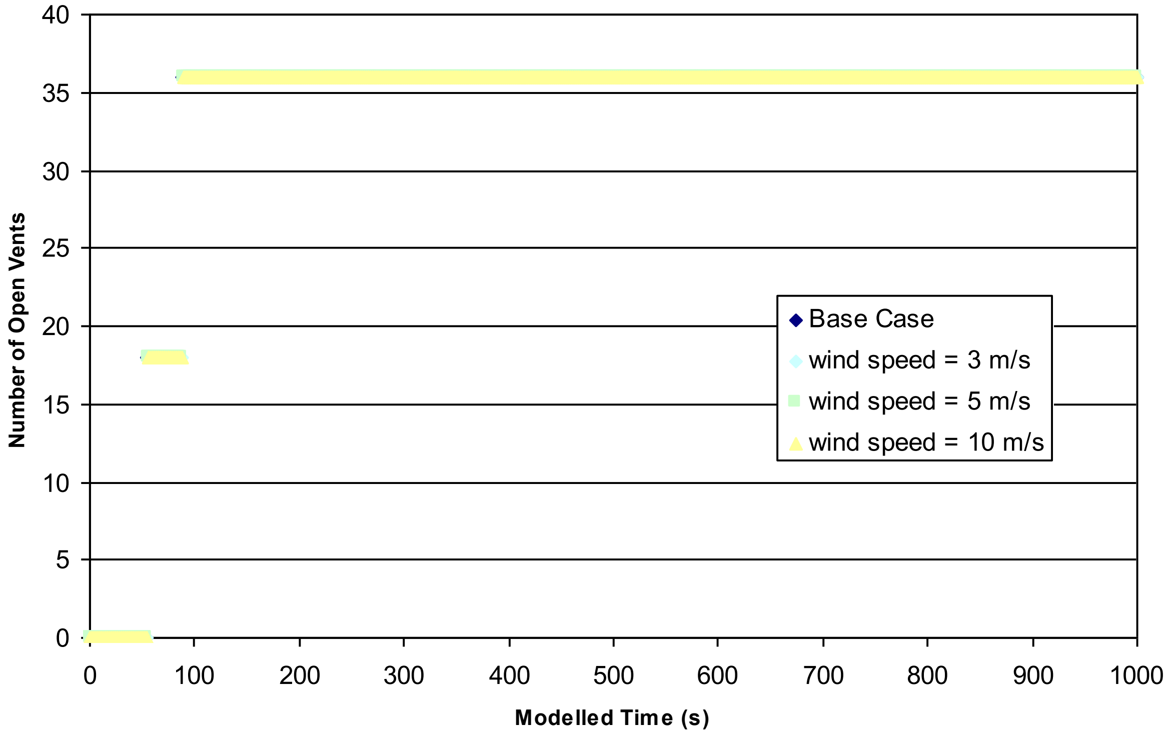


Figure 105: Number of open vents for various wind speeds.

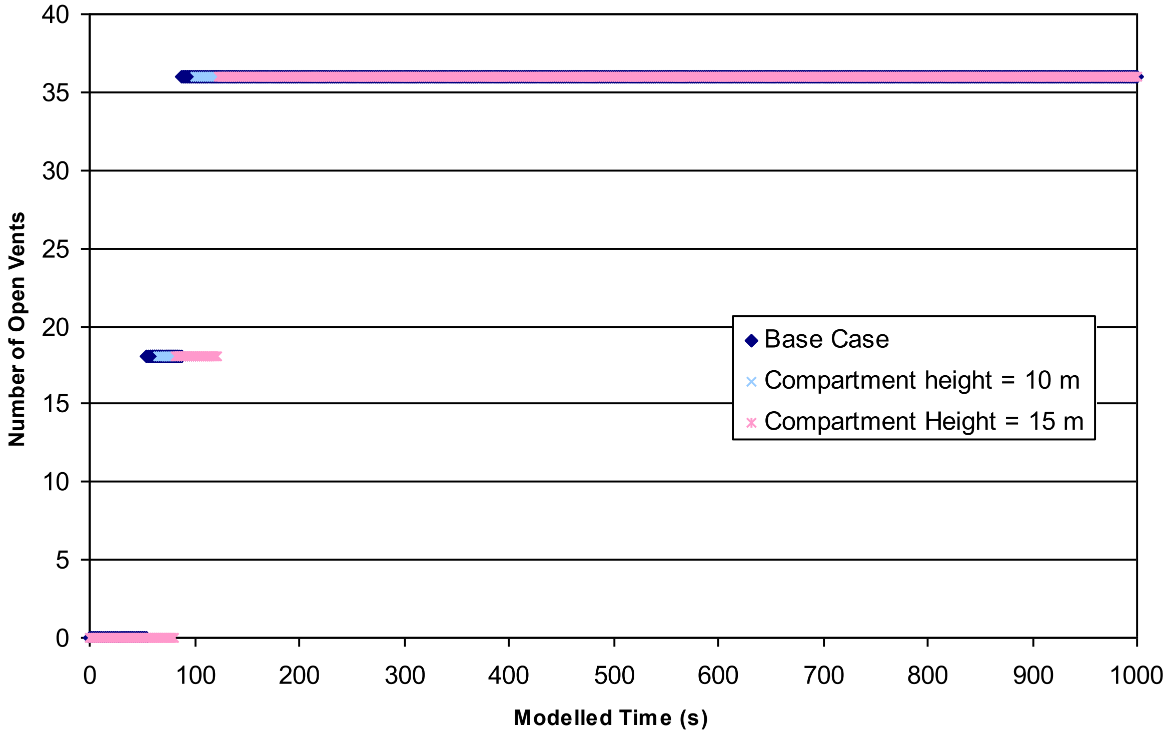


Figure 106: Number of open vents for various compartment heights.

A.5 Comparison of Scenario Results

Table 10: Comparison of the base case scenario results for the generic warehouse.

Description of Parameters for Comparison	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Time to first vent opens (s)	N/A	~30 s	~ 30 s	~16 s
Radius (m) where radiant intensity exceeds 4.5 kW/m² at t = 1,000 s	~13 m	~11 m	~10 m	~11 m
Time (s) when visibility is less than 20 m	~410 s	N/A [a]	N/A [a]	N/A [a]
Time (s) when visibility is less than 15 m	~560 s	N/A [a]	N/A [a]	N/A [a]

Note:
[a] Model results for visibility did not fall below 20 m.

APPENDIX.B SECTIONED GENERIC WAREHOUSE MODELLING RESULTS - FDS

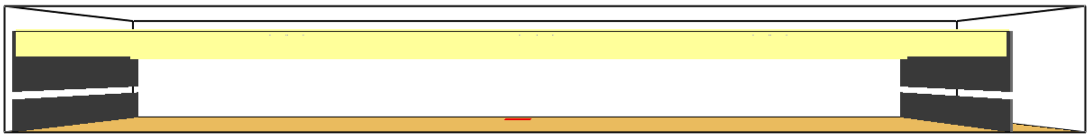
The appropriateness of investigating fire venting in large warehouses using a section of the warehouse (e.g. a section contained by a smoke reservoir) was considered.

B.1 Scenario 1: Single Smoke Reservoir and No Fire Venting

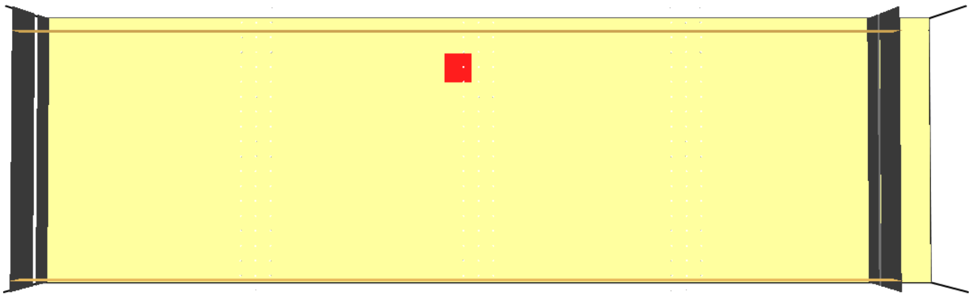
This method was not considered appropriate for the scenarios where no smoke reservoirs were present.

B.1.1 Scenario 1b: Four Smoke Reservoirs and no Fire Venting

Scenario 1 was modified so that the modelled section including one smoke reservoir was considered. This provides a base case for comparison with other scenarios.

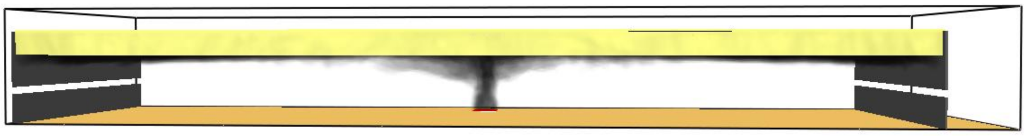


(a)

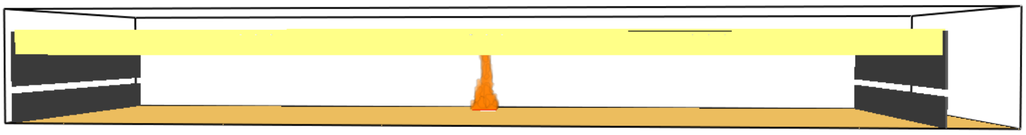


(b)

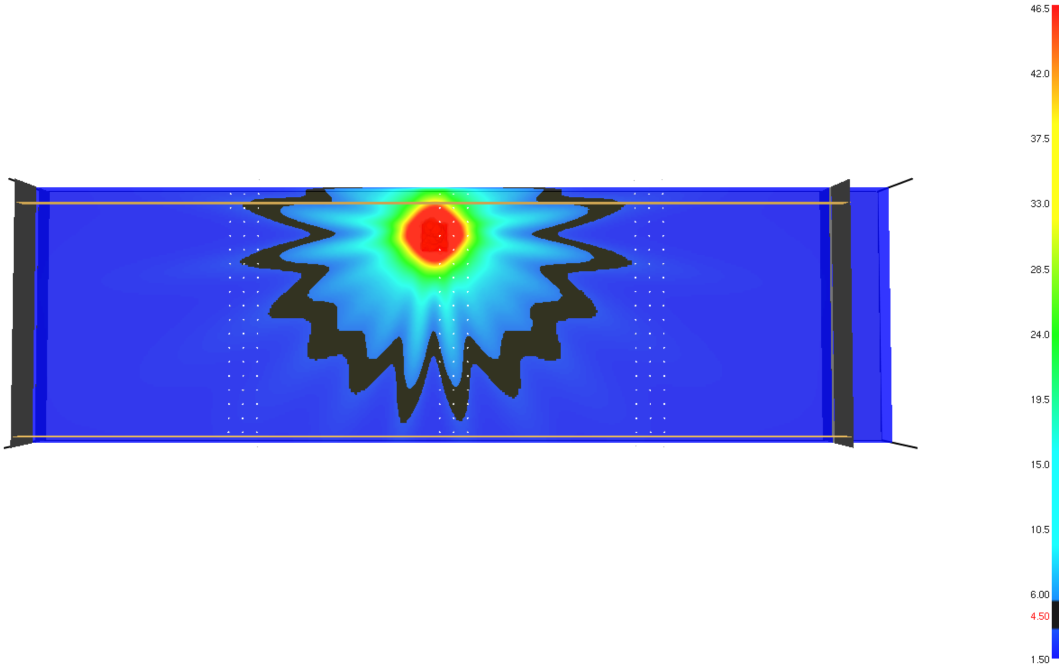
Figure 107: Schematics of the section of warehouse modelled.



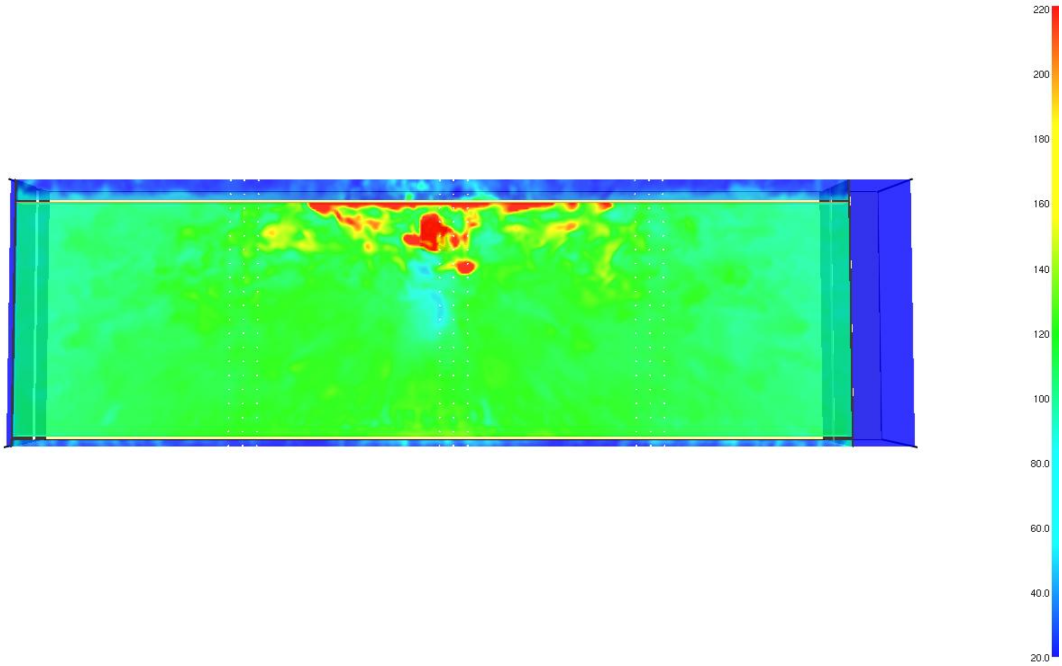
(a)



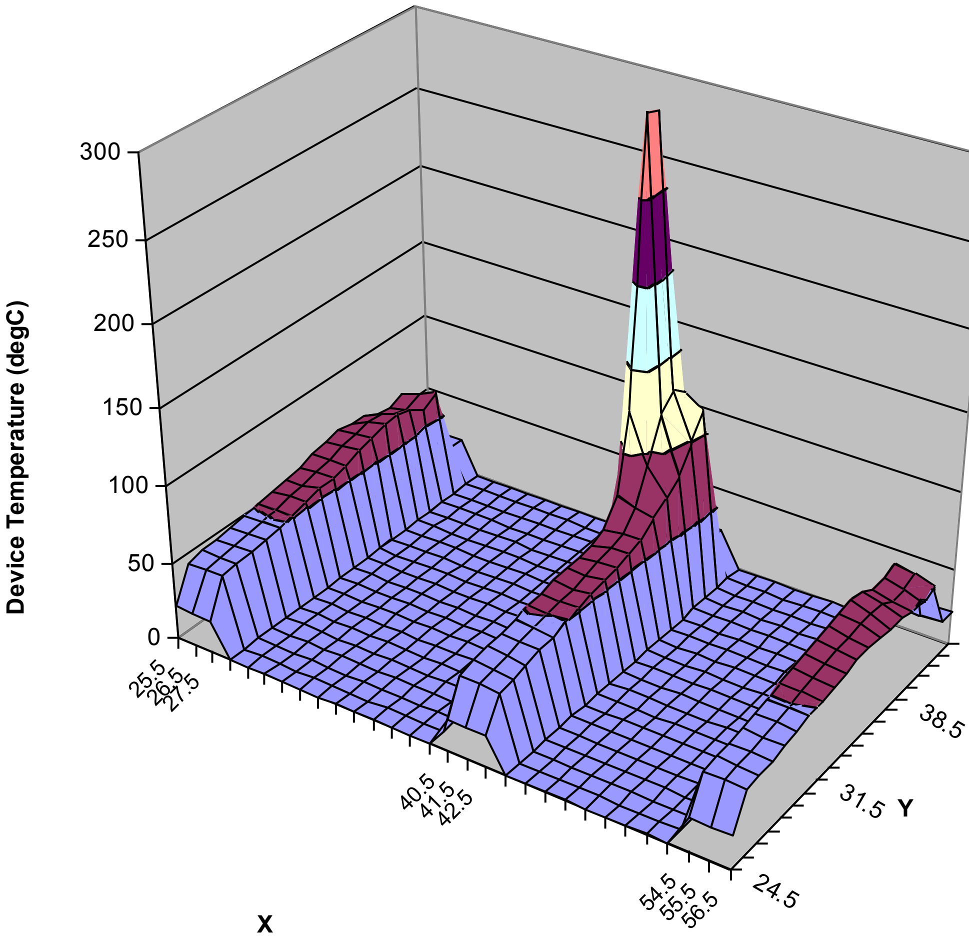
(b)


46.5
42.0
37.5
33.0
28.5
24.0
19.5
15.0
10.5
6.00
4.50
1.50

(c)

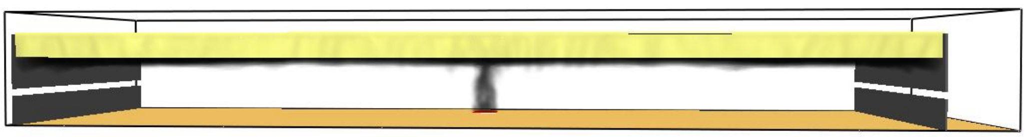

220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

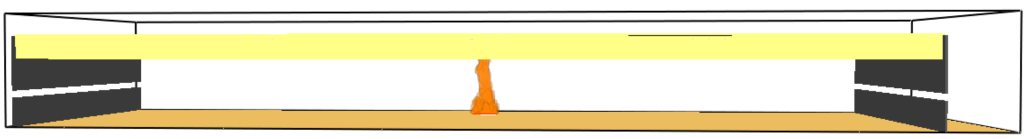


(e)

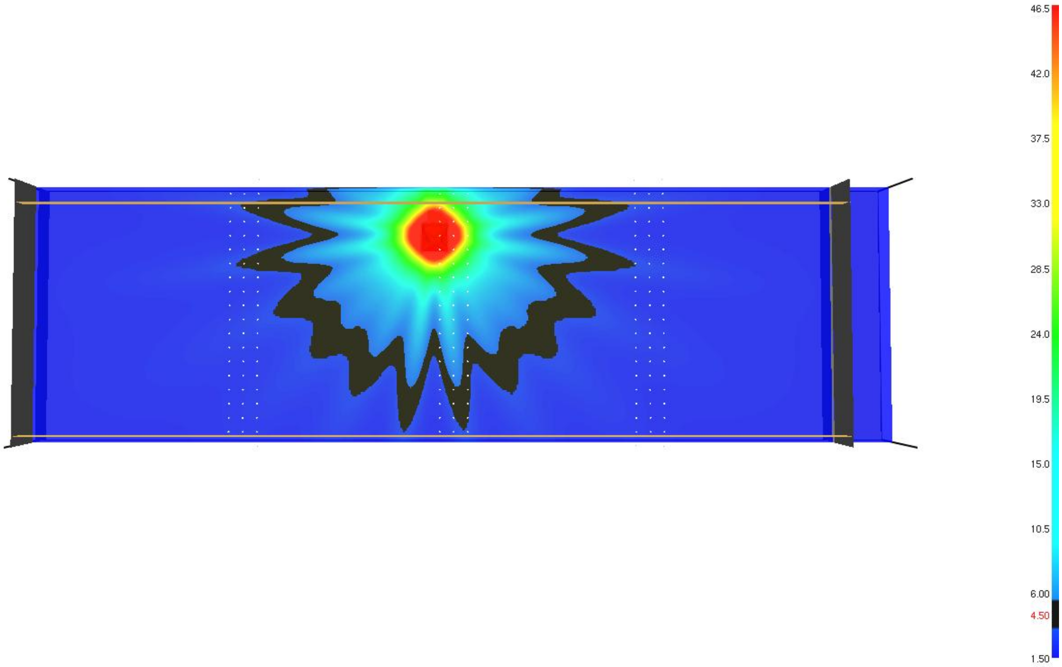
Figure 108: At t = 50 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (f) device temperatures (°C).



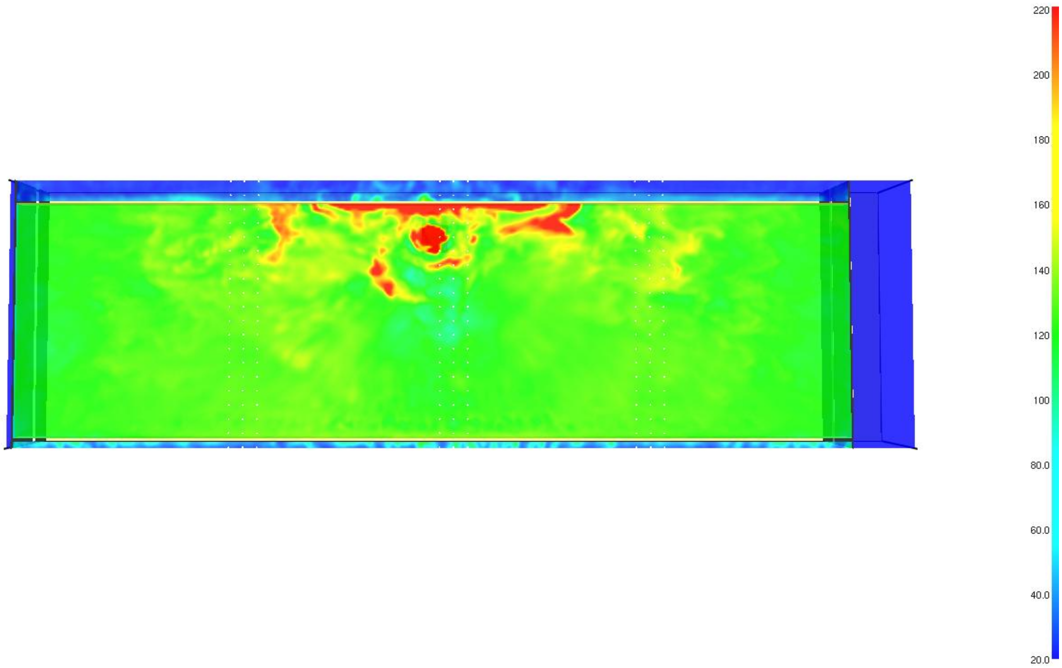
(a)



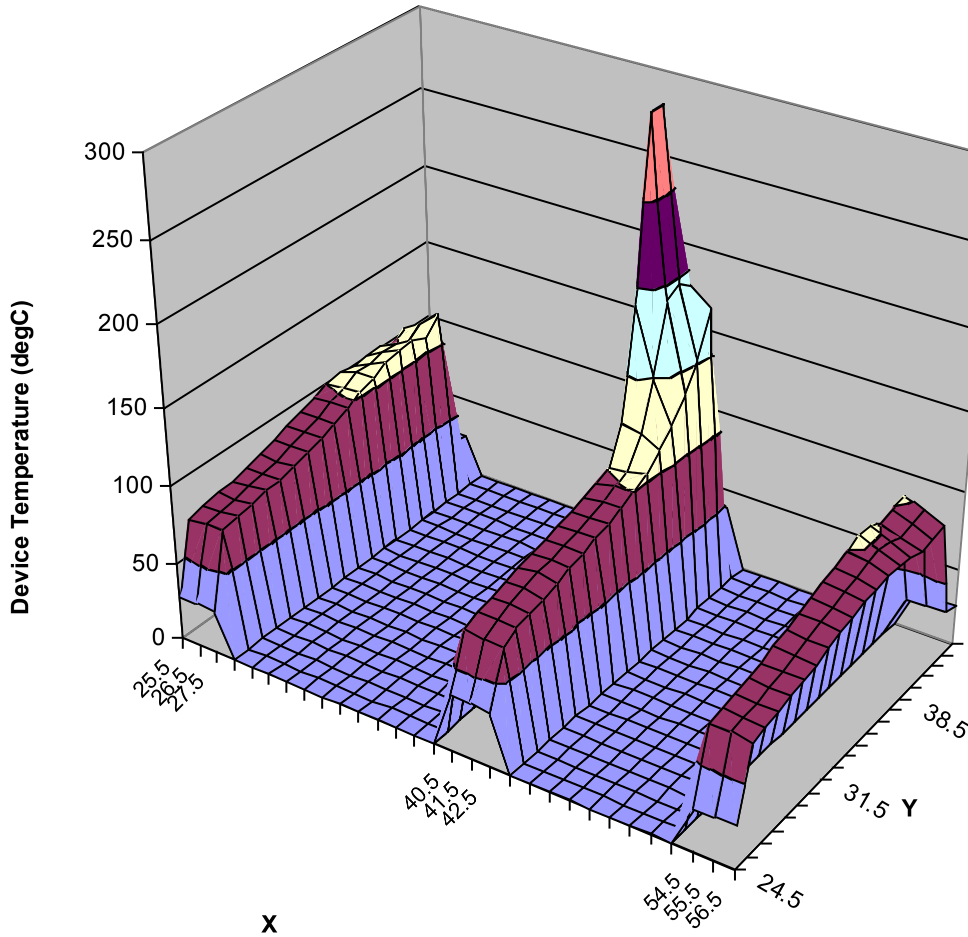
(b)


46.5
42.0
37.5
33.0
28.5
24.0
19.5
15.0
10.5
6.00
4.50
1.50

(c)

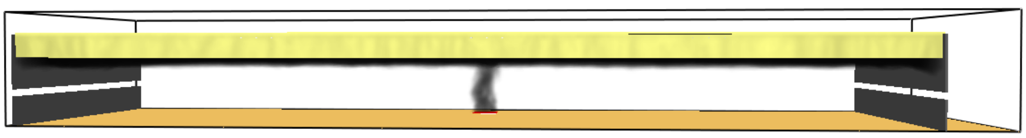

220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

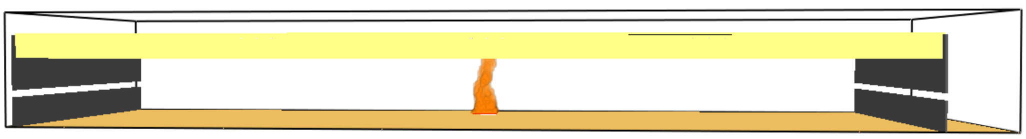


(e)

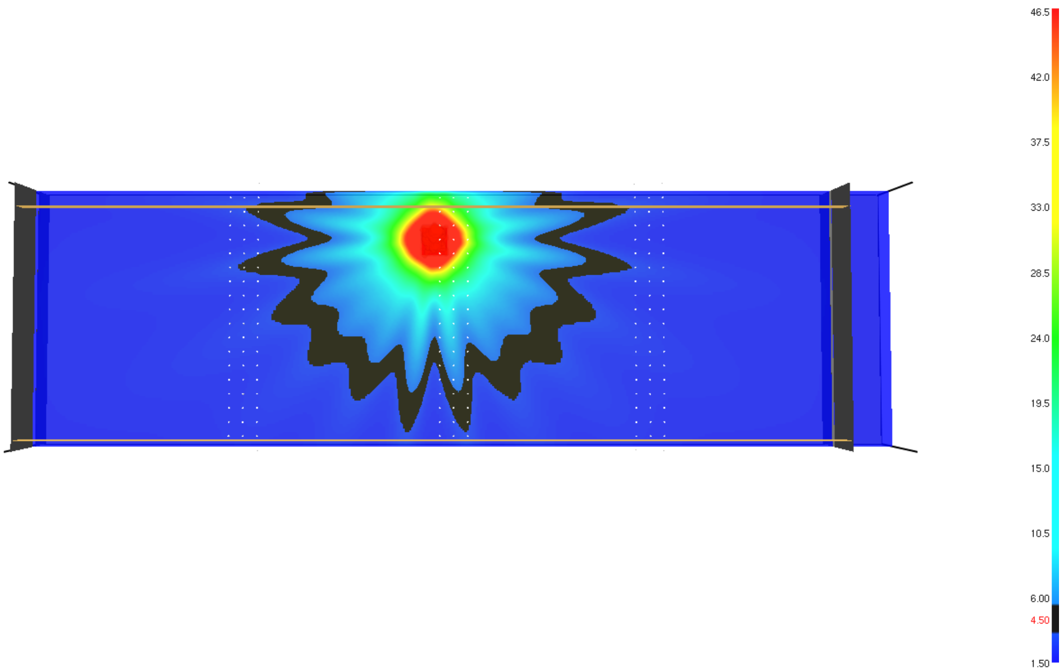
Figure 109: At t = 100 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



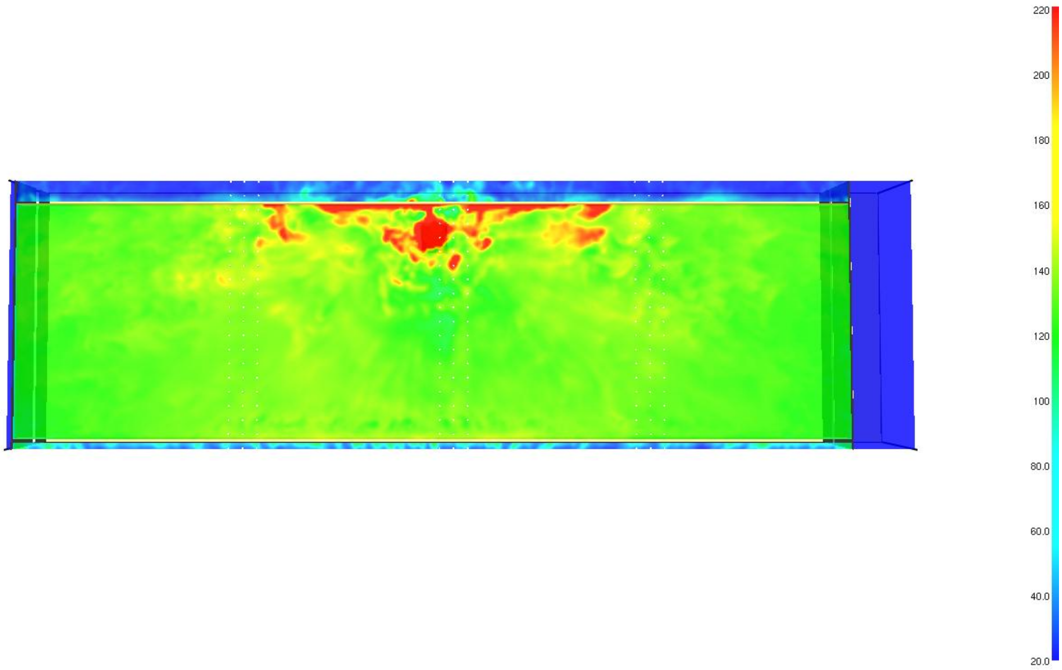
(a)



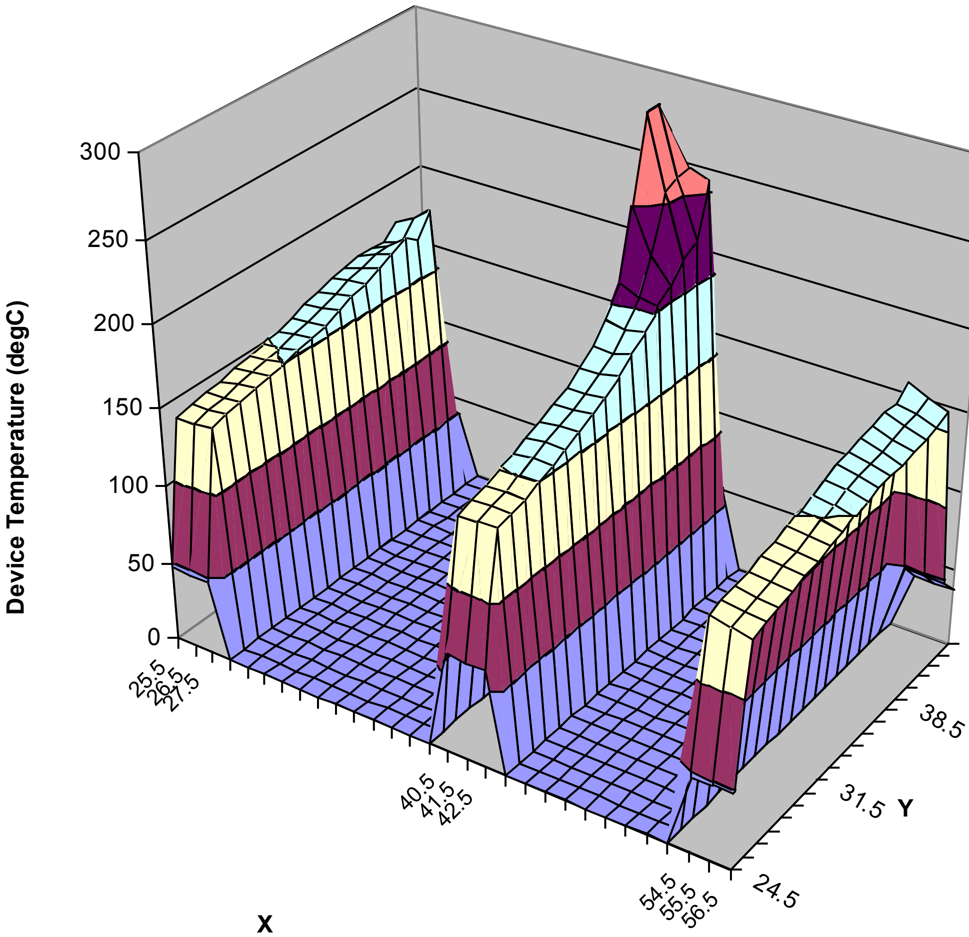
(b)


46.5
42.0
37.5
33.0
28.5
24.0
19.5
15.0
10.5
6.00
4.50
1.50

(c)

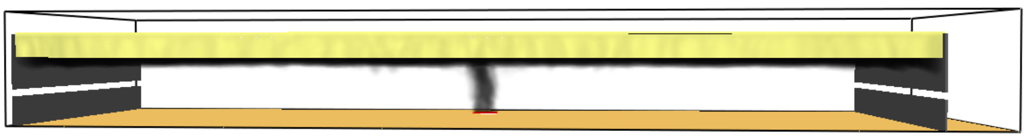

220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

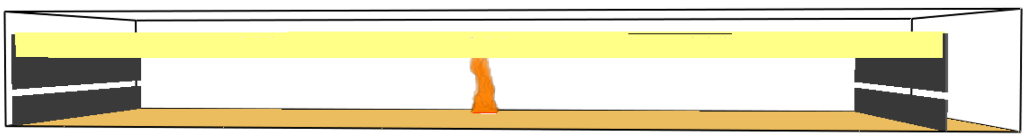


(e)

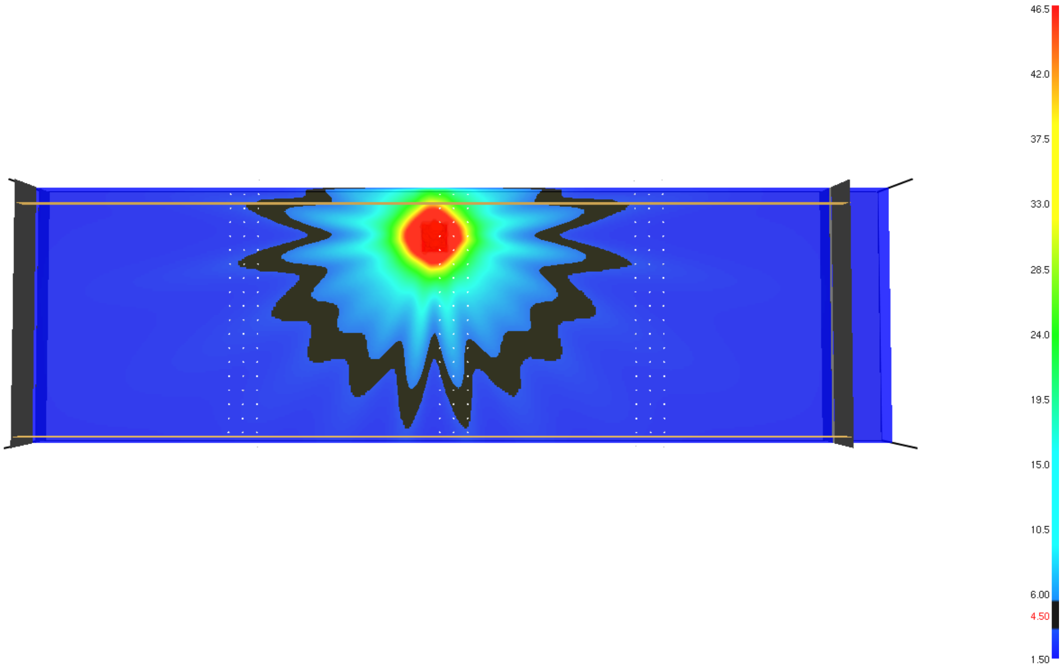
Figure 110: At t = 500 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



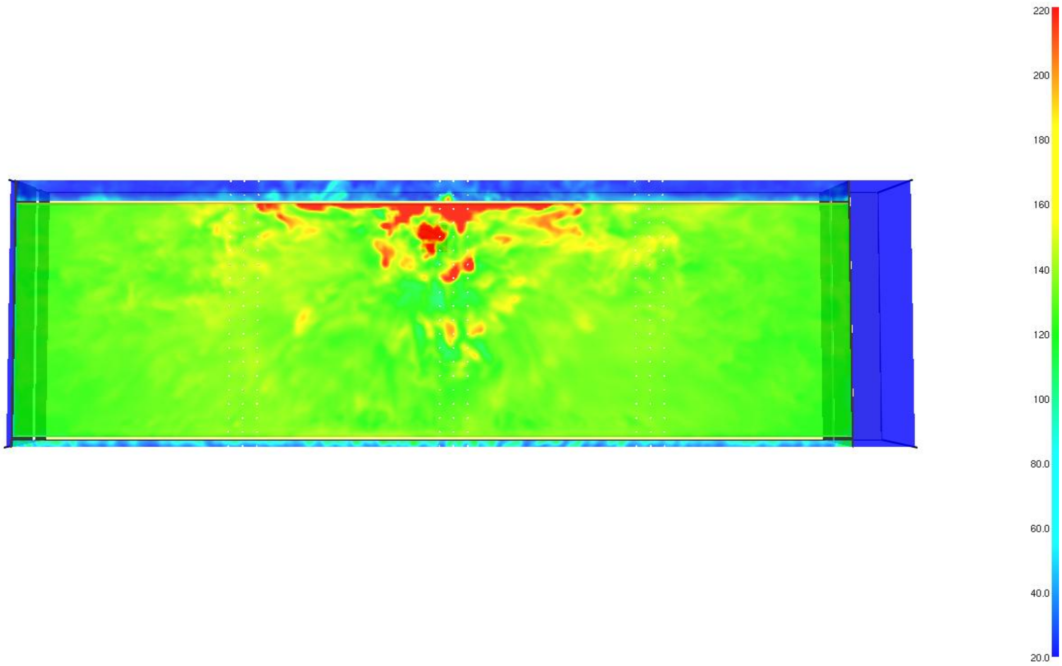
(a)



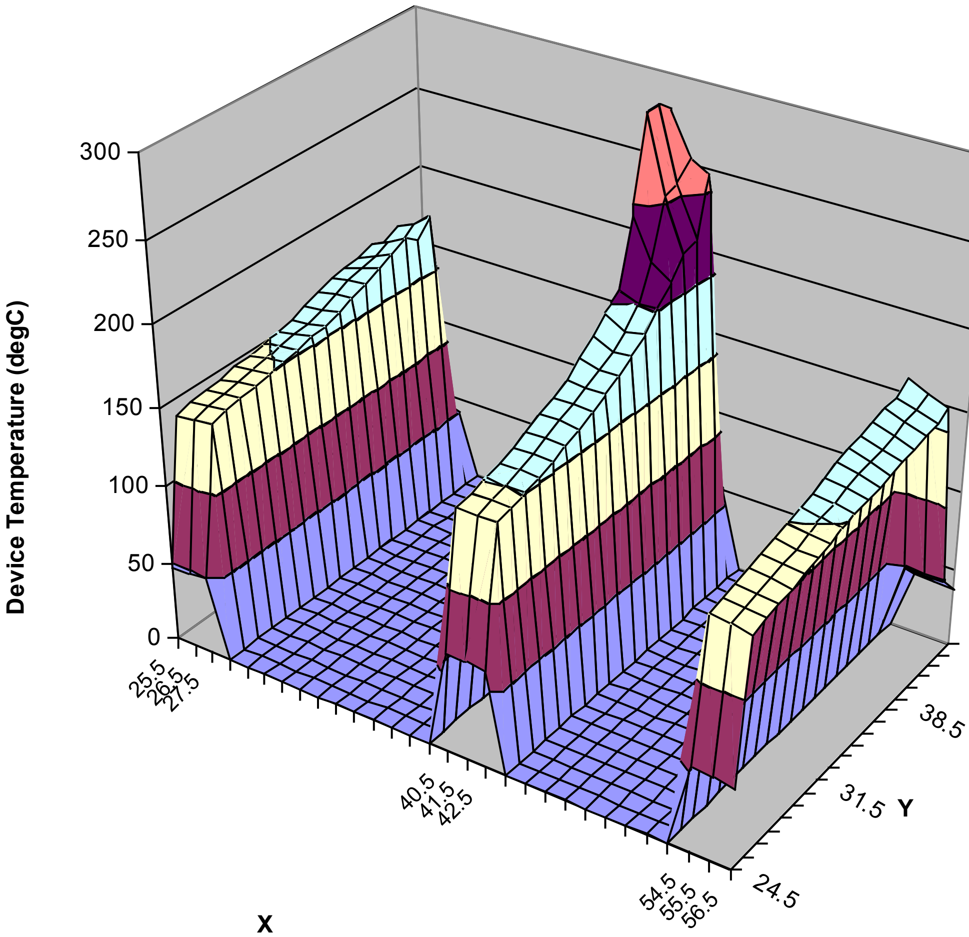
(b)


46.5
42.0
37.5
33.0
28.5
24.0
19.5
15.0
10.5
6.00
4.50
1.50

(c)


220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)



(e)

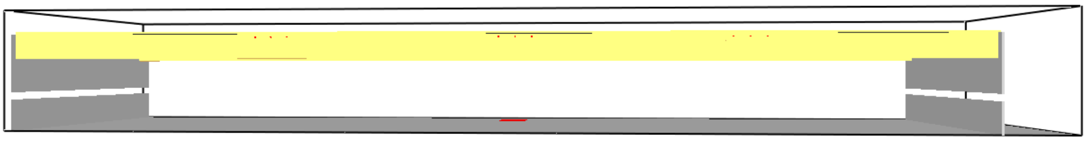
Figure 111: At t = 1,000 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).

B.2 Scenario 2: Single Smoke Reservoir and Local 120°C Fire Venting and Vent Area of 15% Floor Area

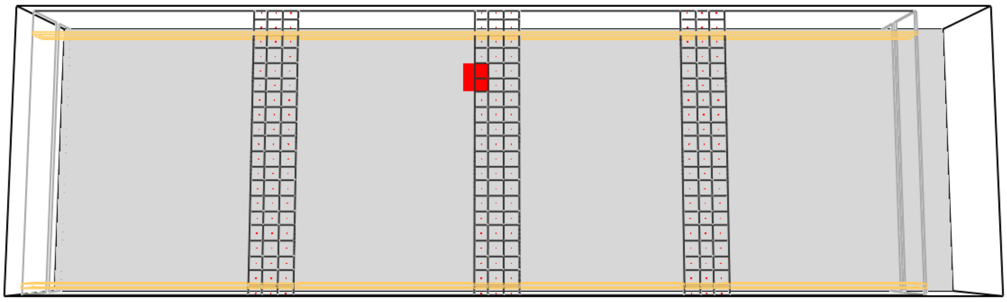
This method was not considered appropriate for the scenarios where no smoke reservoirs were present.

B.3 Scenario 3:

B.3.1 Four Smoke Reservoirs and Local 120ºC Fire Venting and Vent Area of 15% Reservoir Floor Area

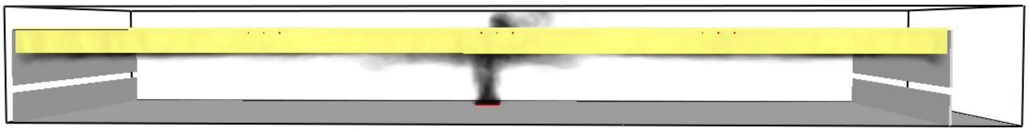


(a)

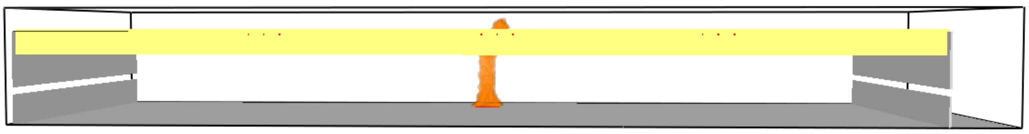


(b)

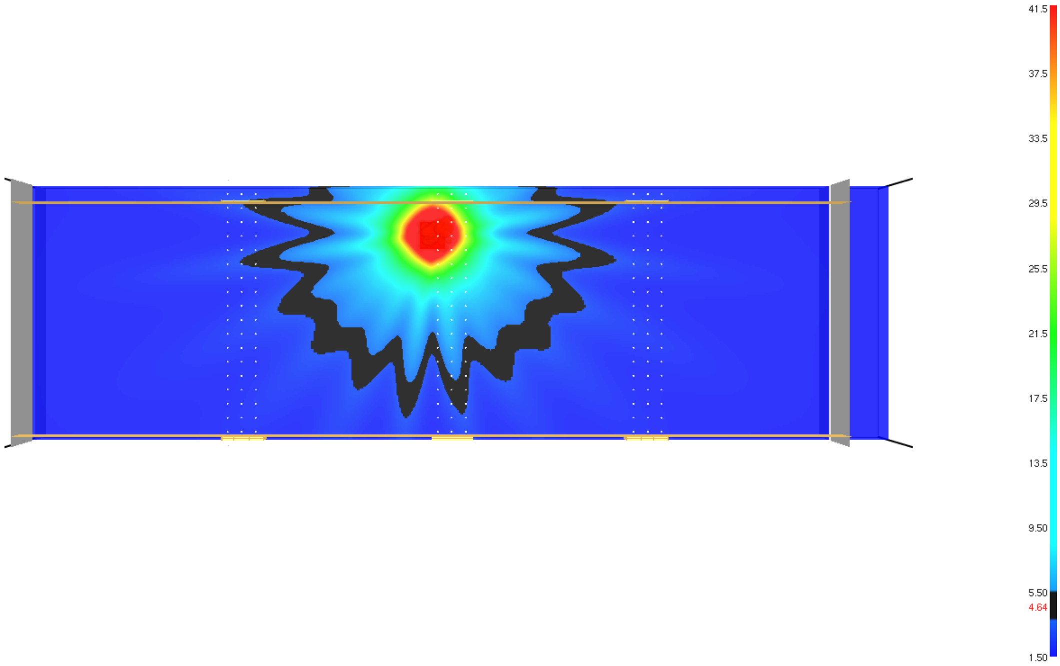
Figure 112: Schematics of the section of warehouse modelled.



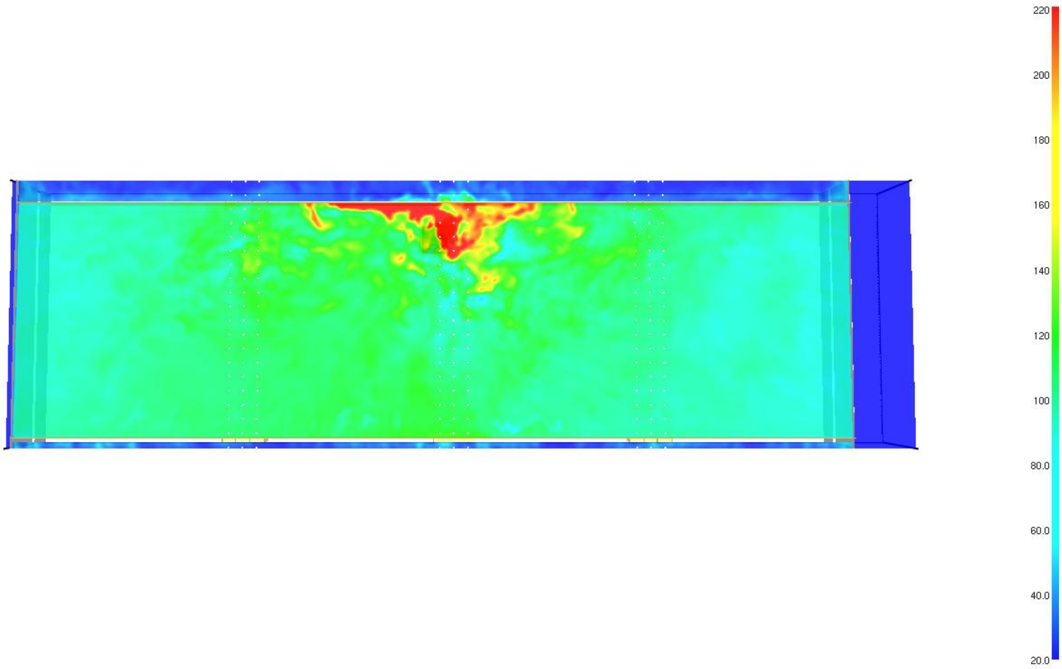
(a)



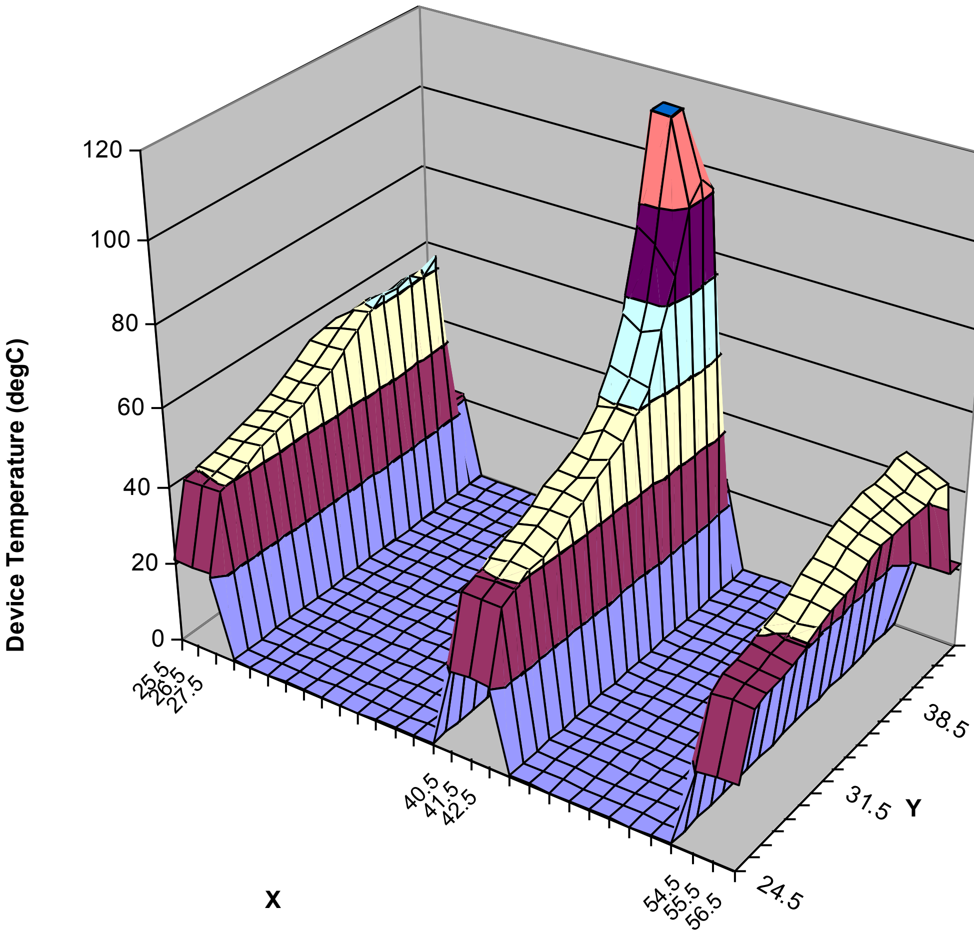
(b)


41.5
37.5
33.5
29.5
25.5
21.5
17.5
13.5
9.50
5.50
4.64
1.50

(c)

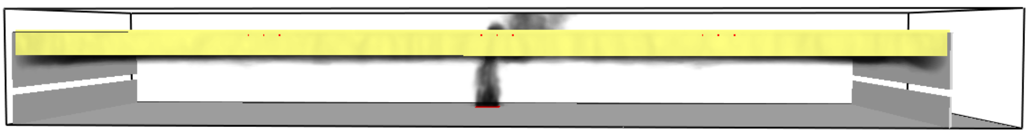

220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

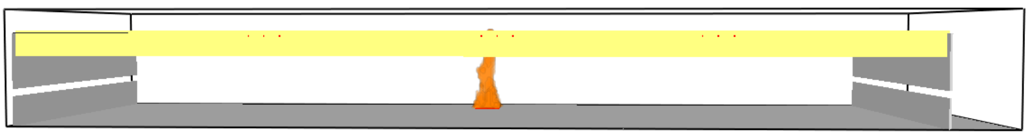


(e)

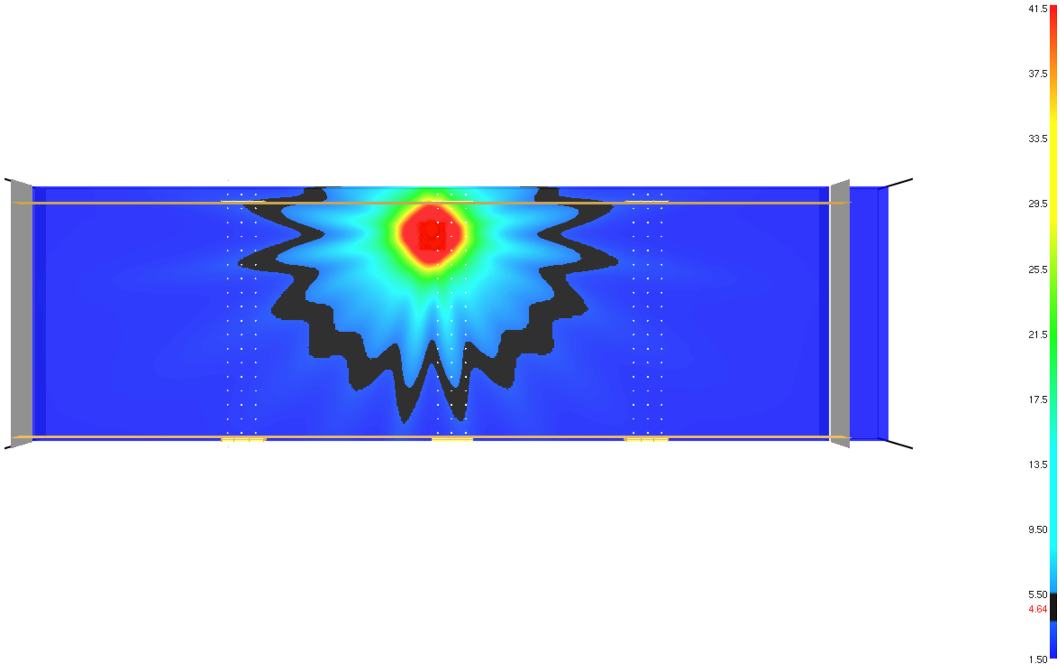
Figure 113: At t = 50 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



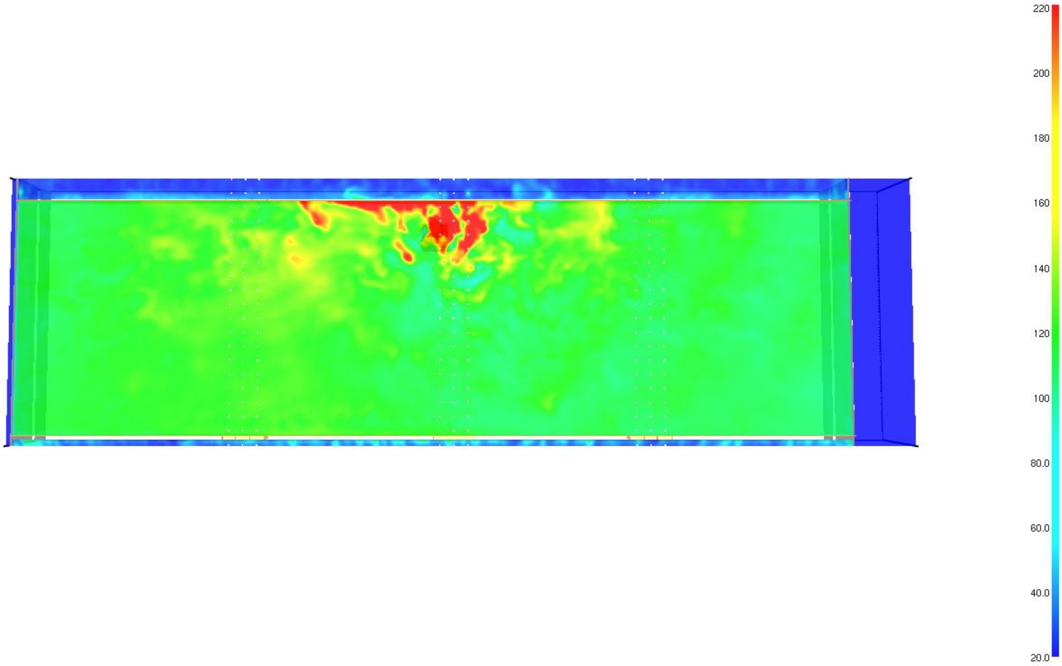
(a)



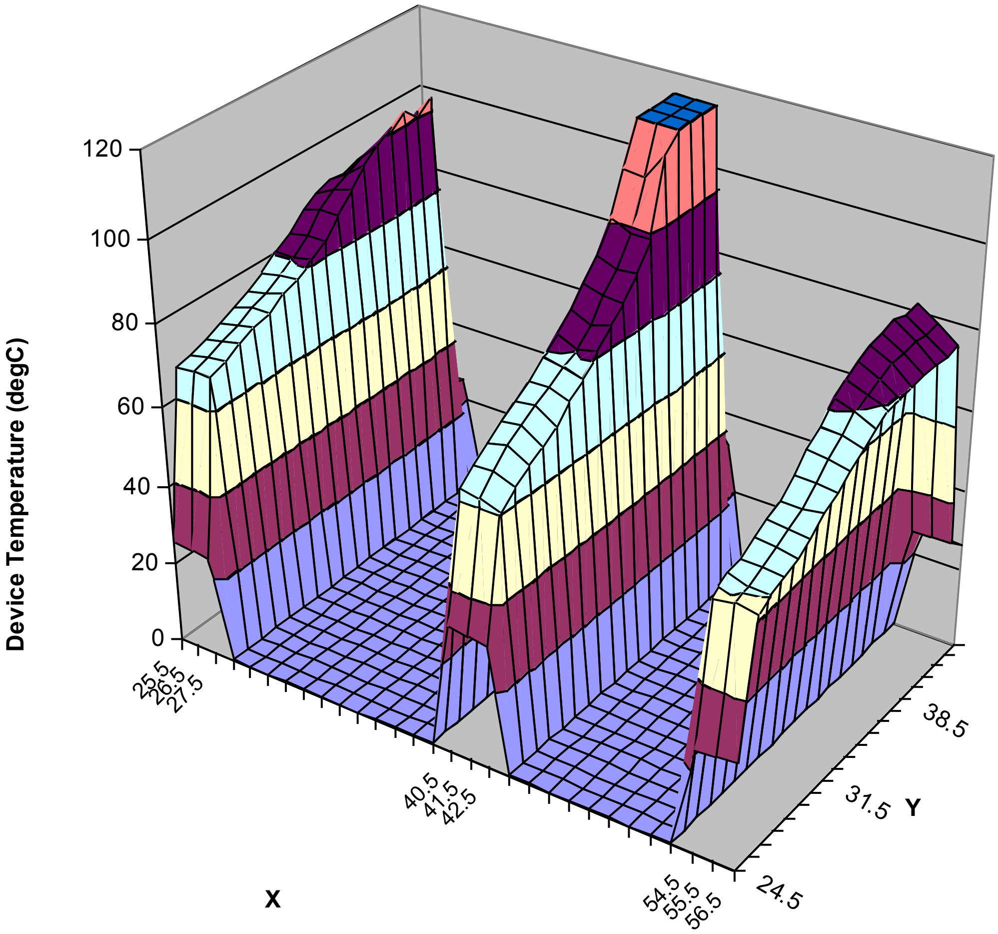
(b)


41.5
37.5
33.5
29.5
25.5
21.5
17.5
13.5
9.50
5.50
4.64
1.50

(c)

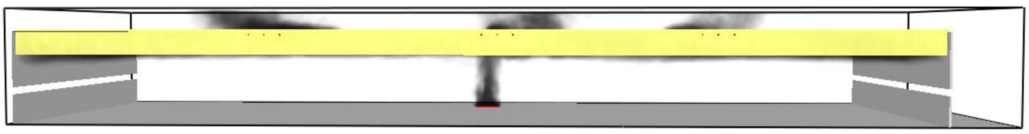

220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

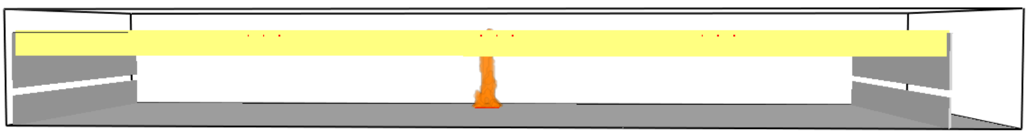


(e)

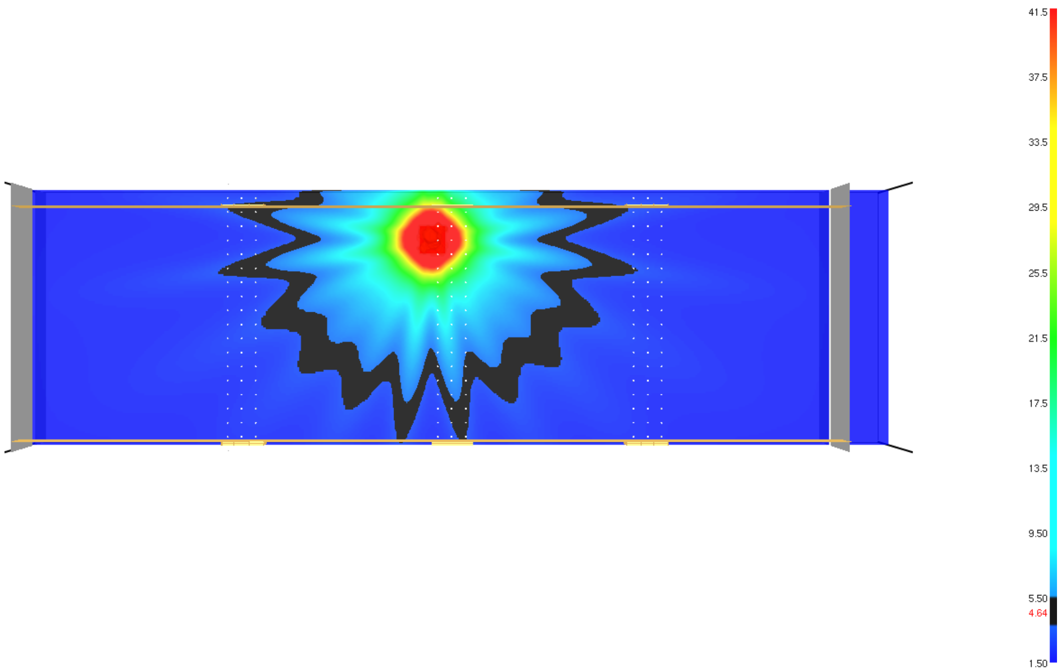
Figure 114: At t = 100 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



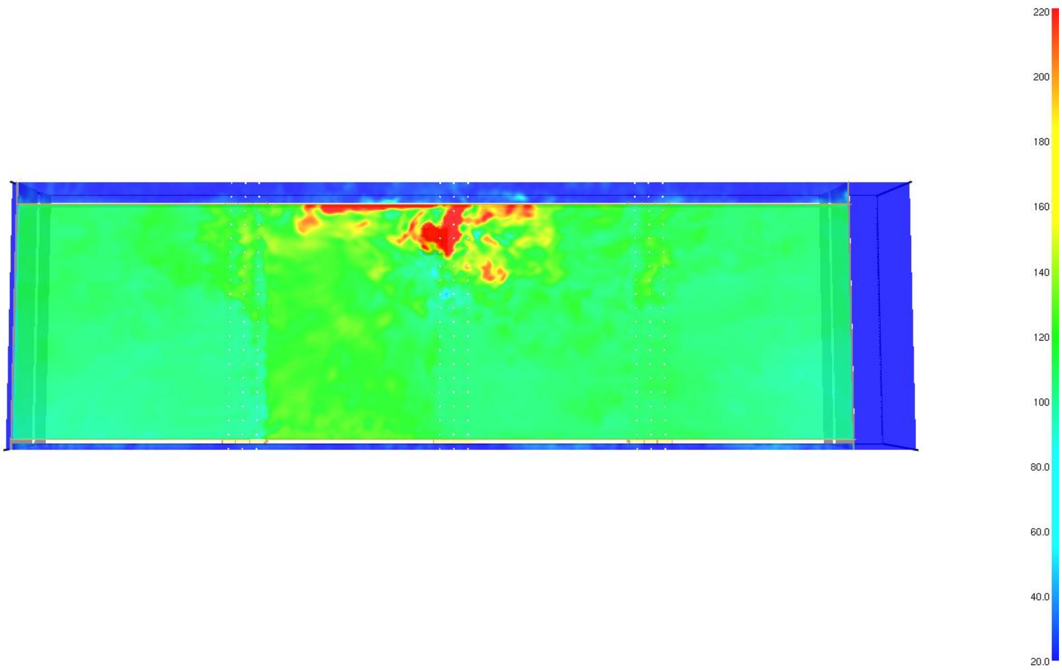
(a)



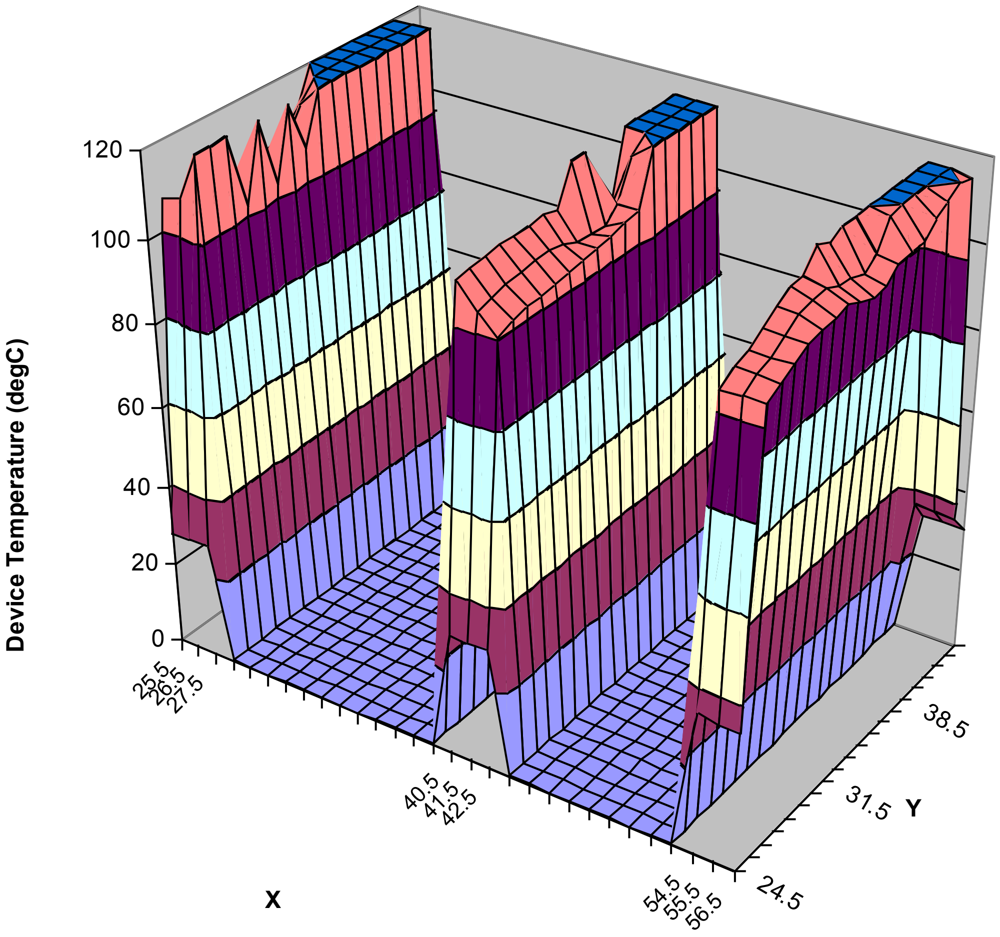
(b)


41.5
37.5
33.5
29.5
25.5
21.5
17.5
13.5
9.50
5.50
4.64
1.50

(c)

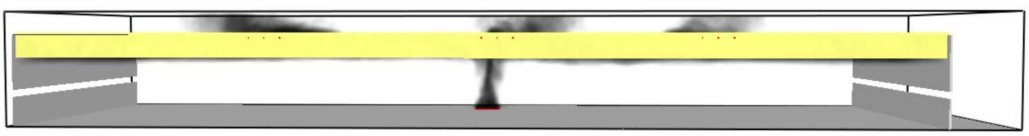

220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

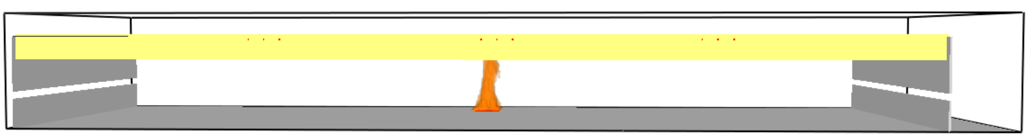


(e)

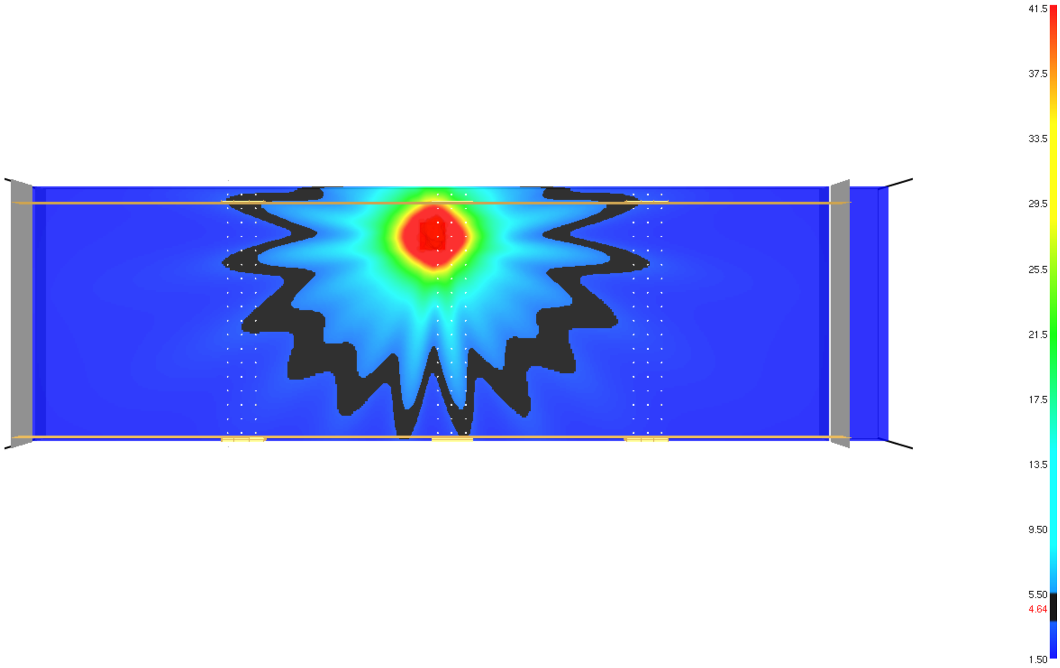
Figure 115: At t = 500 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



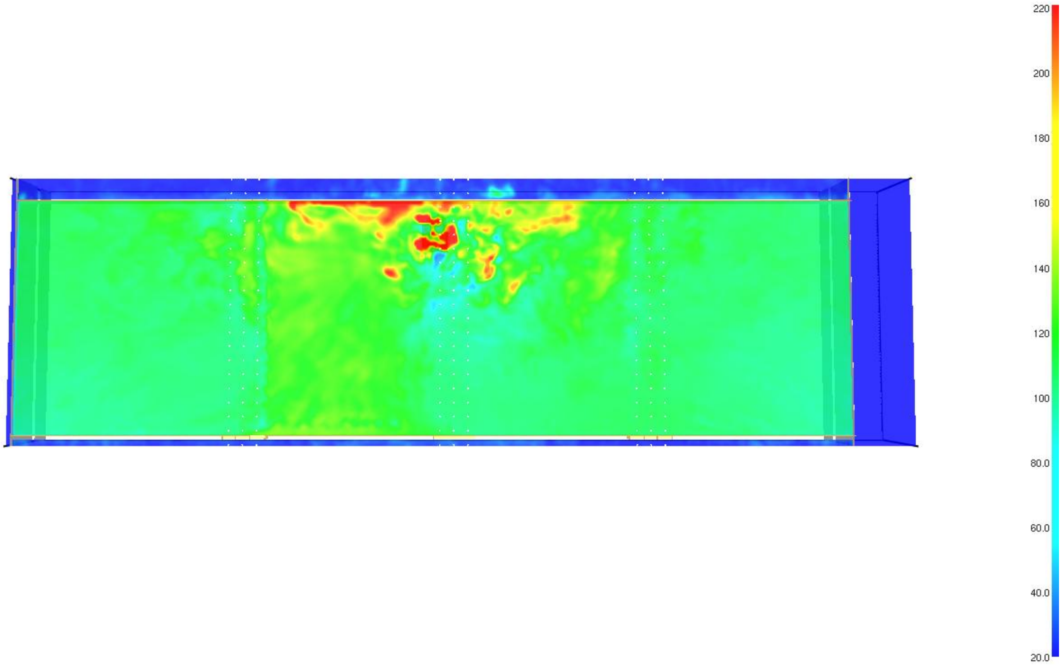
(a)



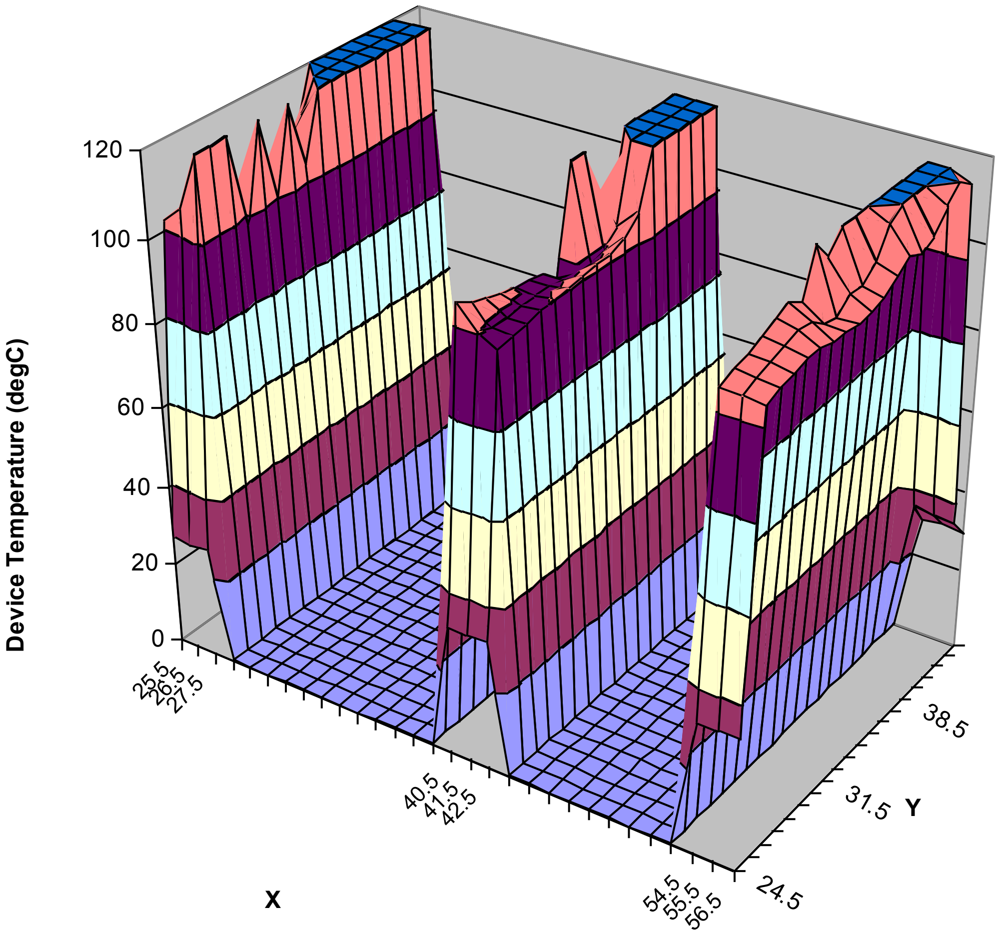
(b)



(c)



(d)

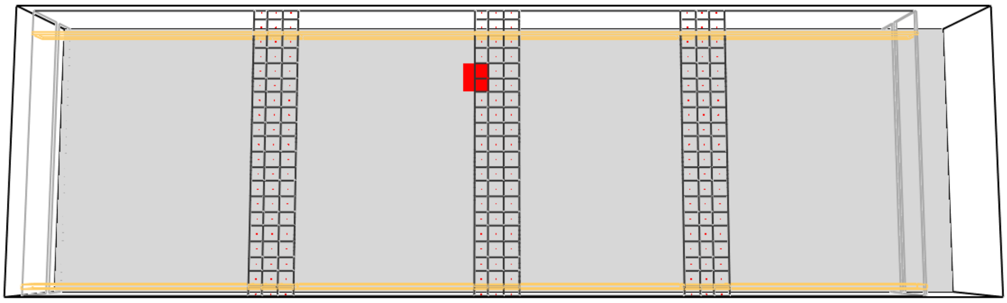


(e)

Figure 116: At t = 100 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).

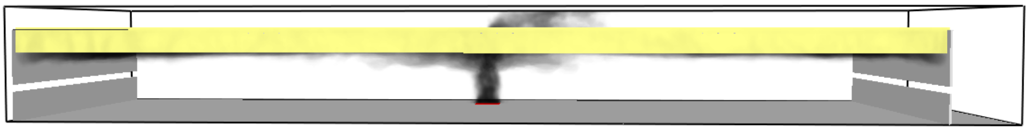
B.3.2 Scenario 3b: Four Smoke Reservoirs and Local 300°C Fire Venting and Vent Area of 15% Reservoir Floor Area

(a)

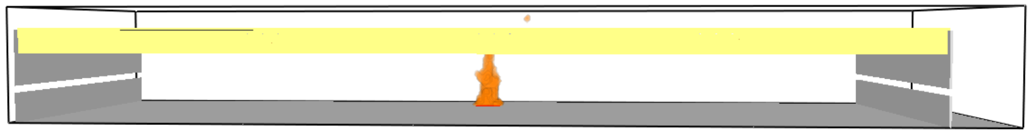


(b)

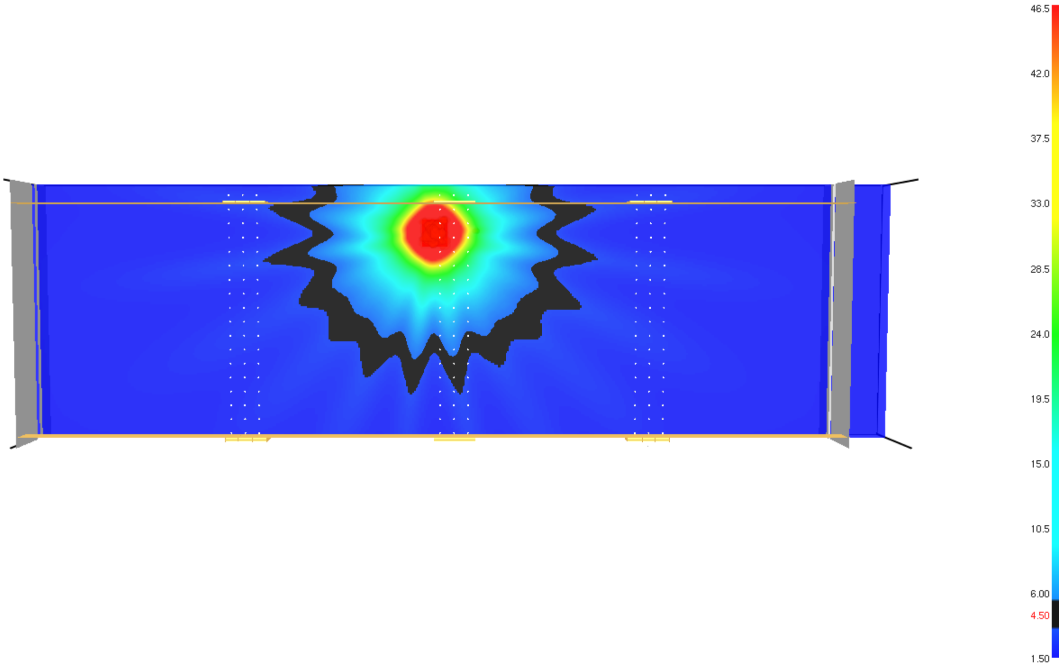
Figure 117: Schematics of the section of warehouse modelled.



(a)

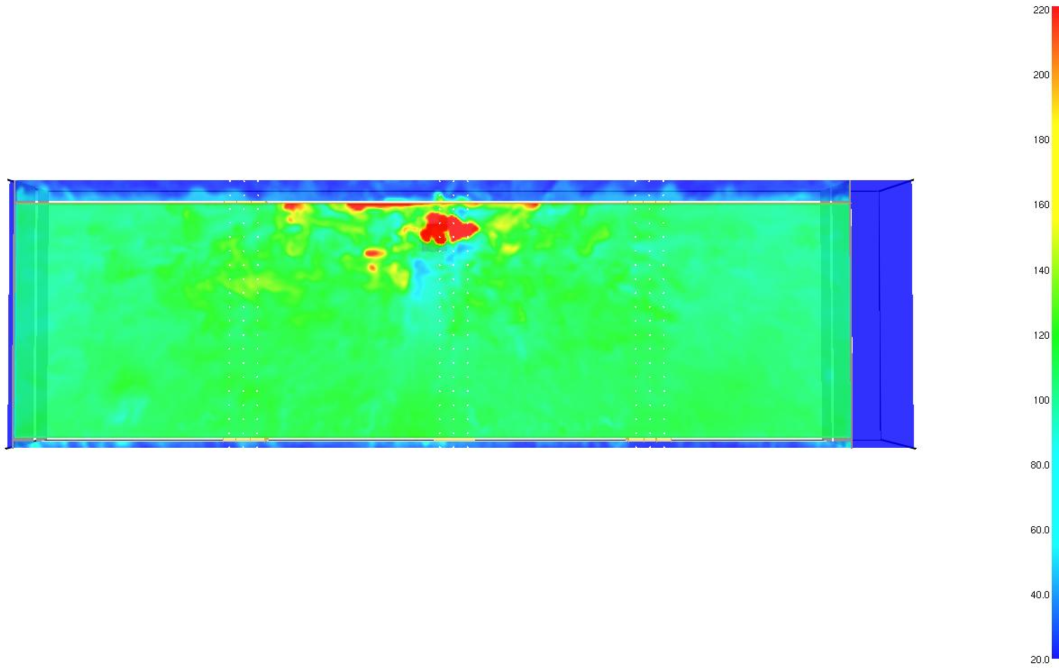


(b)



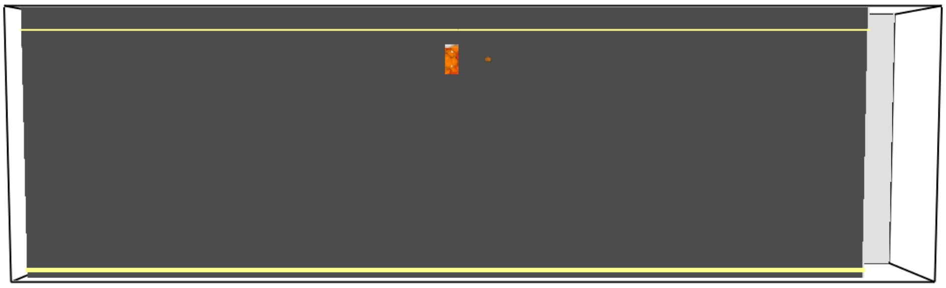
46.5
42.0
37.5
33.0
28.5
24.0
19.5
15.0
10.5
6.00
4.50
1.50

(c)

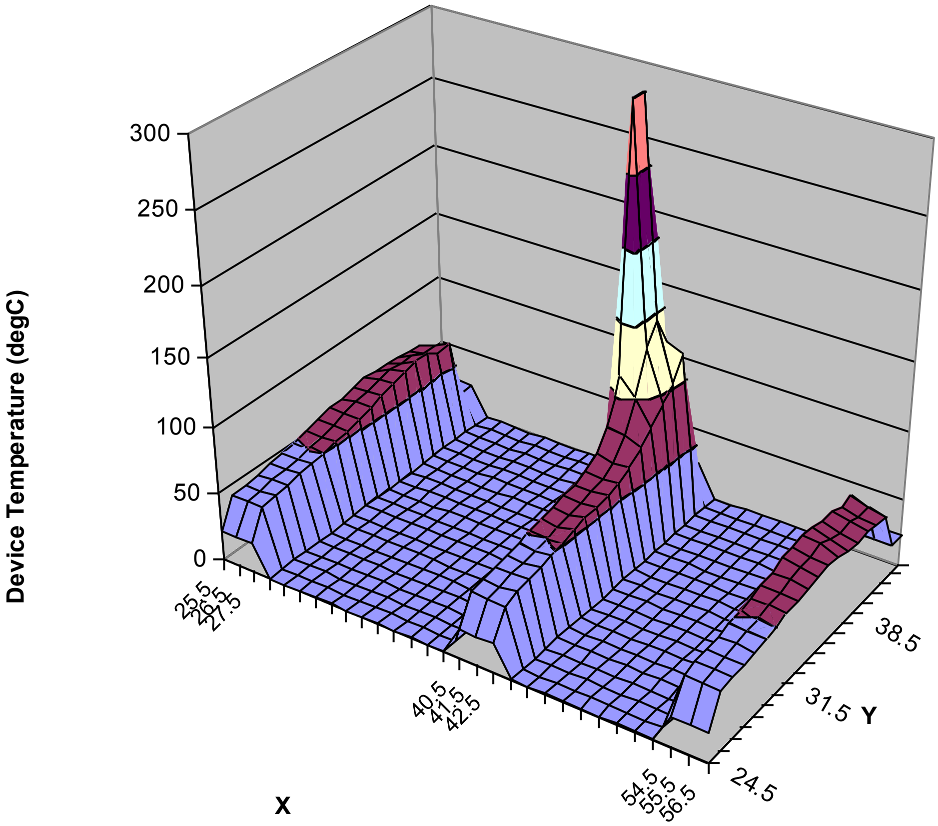


220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

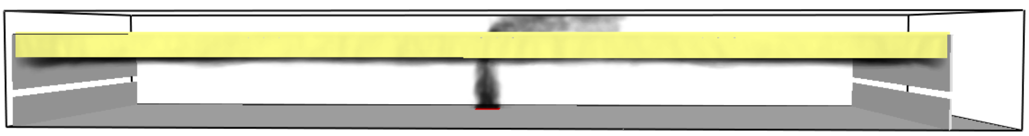


(e)

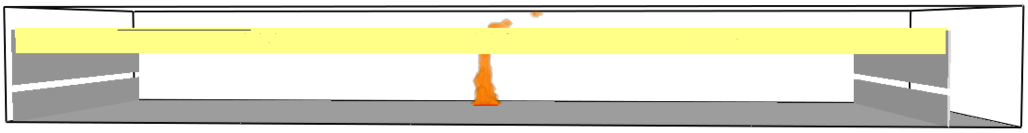


(f)

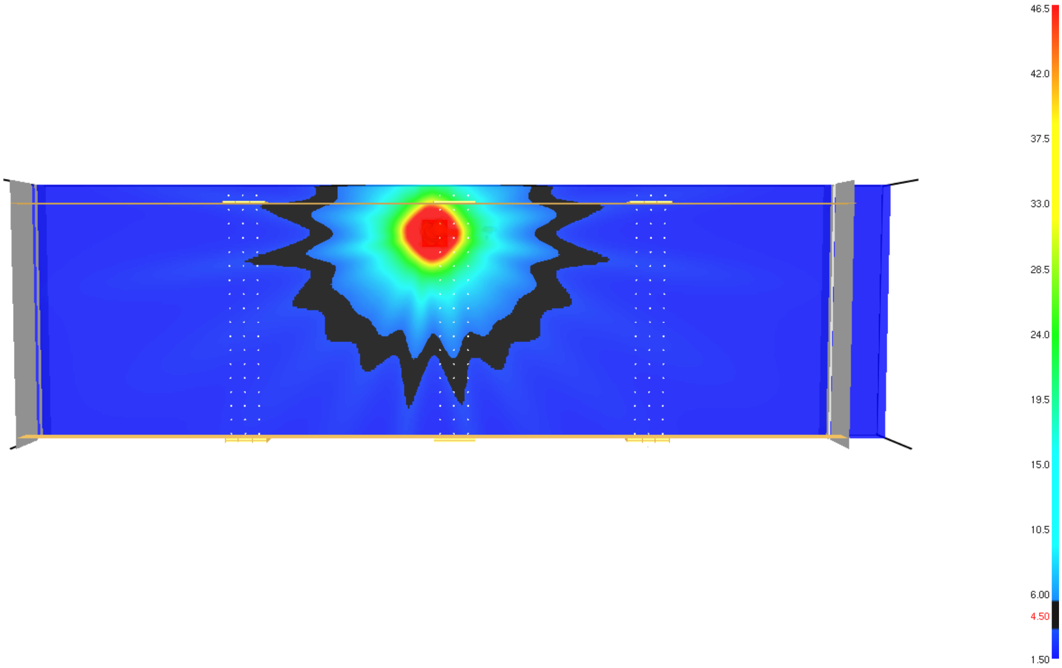
Figure 118: At t = 50 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) view of roof with open panels from above, and (f) device temperatures (°C).



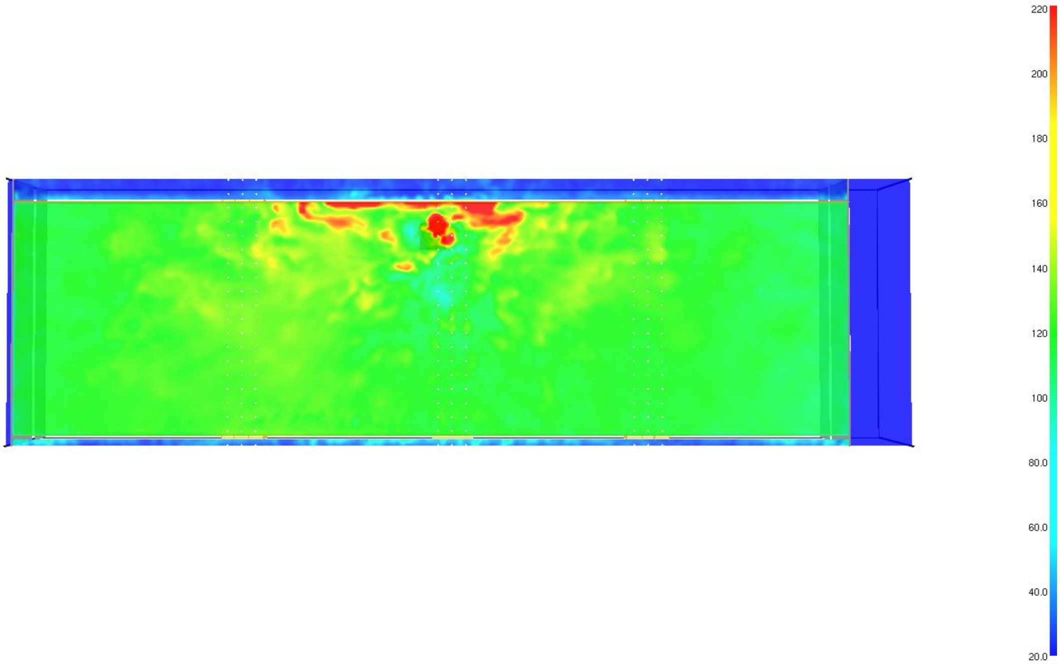
(a)



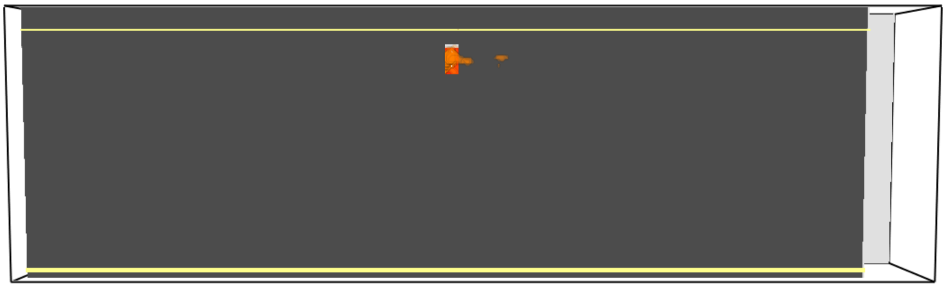
(b)


46.5
42.0
37.5
33.0
28.5
24.0
19.5
15.0
10.5
6.00
4.50
1.50

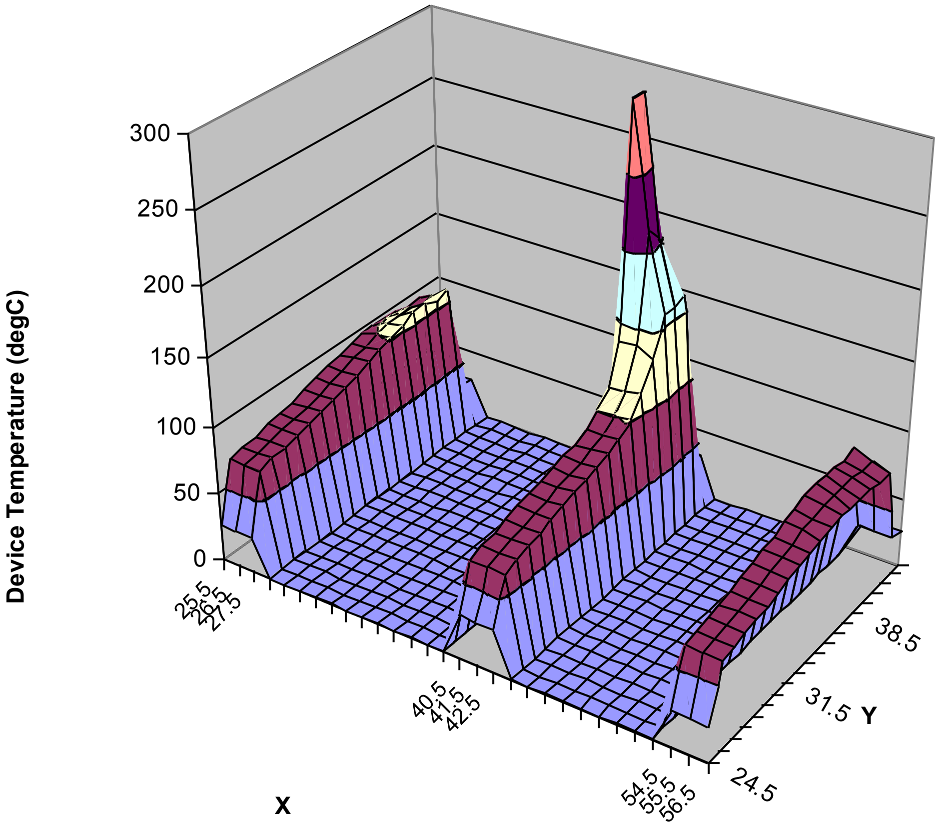
(c)


220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

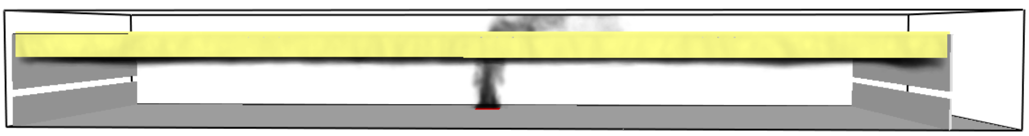


(e)

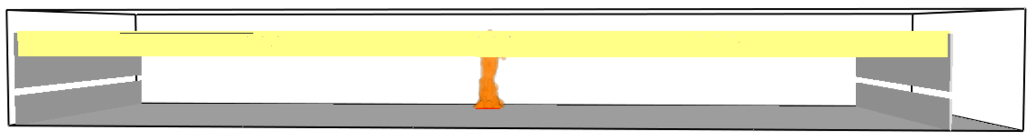


(f)

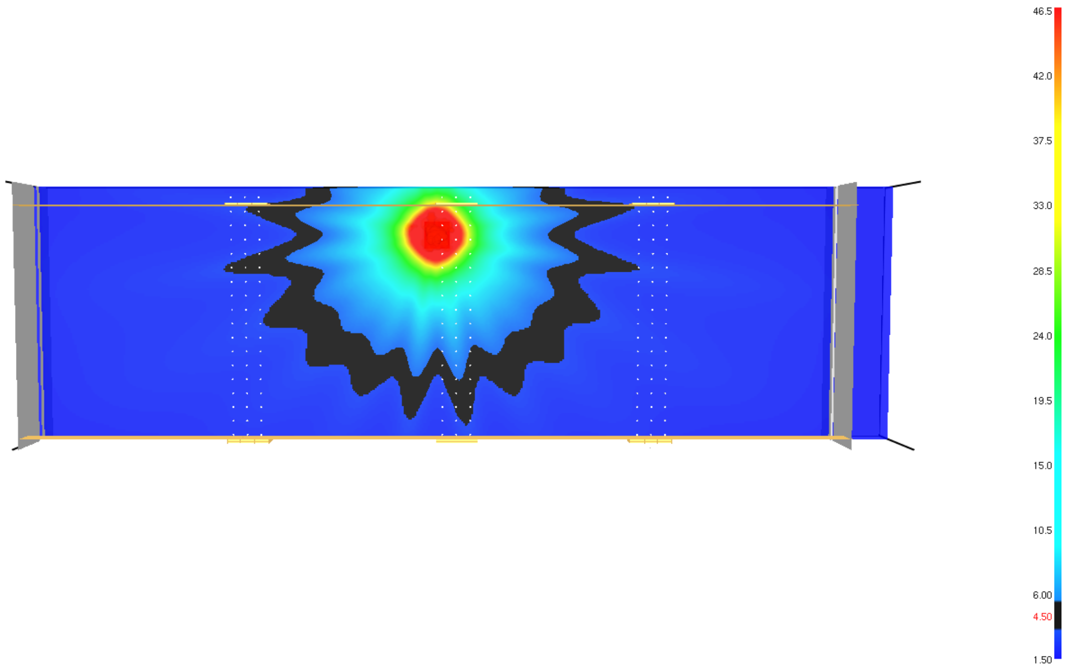
Figure 119: At t = 100 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) view of the roof and open panels from above, and (f) device temperatures (°C).



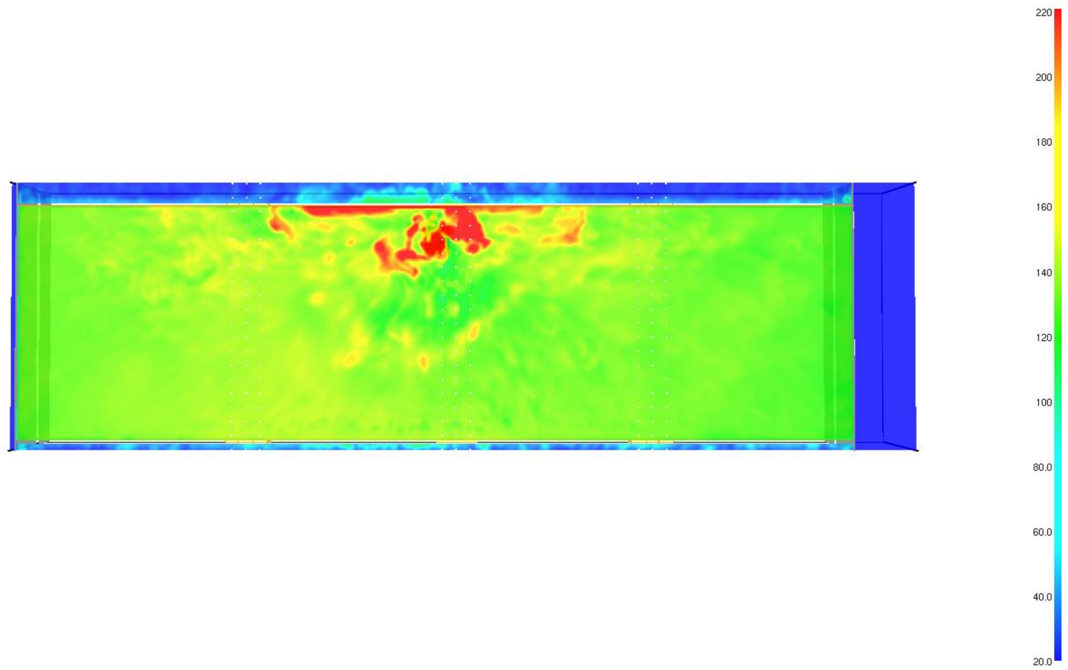
(a)



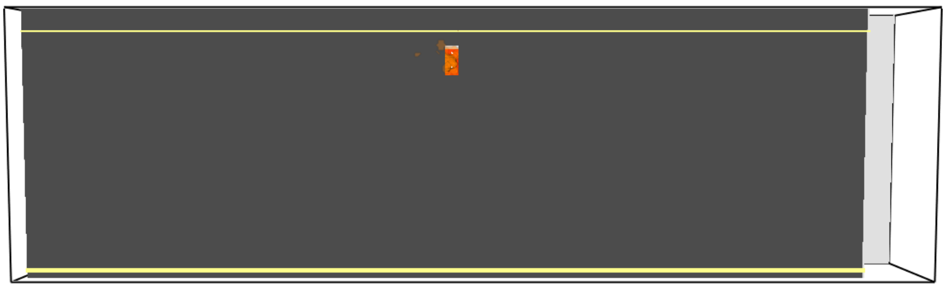
(b)


46.5
42.0
37.5
33.0
28.5
24.0
19.5
15.0
10.5
6.00
4.50
1.50

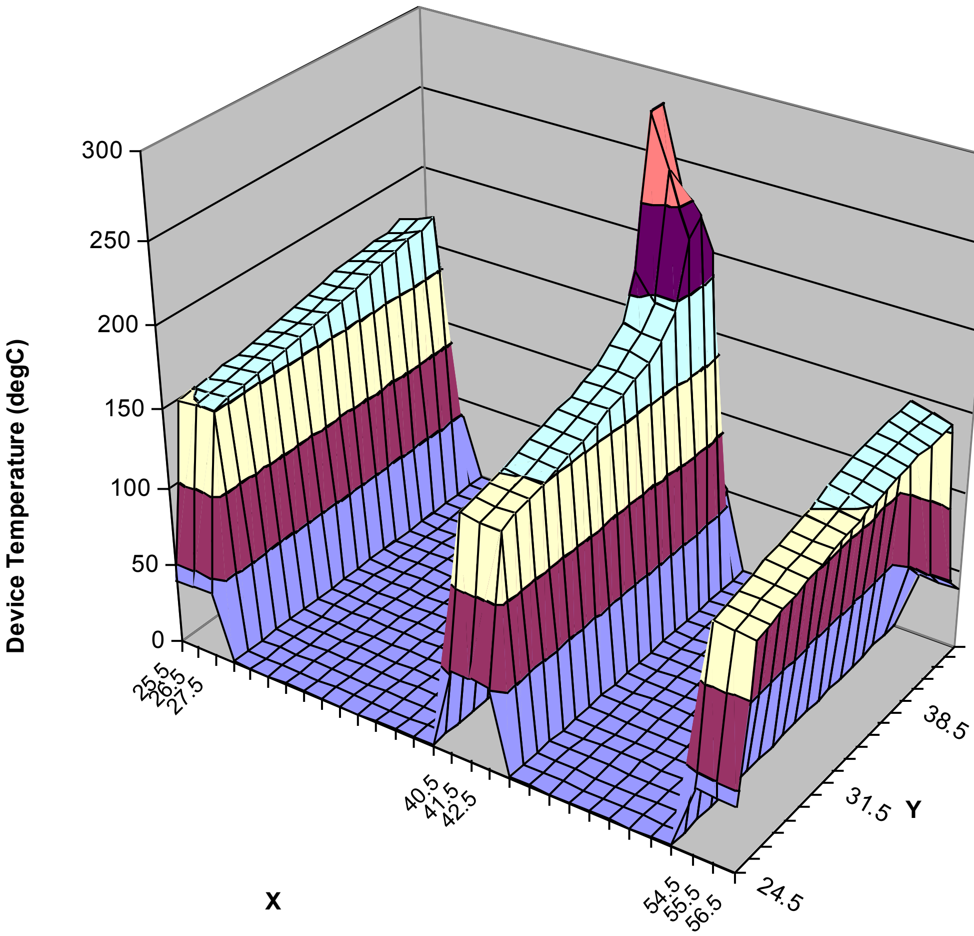
(c)


220
200
180
160
140
120
100
80.0
60.0
40.0
20.0

(d)

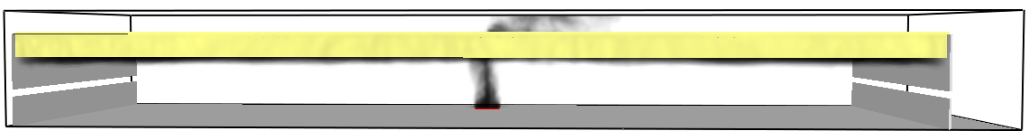


(e)

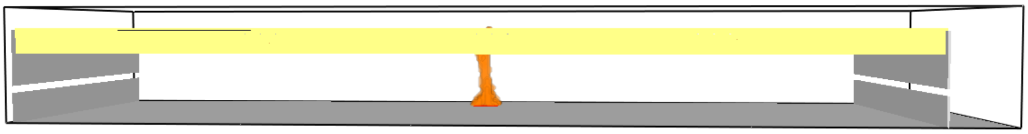


(f)

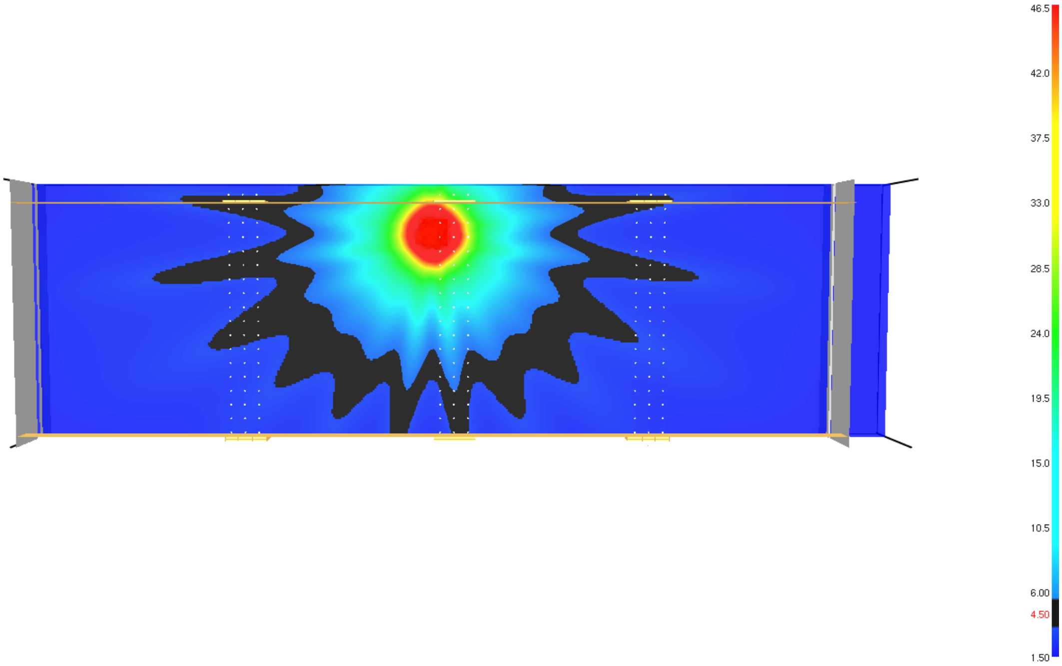
Figure 120: At t = 500 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) view of roof with open panels from above, and (f) device temperatures (°C).



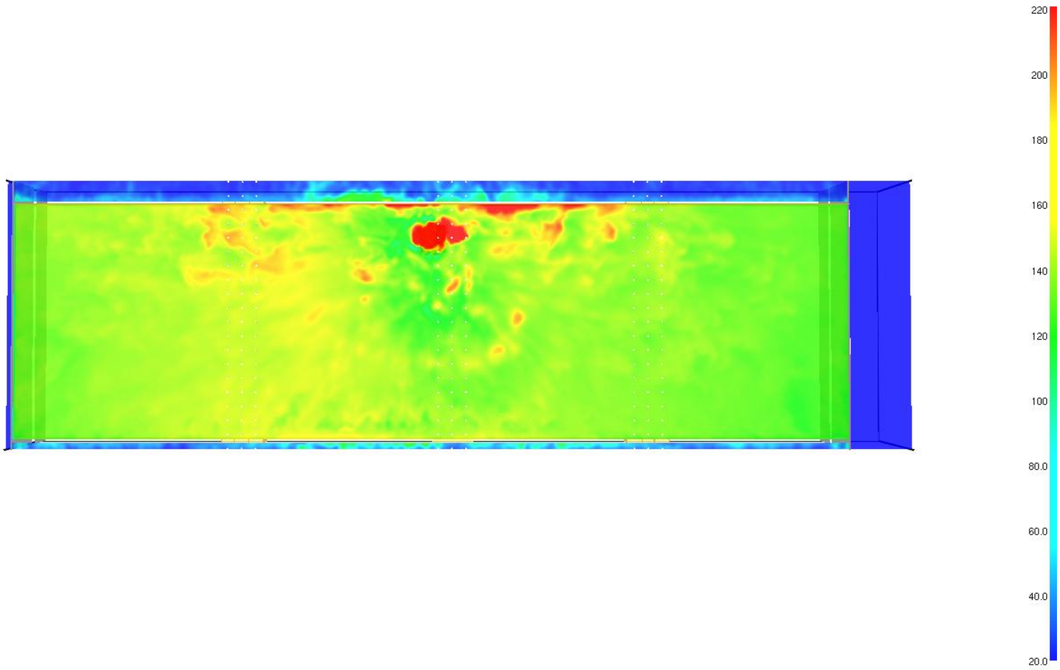
(a)



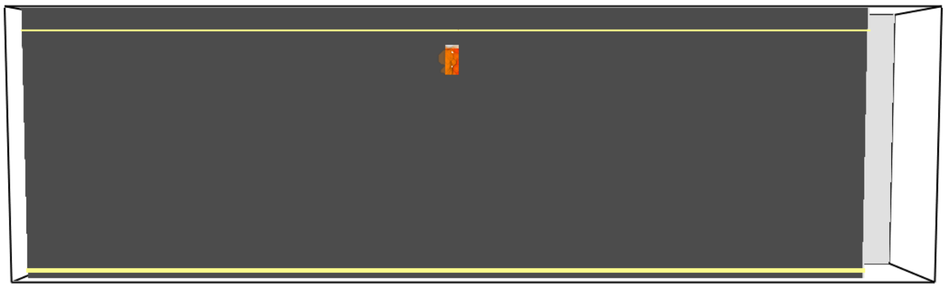
(b)



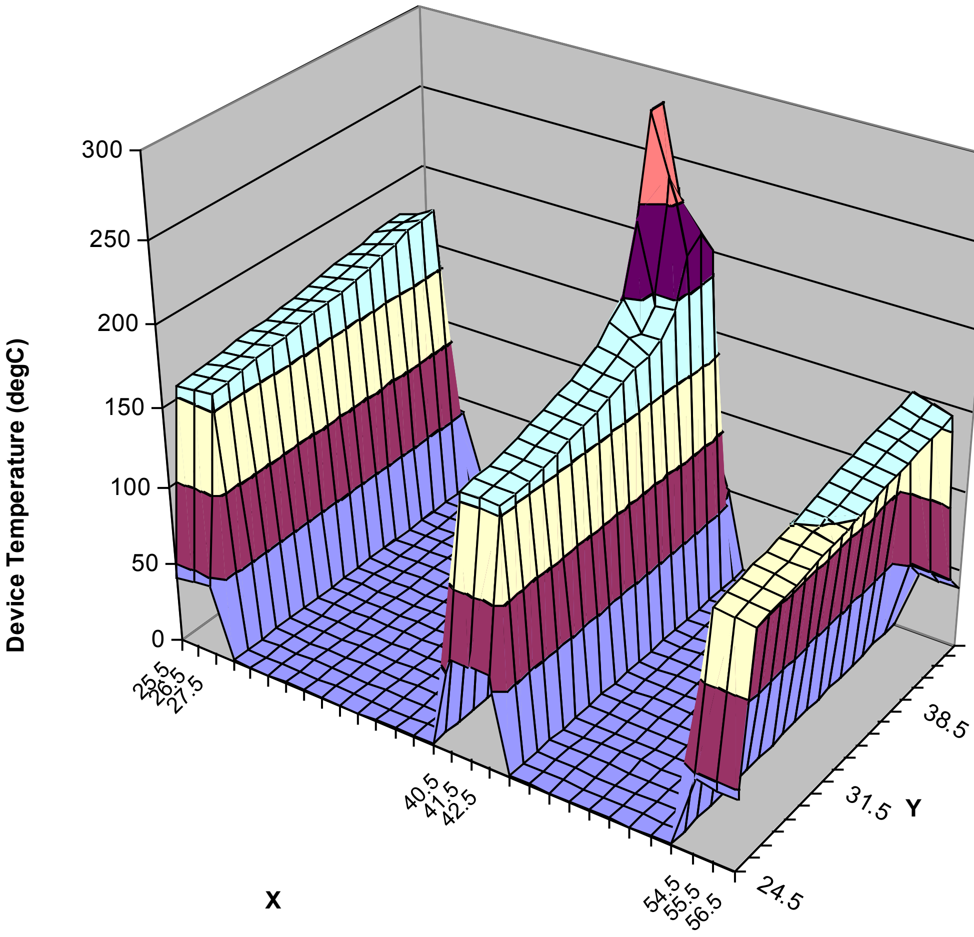
(c)



(d)



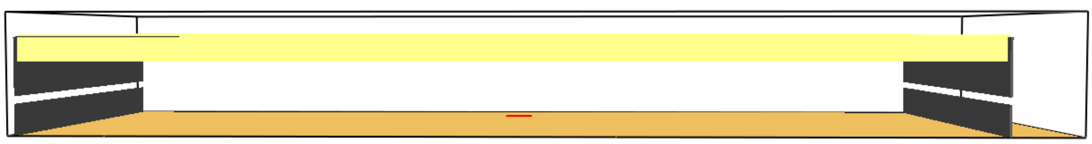
(e)



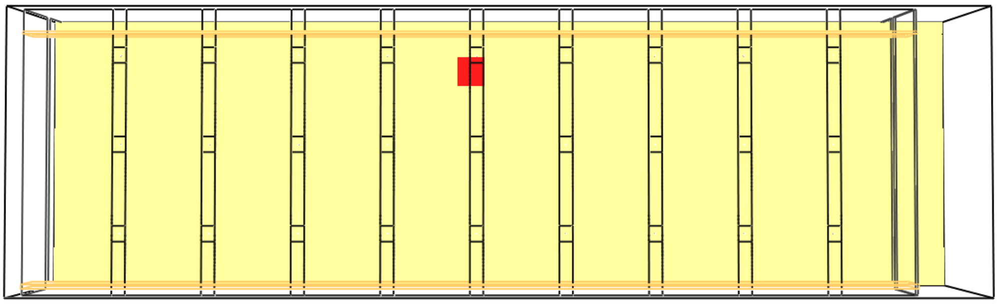
(f)

Figure 121: At t = 1,000 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) view of roof with open panels from above, and (f) device temperatures (°C).

B.4 Scenario 4: Four Smoke Reservoirs and Simultaneous Activation of 68ºC Fire Venting in each Smoke Reservoir and Vent Area of 3% Reservoir Floor Area

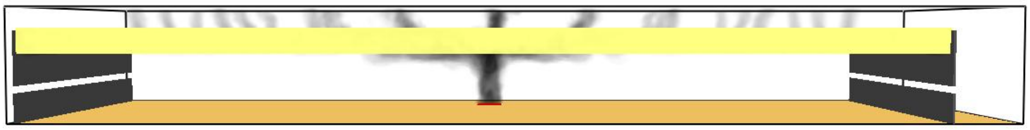


(a)

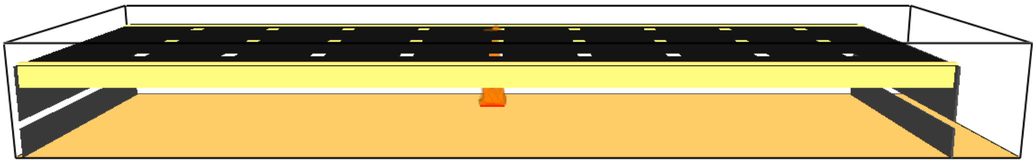


(b)

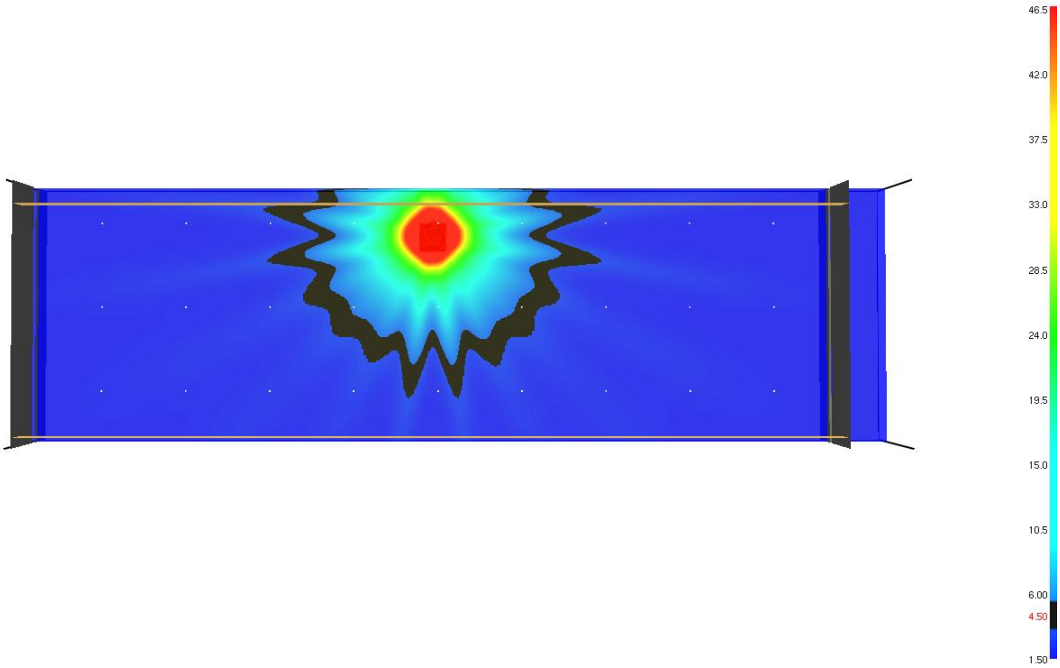
Figure 122: Schematics of the section of warehouse modelled.



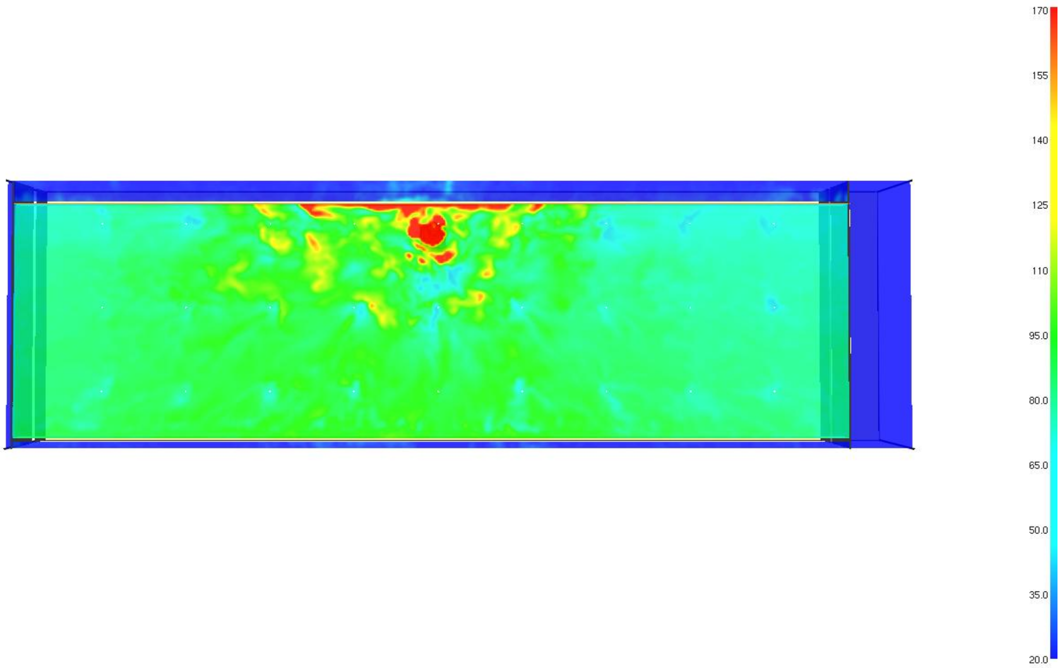
(a)



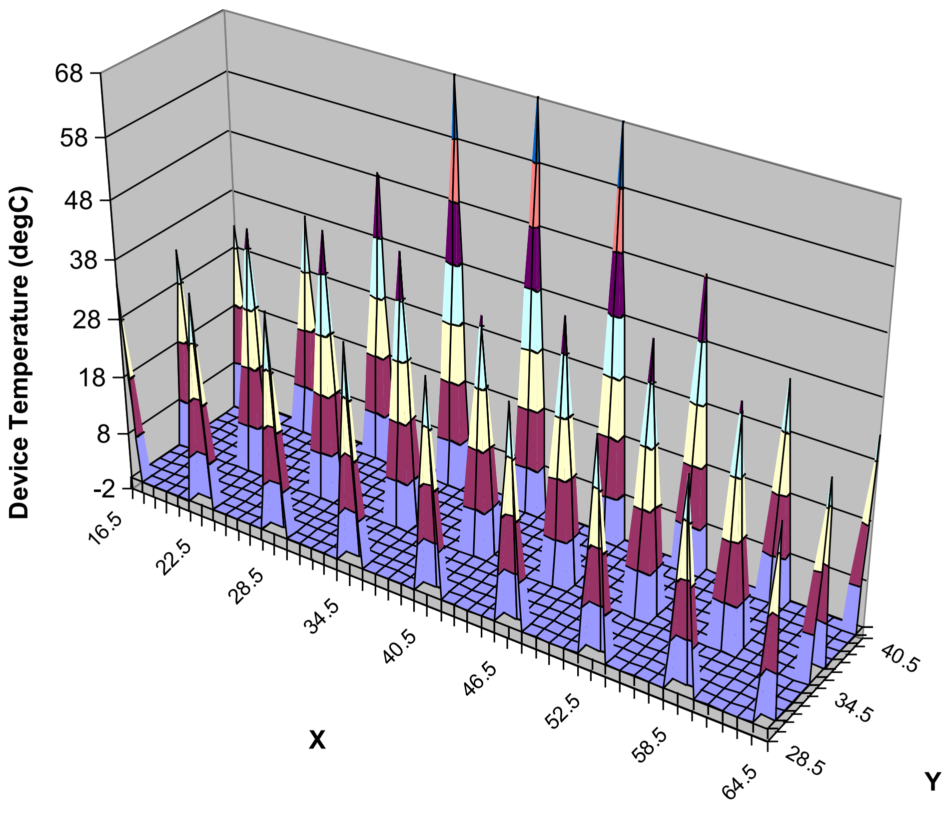
(b)



(c)

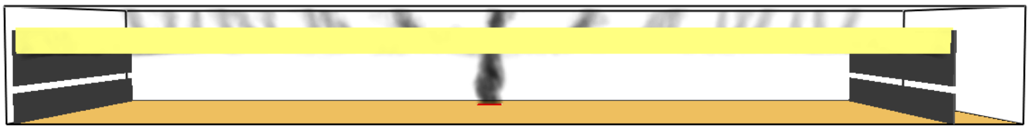


(d)

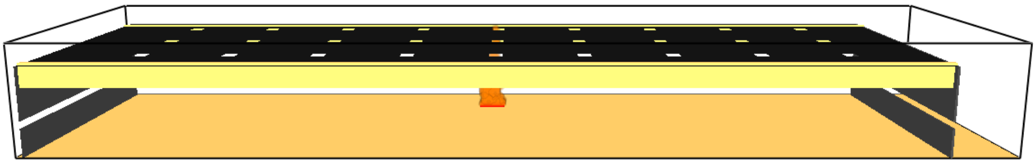


(e)

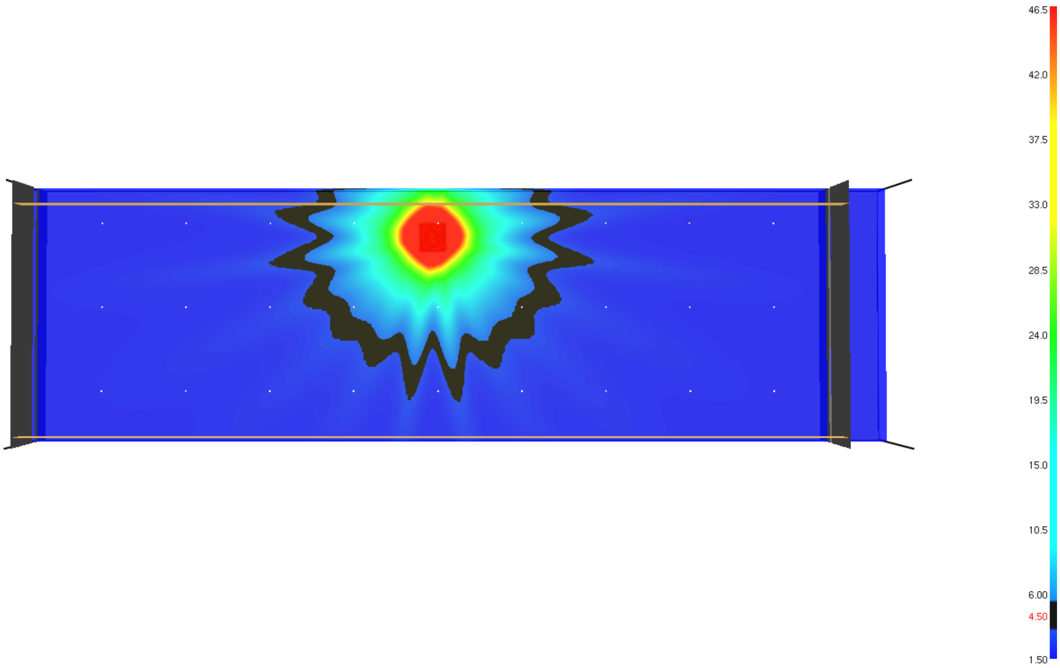
Figure 123: At t = 20 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



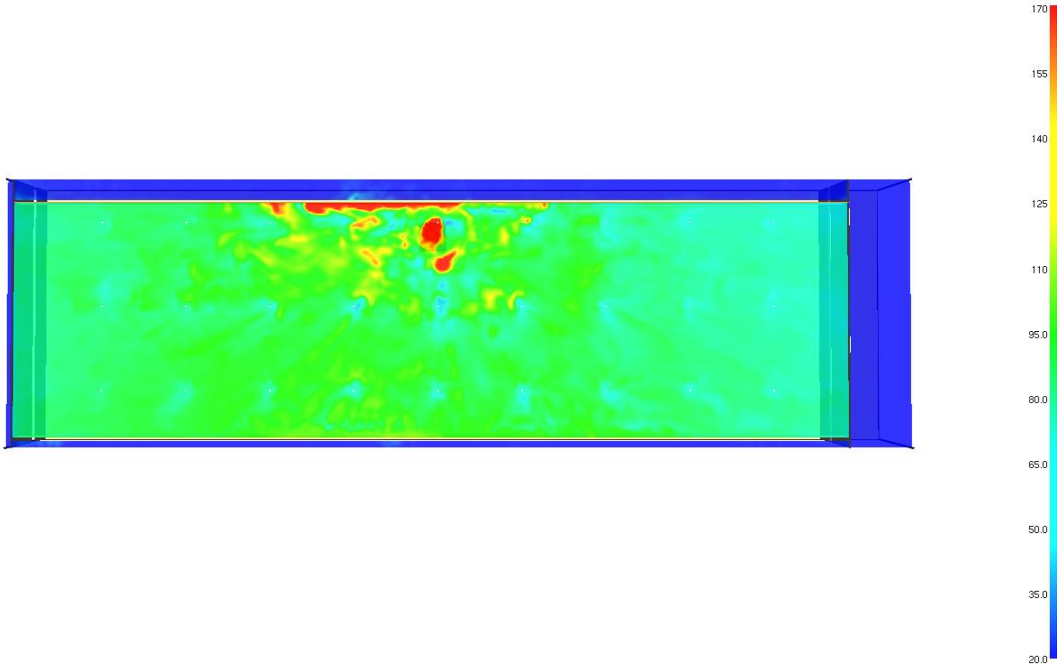
(a)



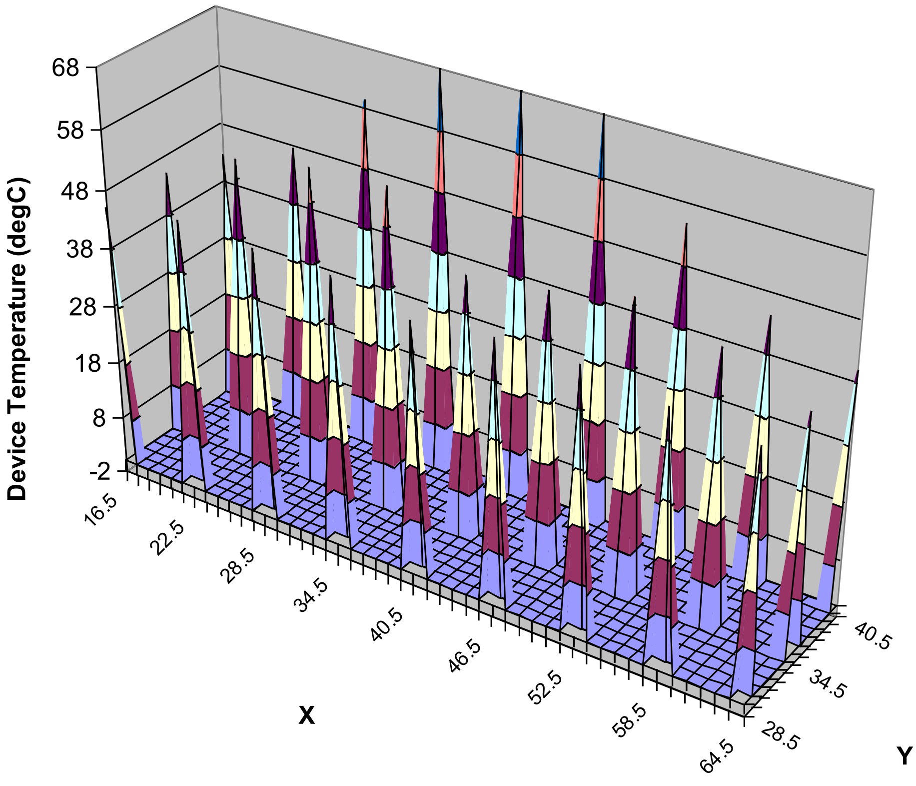
(b)



(c)

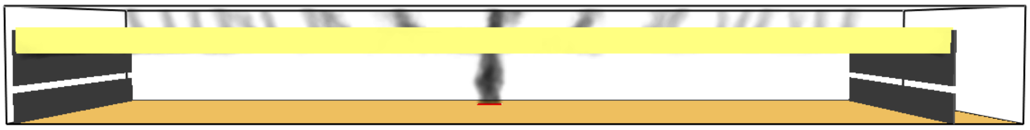


(d)

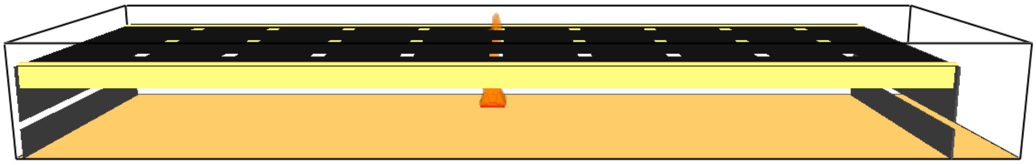


(e)

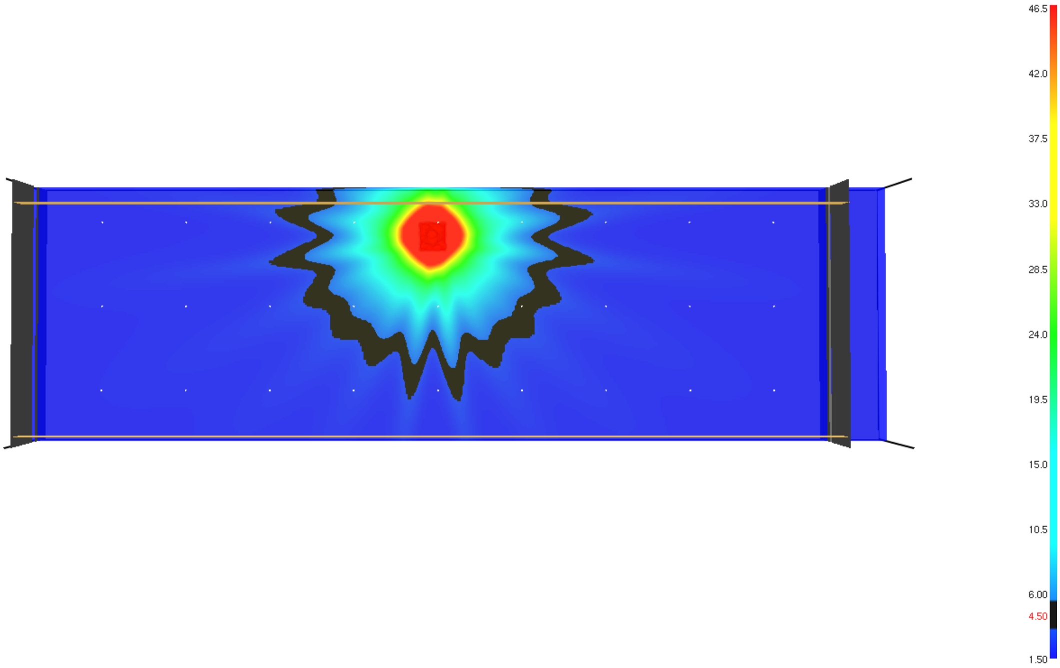
Figure 124: At t = 45 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



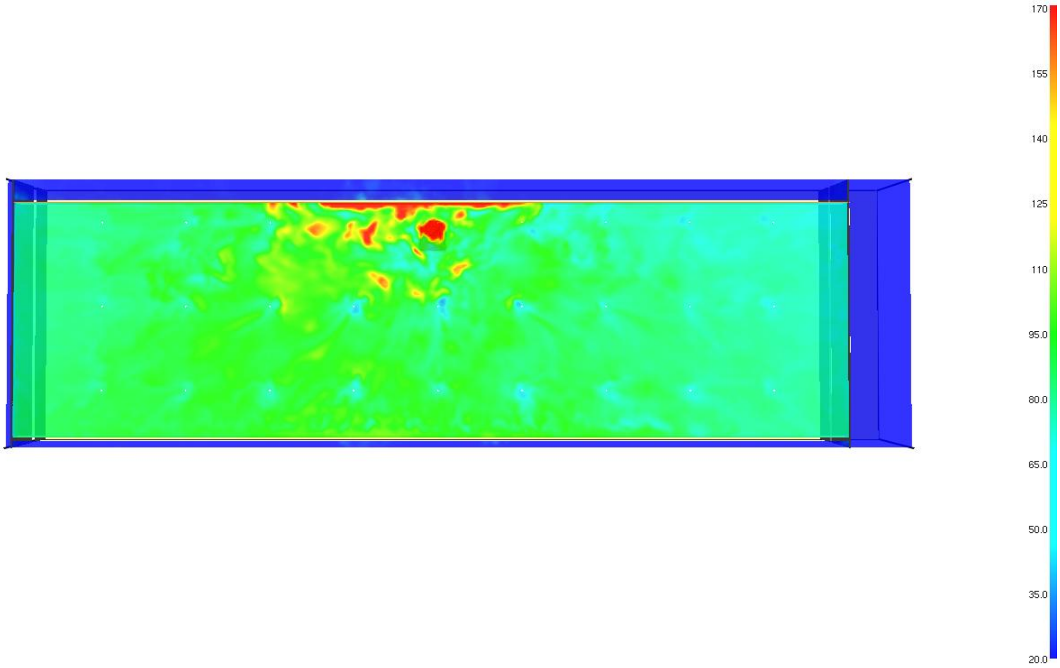
(a)



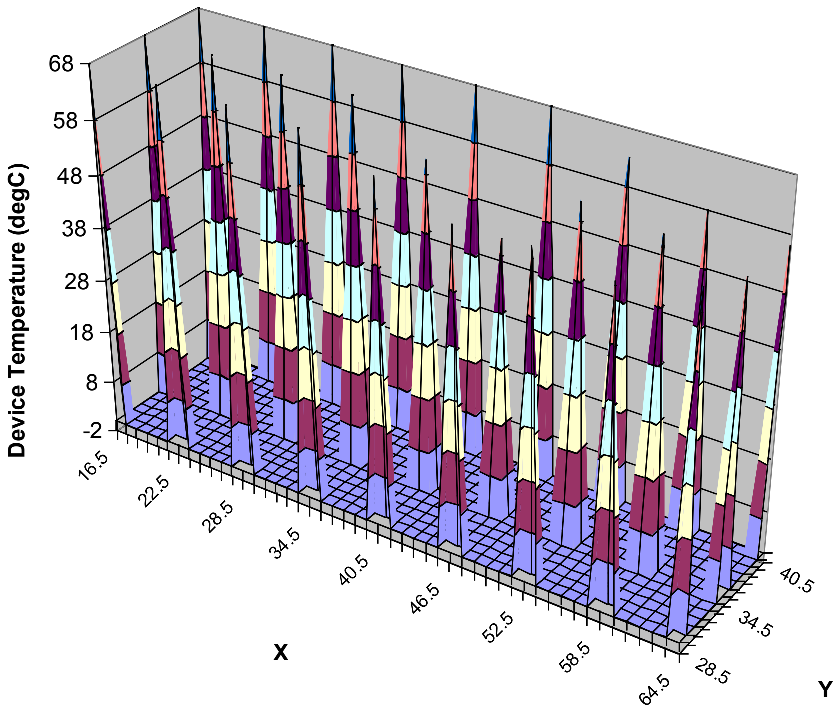
(b)



(c)

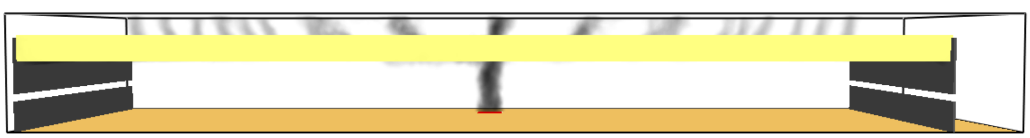


(d)

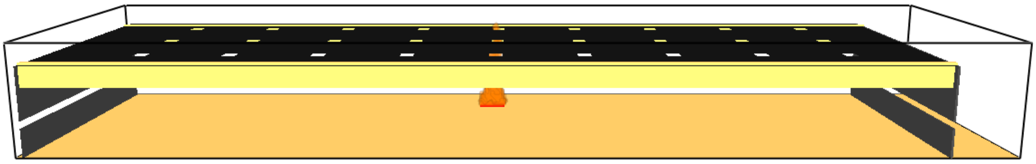


(e)

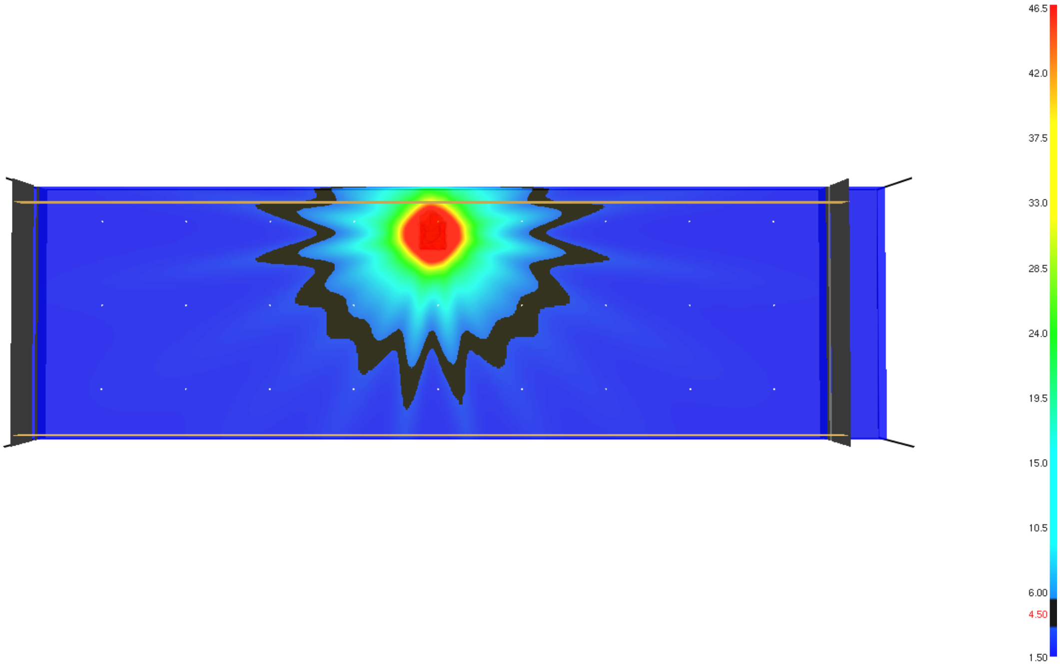
Figure 125: At t = 50 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).



(a)



(b)



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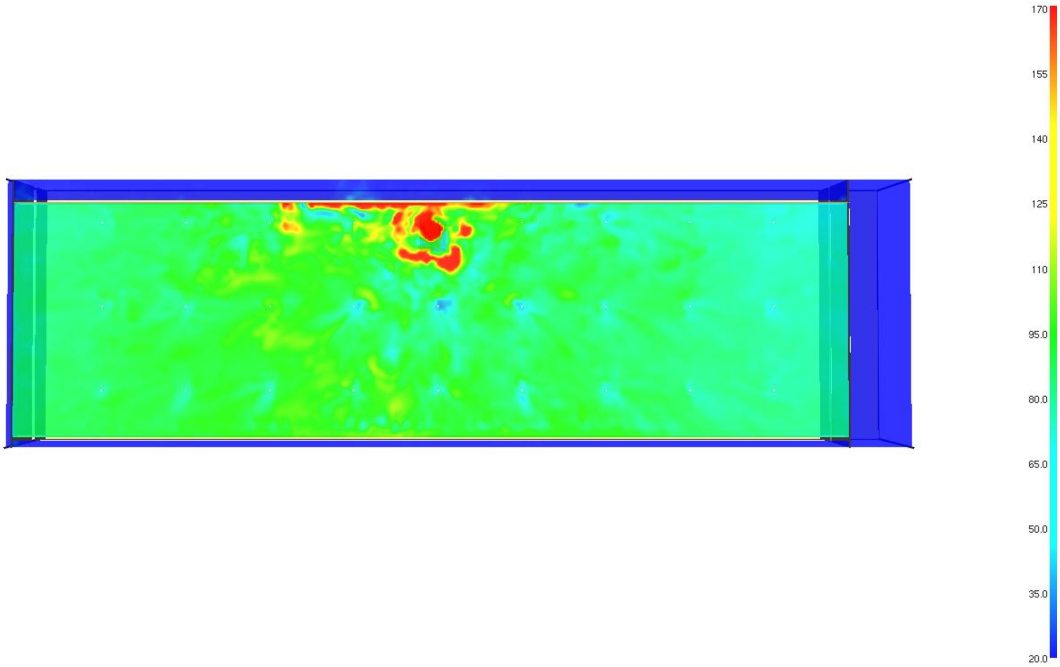
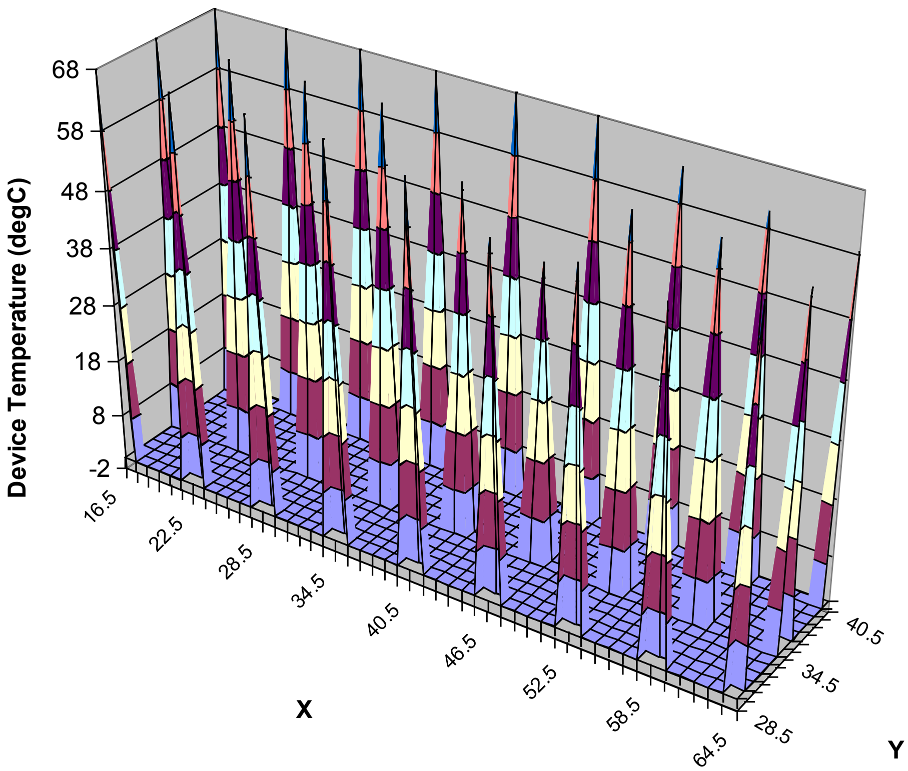


(d)



(e)

Figure 126: At t = 60 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).

APPENDIX.C SECTIONED GENERIC WAREHOUSE MODELLING RESULTS WITH WOOD CRIBS - FDS

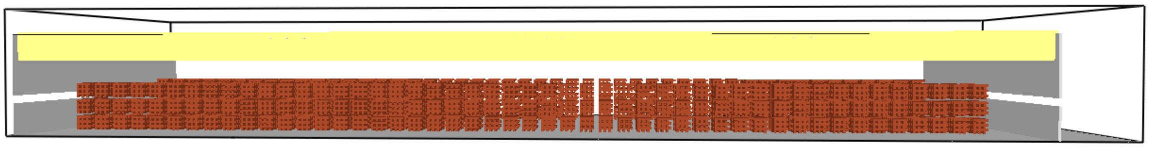
Similar to the approach described in Appendix B, the appropriateness of investigating fire venting in large warehouses using a section of the warehouse (e.g. a section contained by a smoke reservoir) was considered using an alternative fire source. The scenarios considered in Appendix B were challenged with a small burner fire in a section of warehouse with wood cribs stacked to represent a fire hazard category (FHC) of 3.

C.1 Scenario 1: Single Smoke Reservoir and No Fire Venting

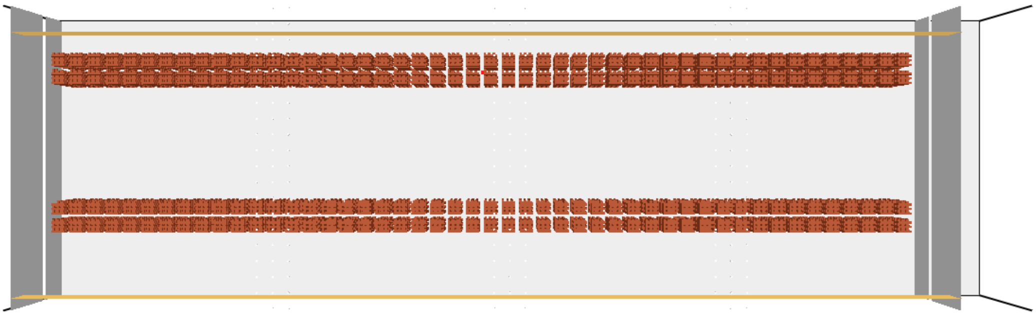
This method was not considered appropriate for the scenarios where no smoke reservoirs were present.

C.1.1 Scenario 1b: Four Smoke Reservoirs and no Fire Venting

Scenario 1 was modified so that the modelled section including one smoke reservoir was considered. This provides a base case for comparison with other scenarios.

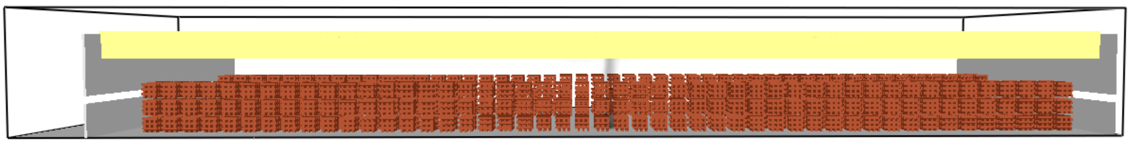


(a)

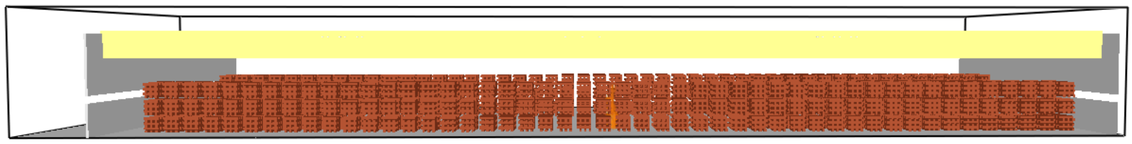


(b)

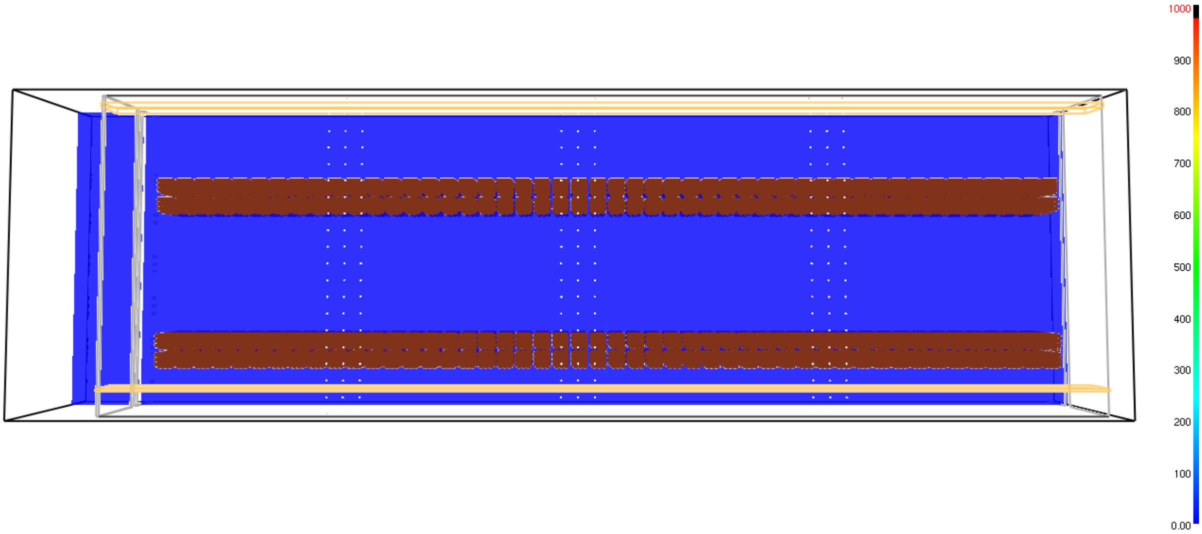
Figure 127: Schematics of the section of warehouse modelled.



(a)



(b)



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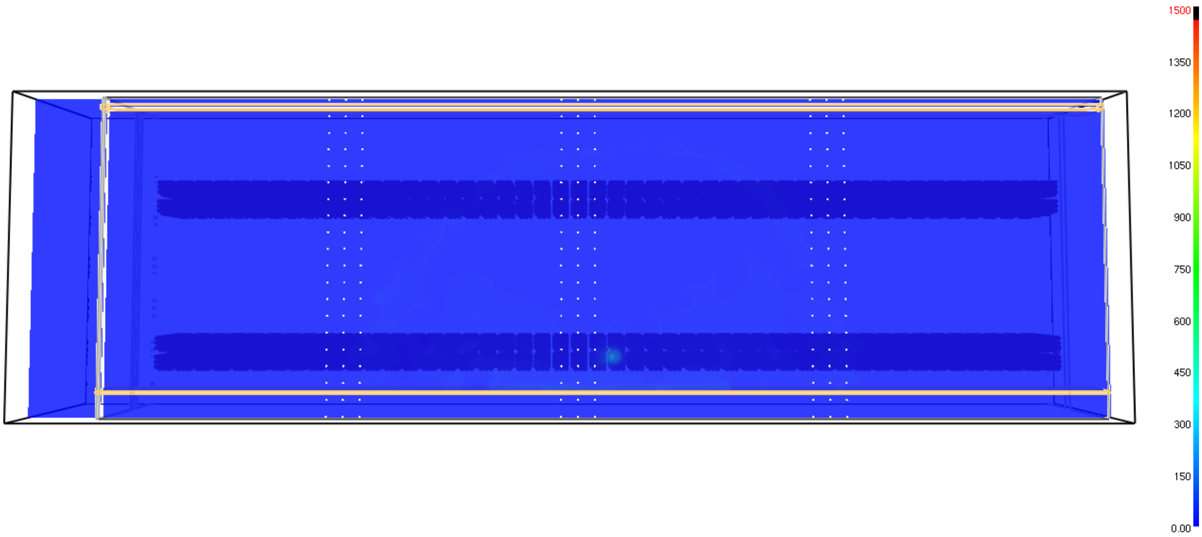

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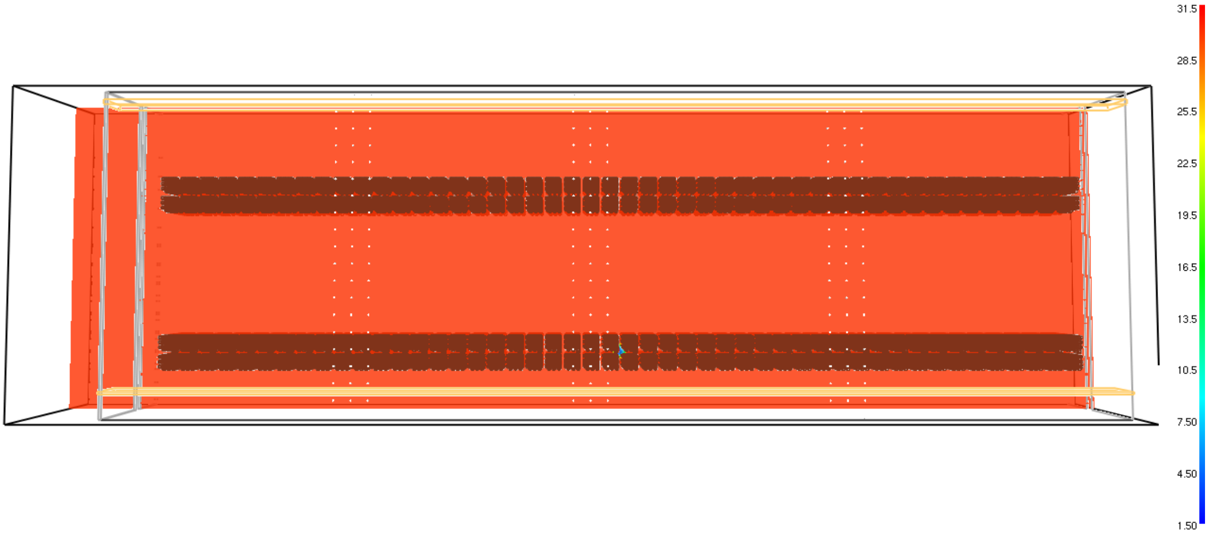

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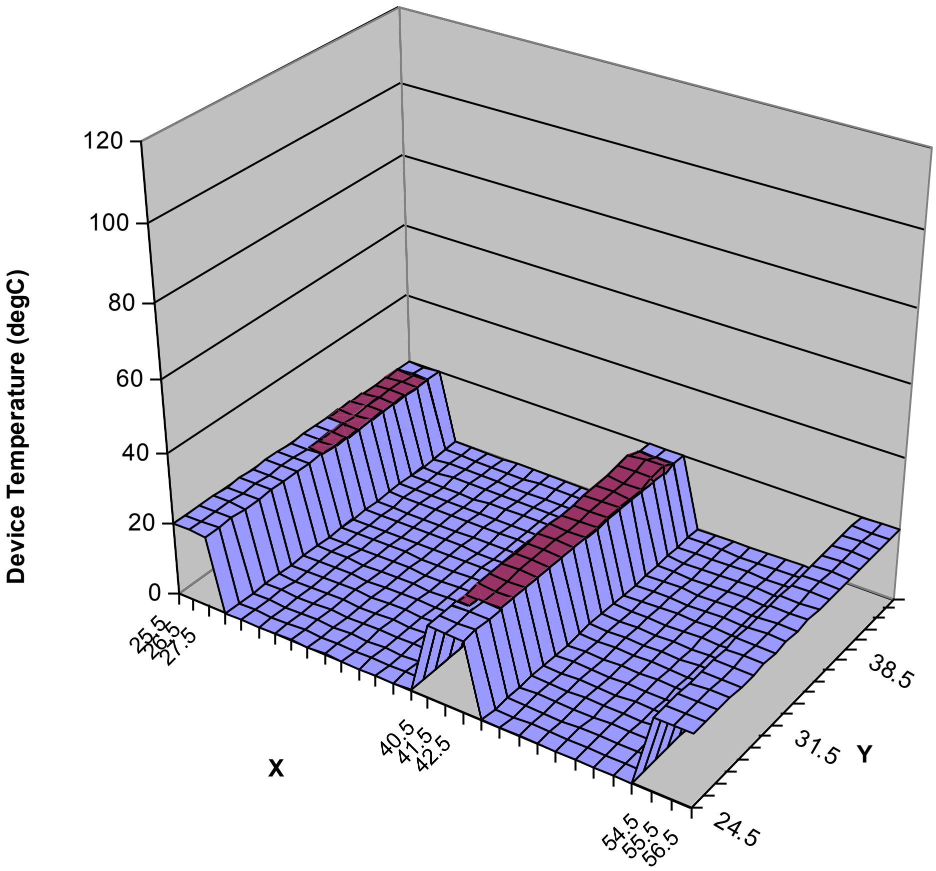
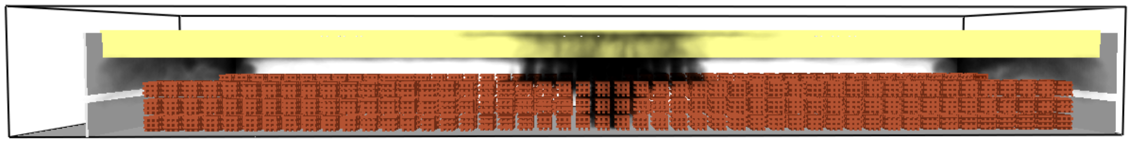
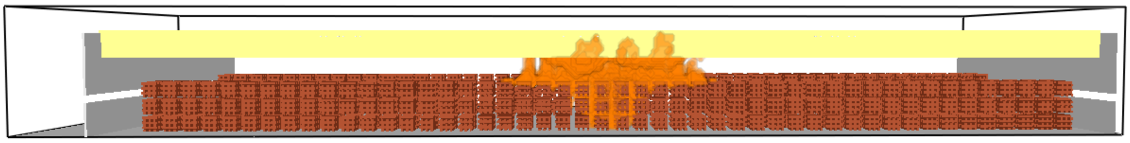


(f)

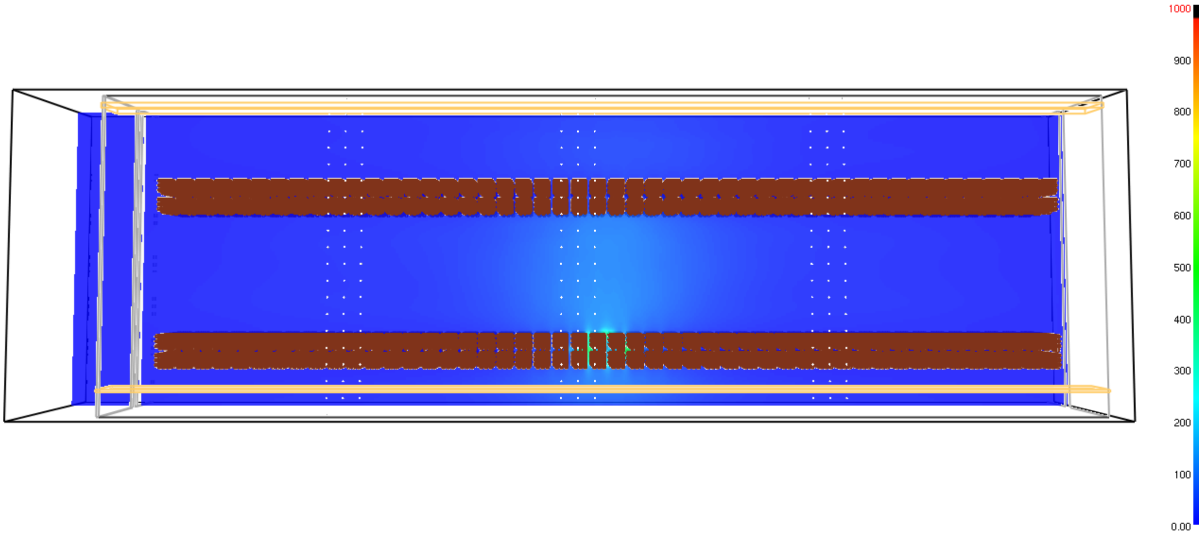
Figure 128: At t = 20 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).



(a)



(b)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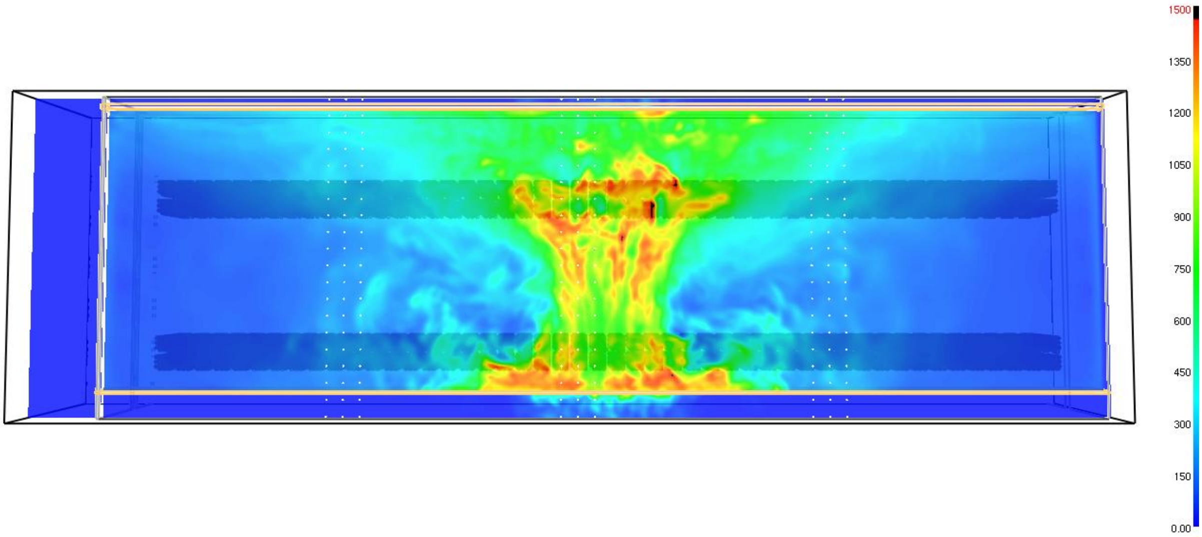
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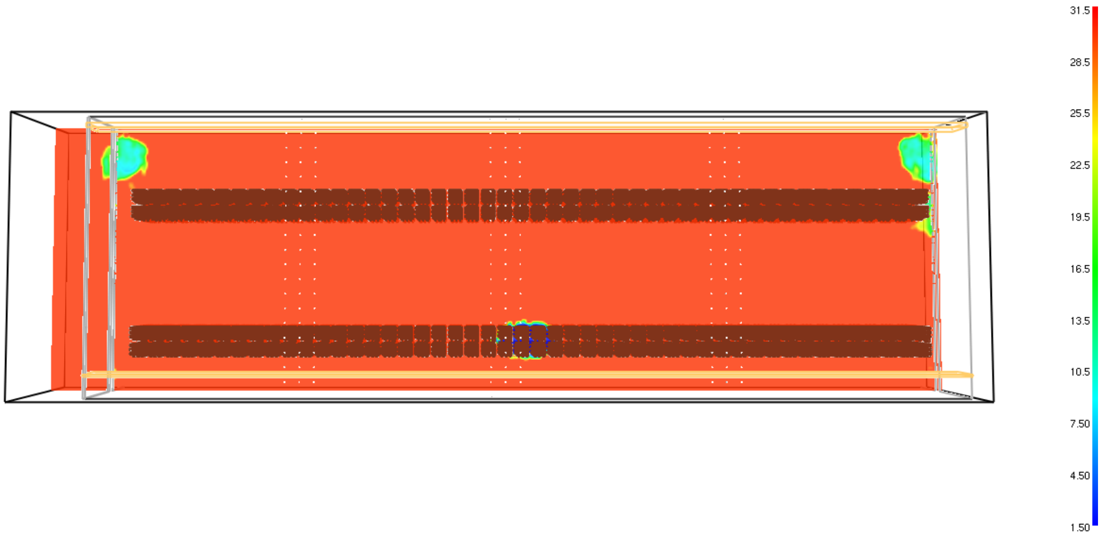
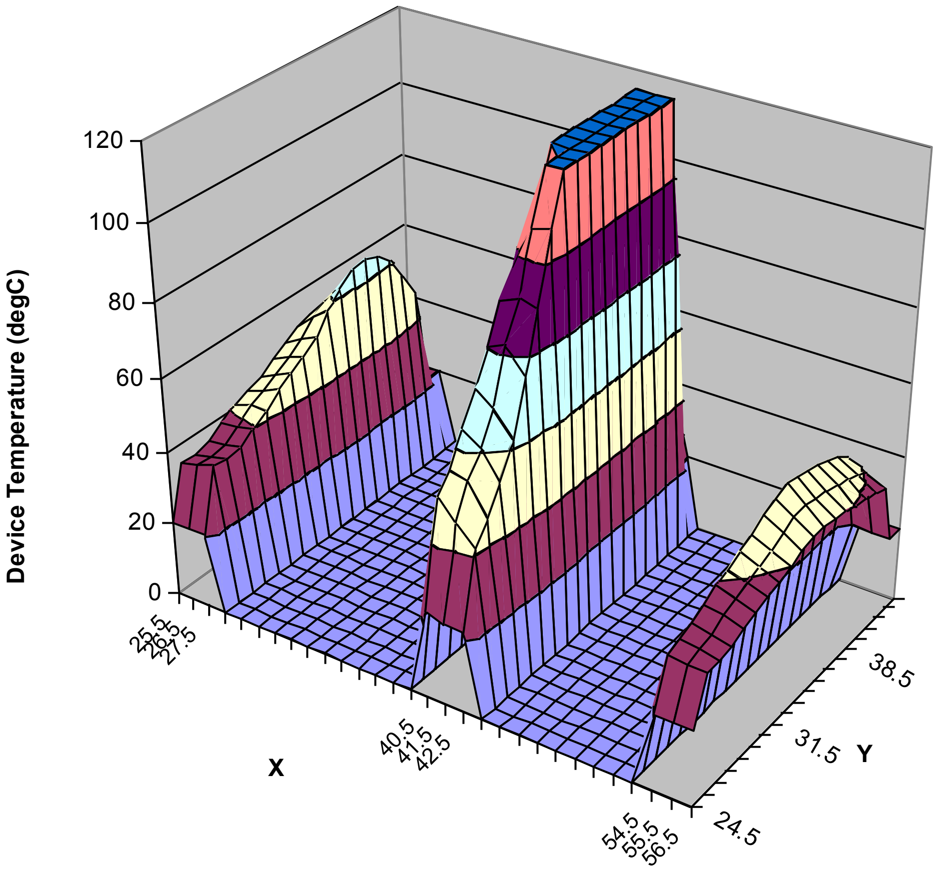
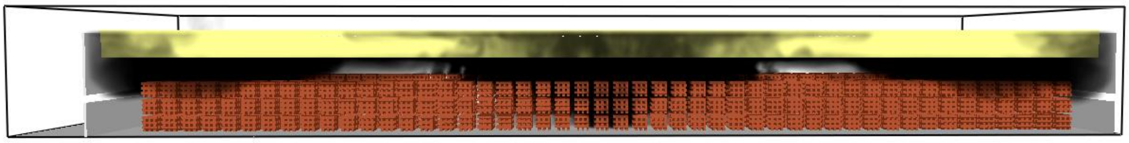


(e)

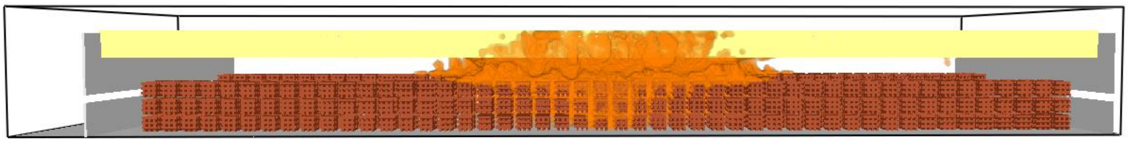


(f)

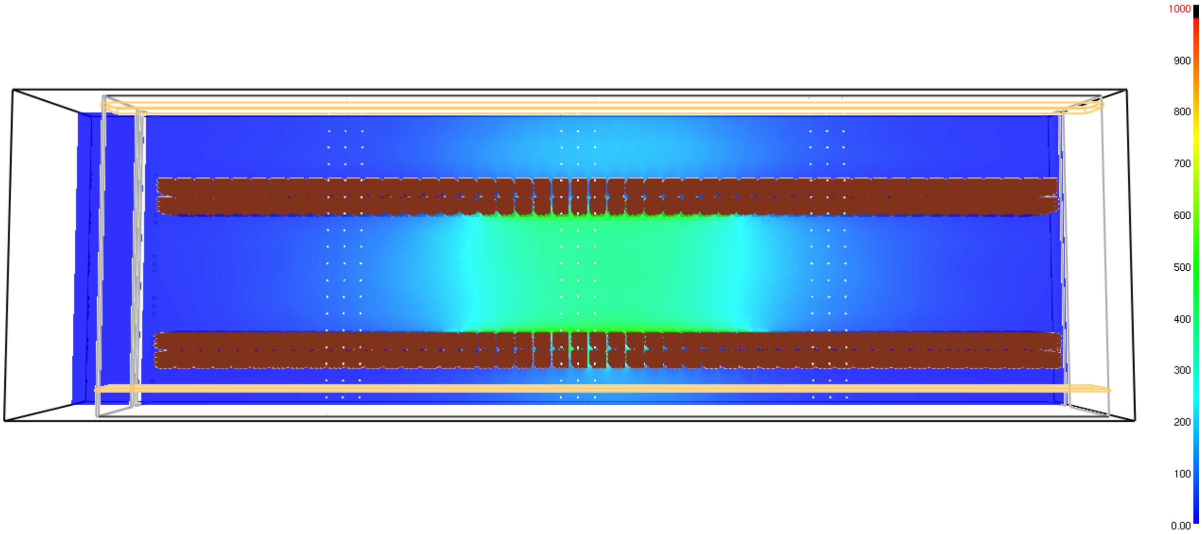
Figure 129: At t = 50 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).



(a)



(b)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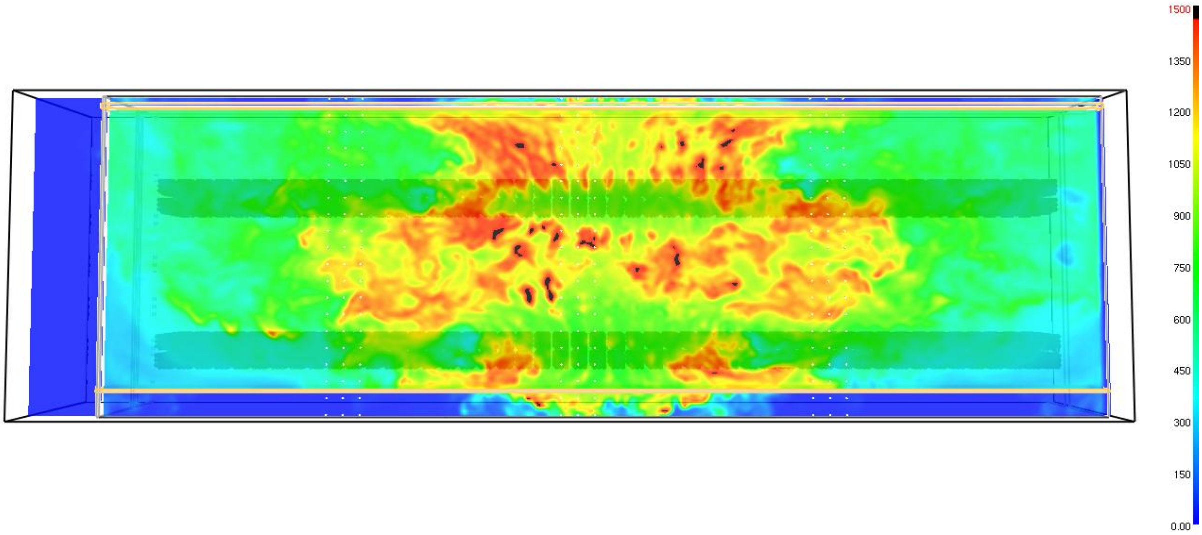
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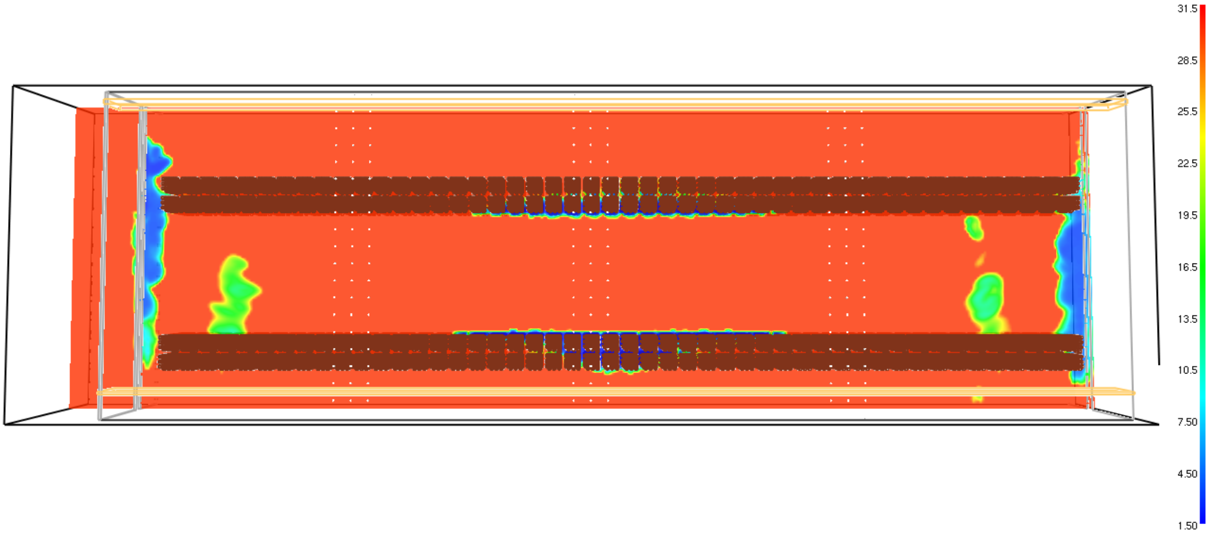
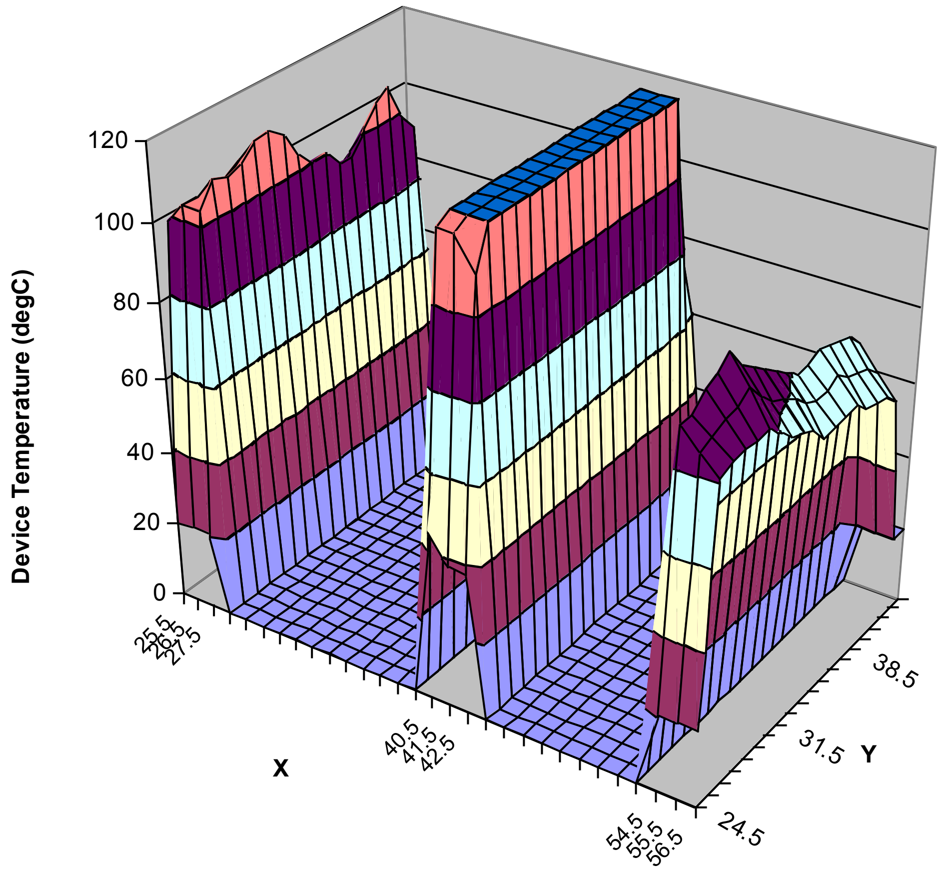
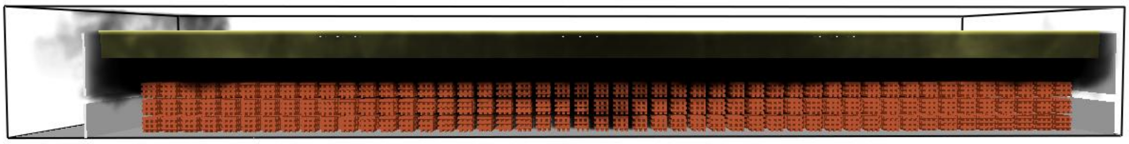


(e)

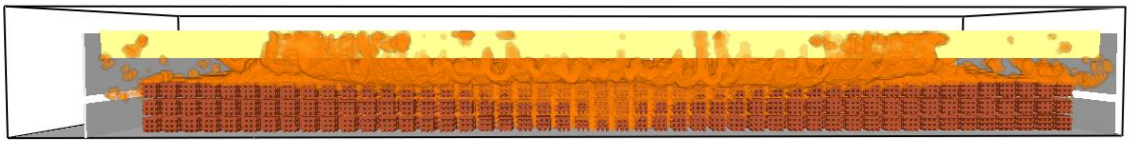


(f)

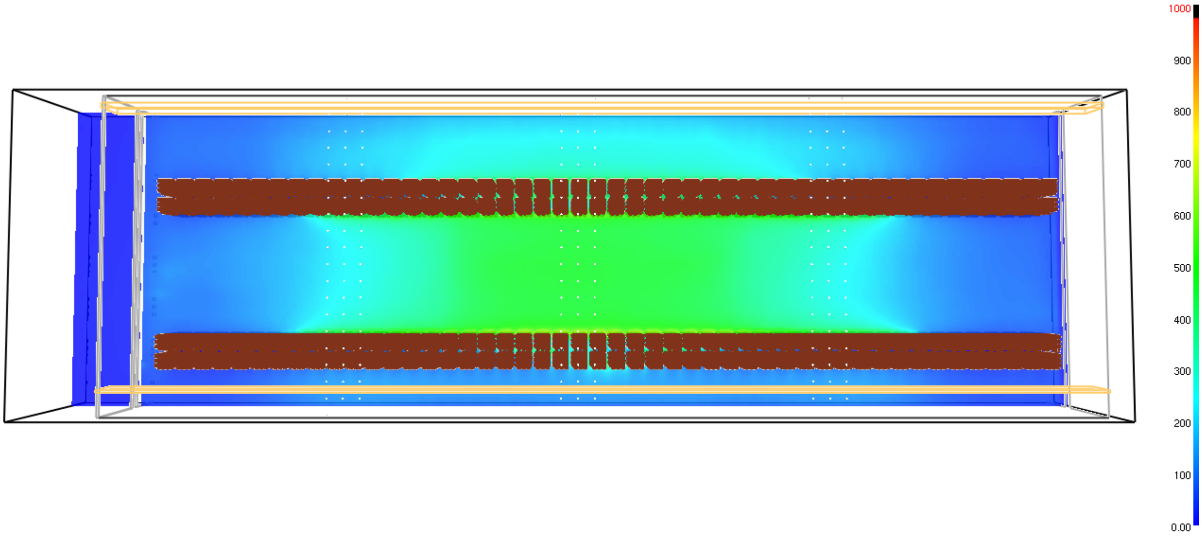
Figure 130: At t = 55 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).



(a)



(b)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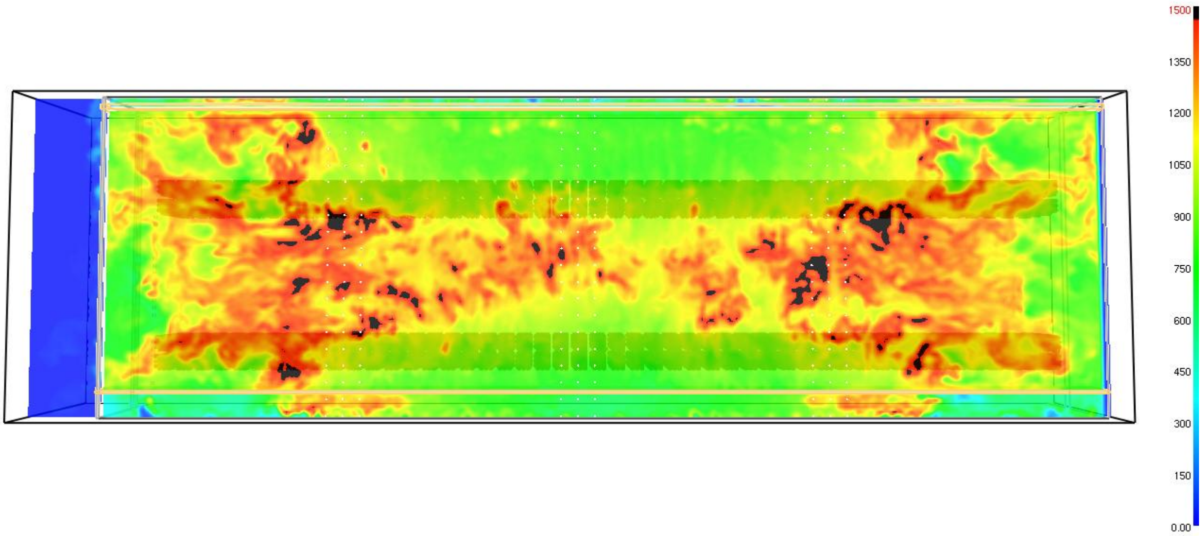
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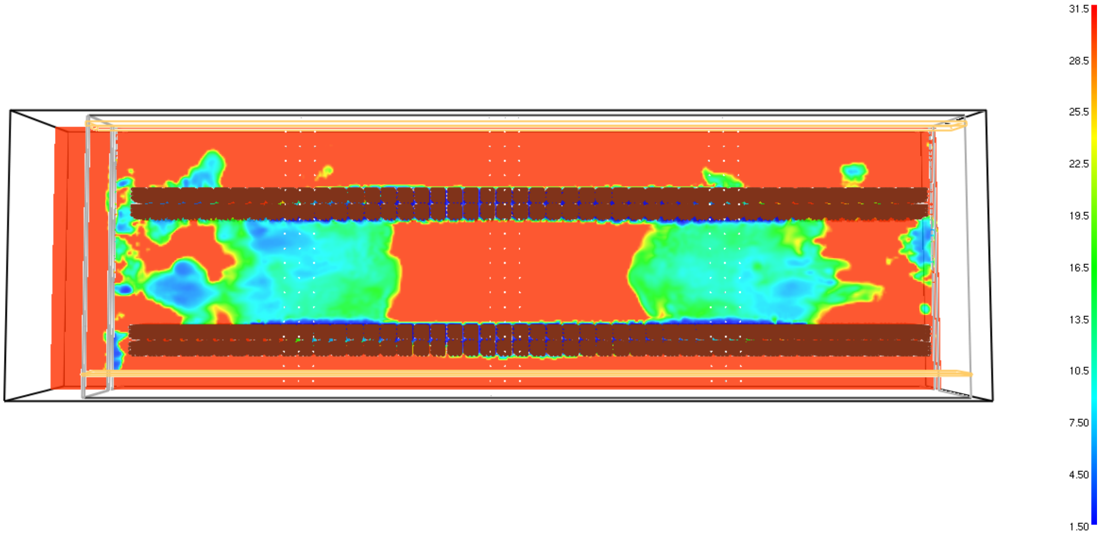

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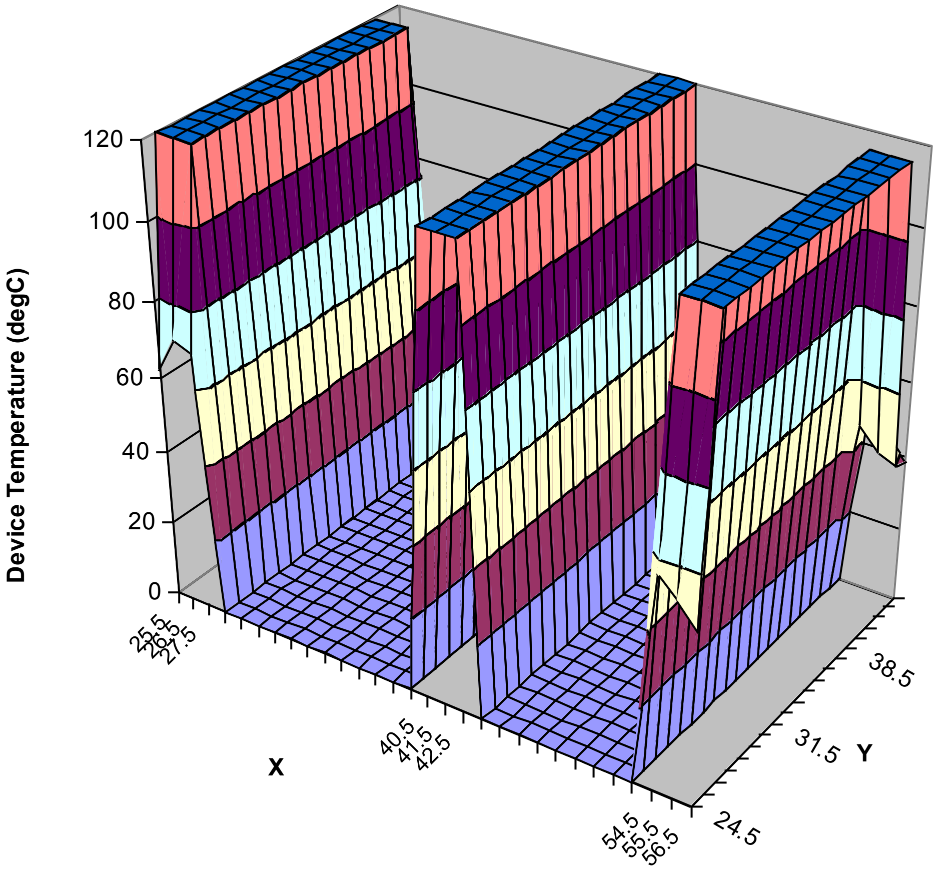


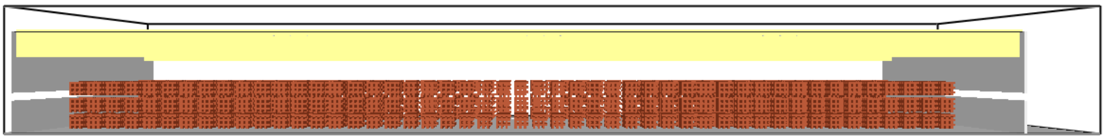
(f)

Figure 131: At t = 60 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).

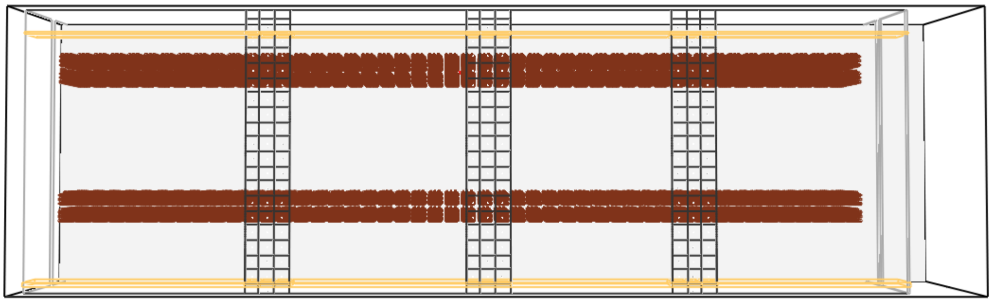
C.2 Scenario 2: Single Smoke Reservoir and Local 120ºC Fire Venting and Vent Area of 15% Floor Area

This method was not considered appropriate for the scenarios where no smoke reservoirs were present.

C.3 Scenario 3: Four Smoke Reservoirs and Local 120°C Fire Venting and Vent Area of 15% Reservoir Floor Area

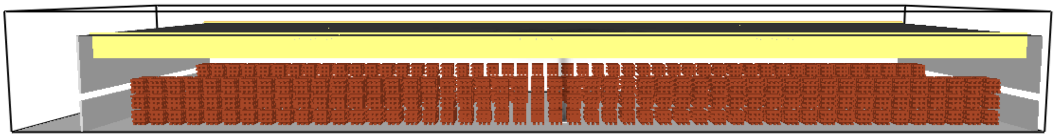


(a)

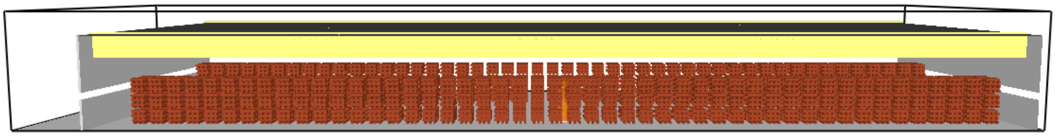


(b)

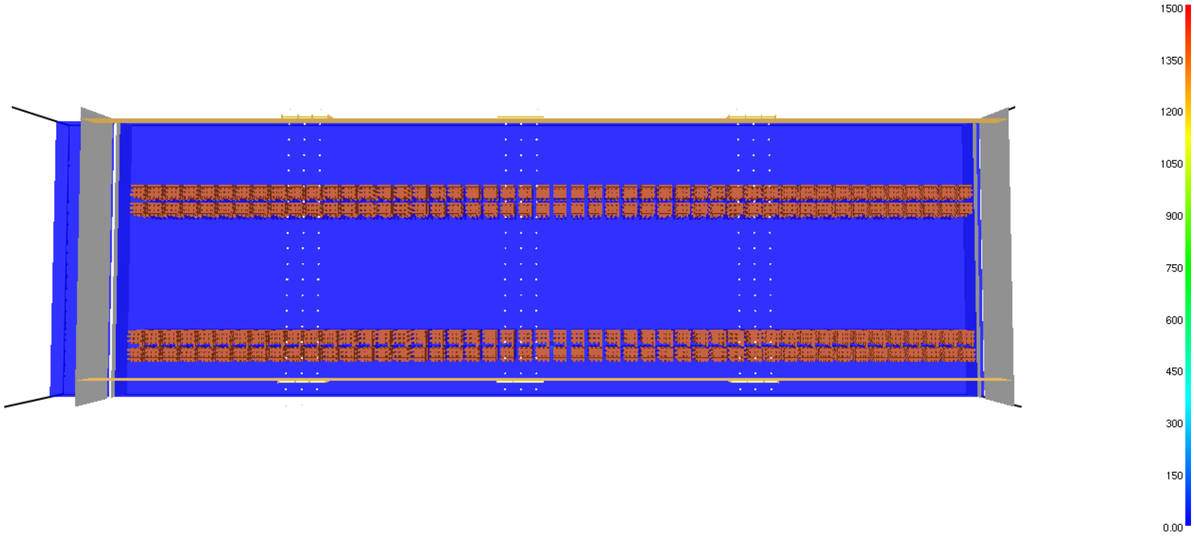
Figure 132: Schematics of the section of warehouse modelled.



(a)



(b)



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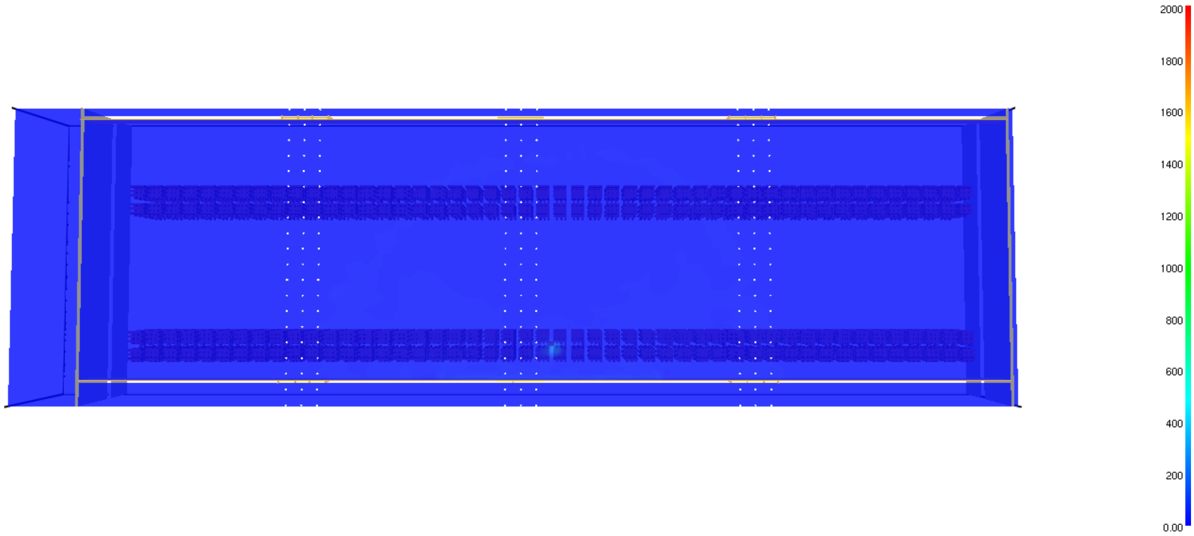

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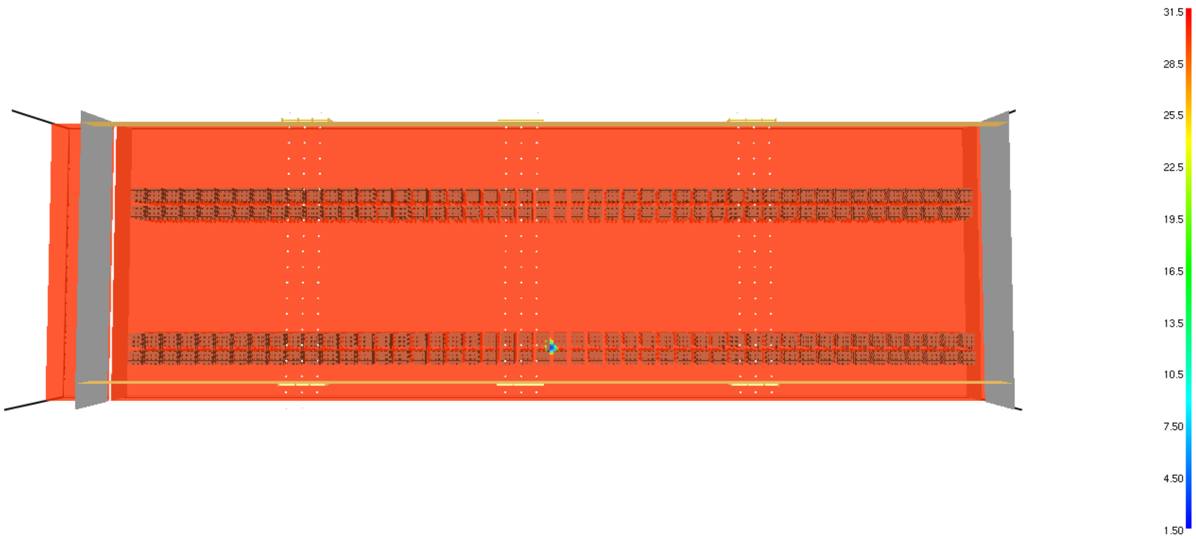
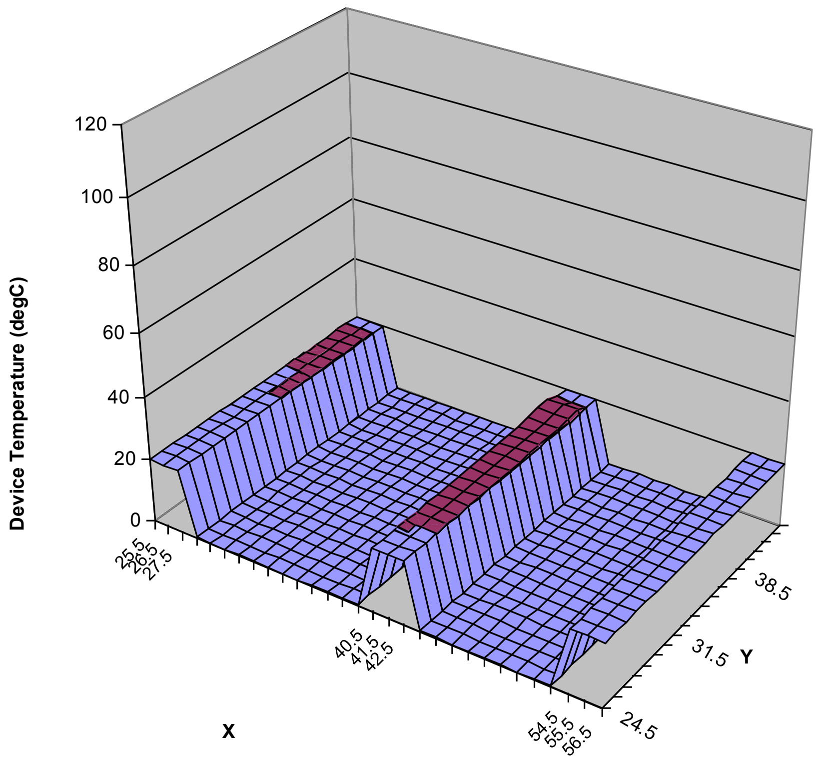
(d)

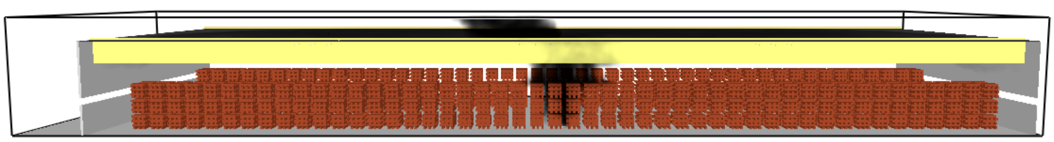


(e)

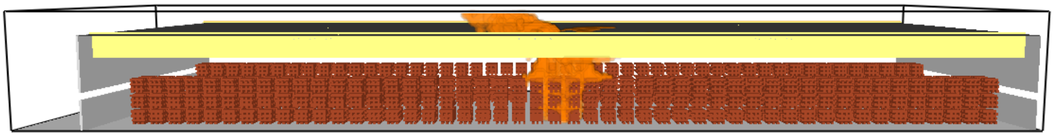


(f)

Figure 133: At t = 20 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).



(a)



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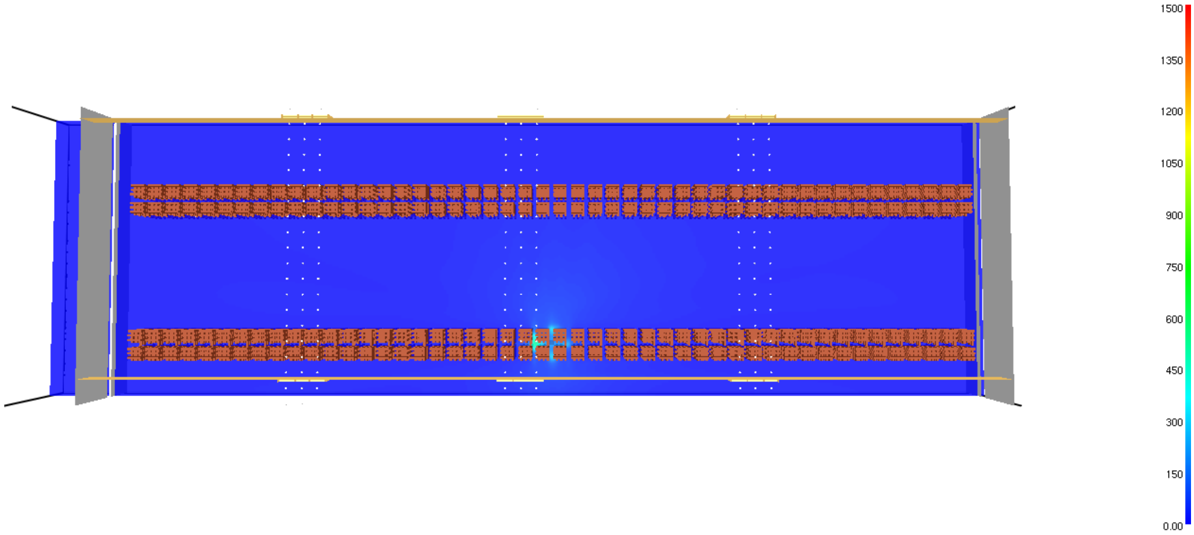
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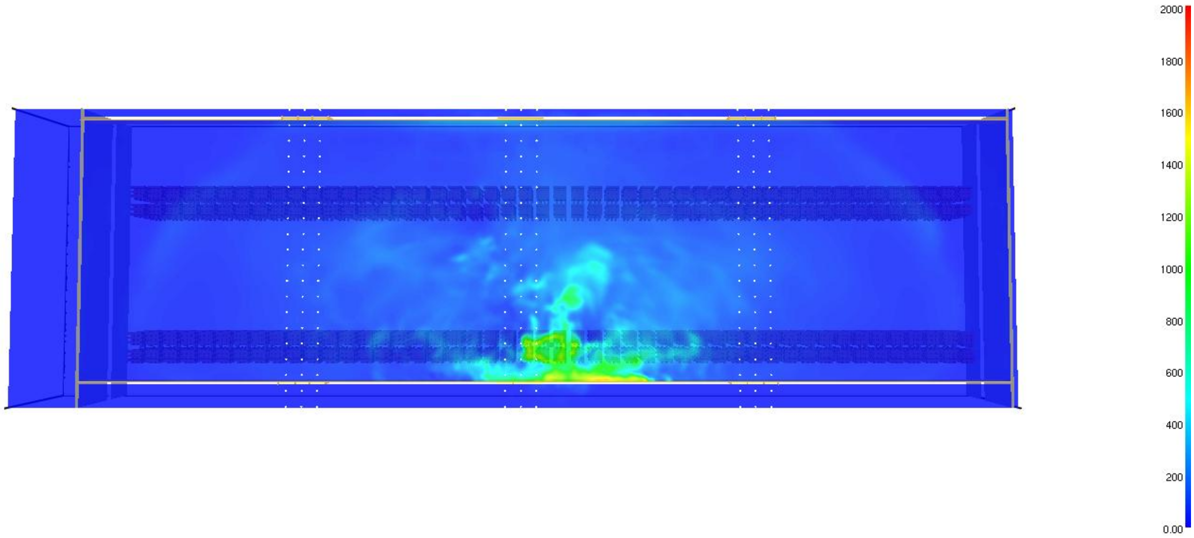
(c)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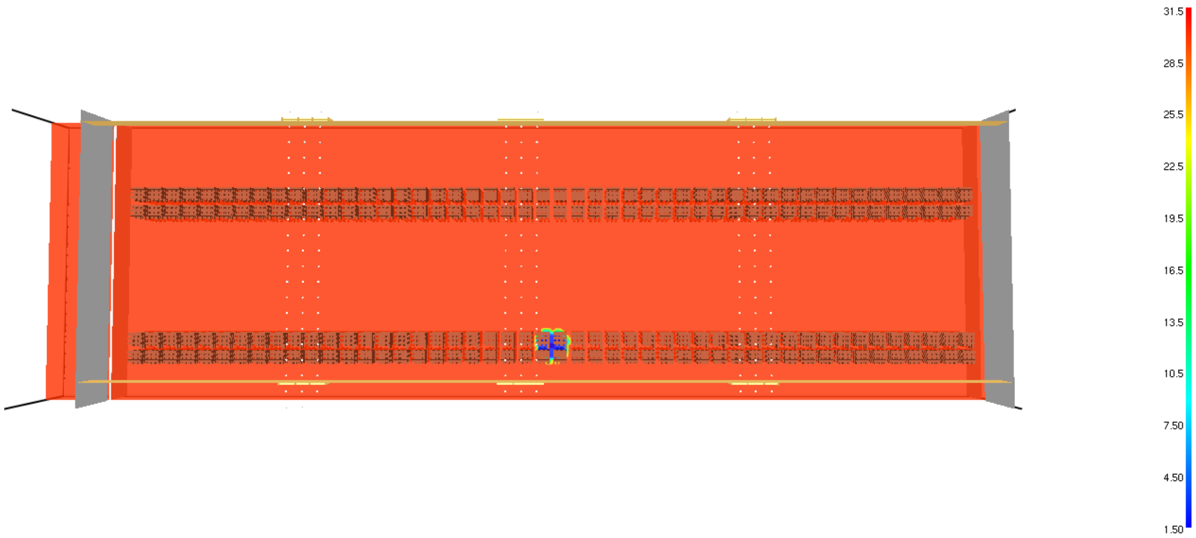
(d)



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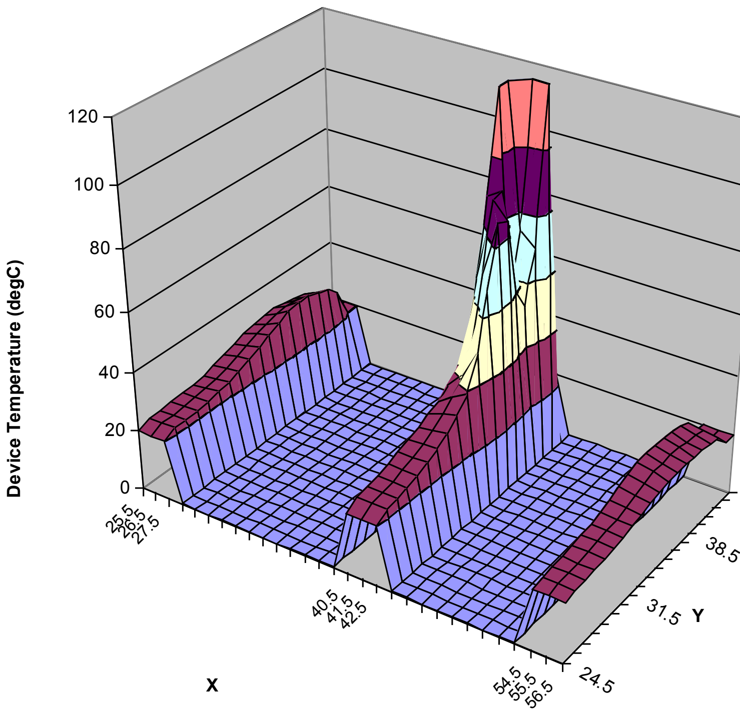
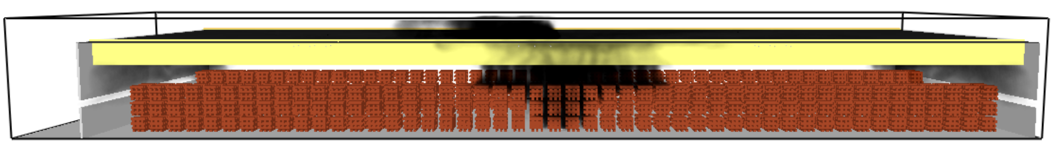
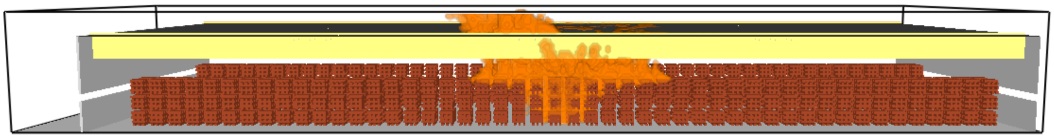


(f)

Figure 134: At t = 45 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).



(a)



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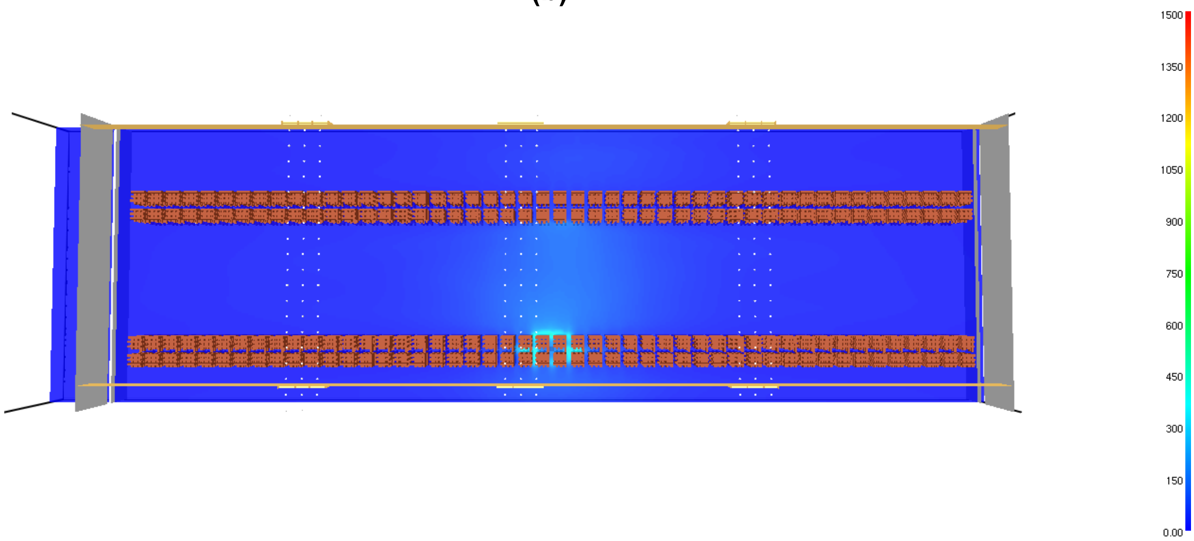
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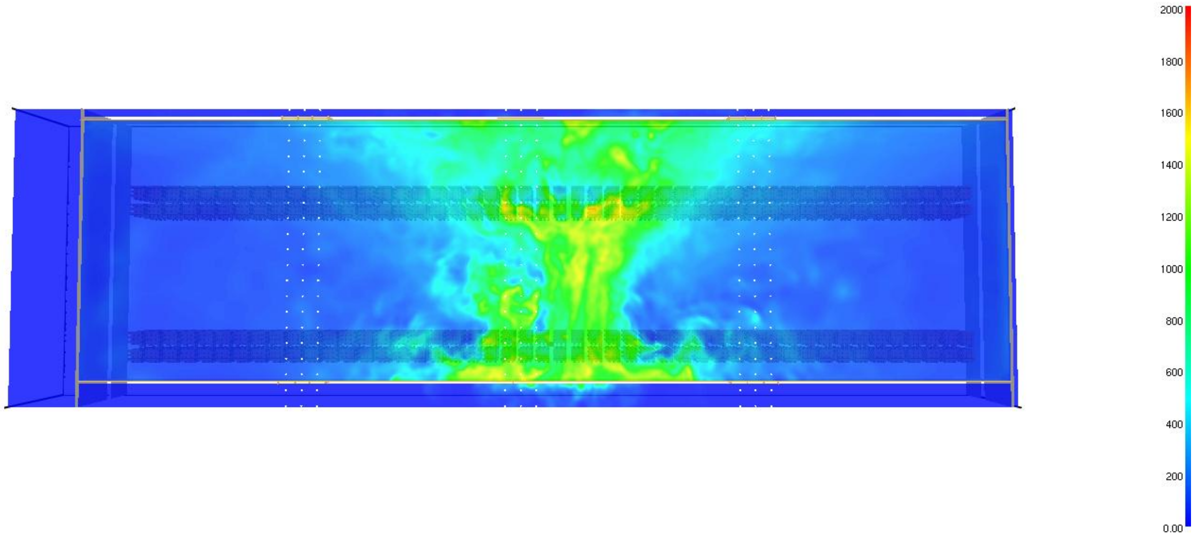
(c)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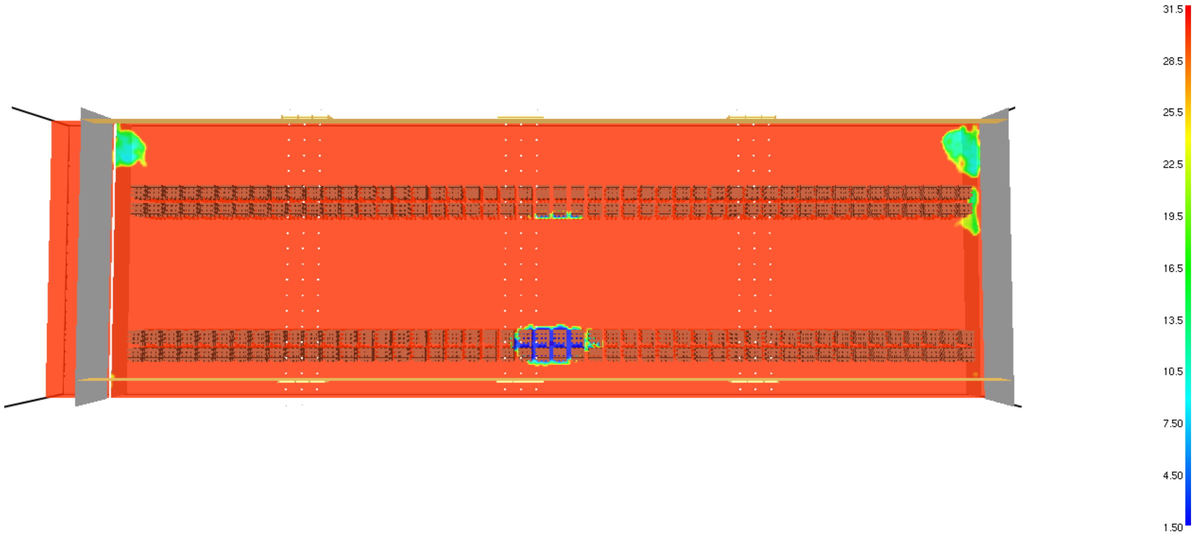
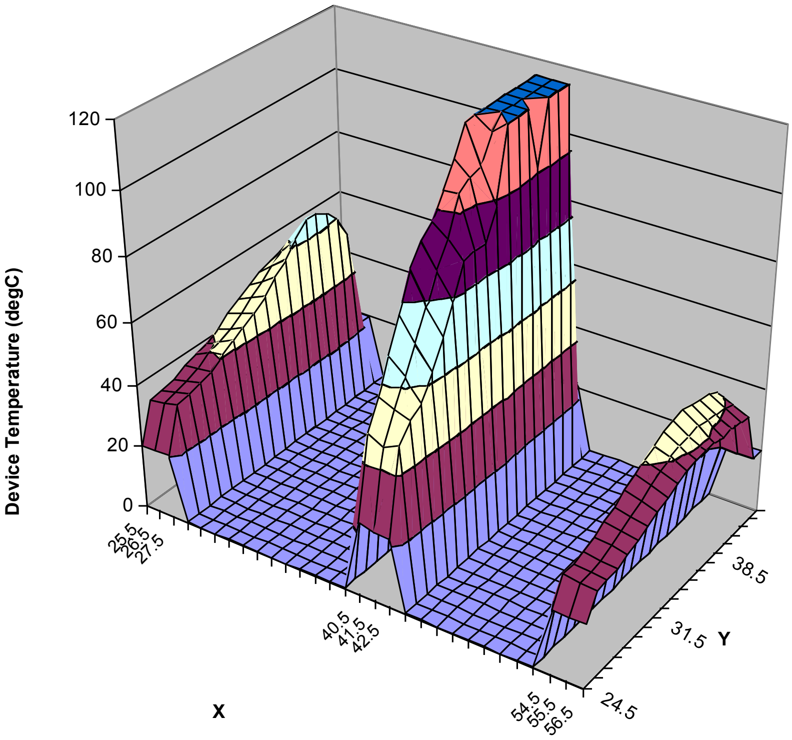
(d)

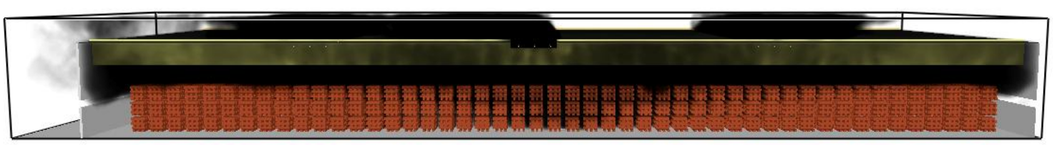


(e)

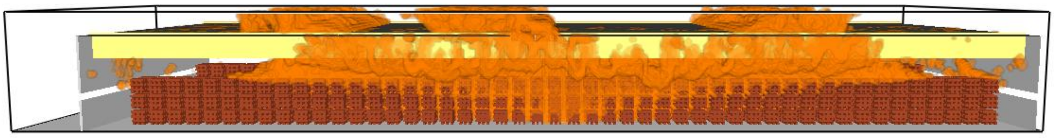


(f)

Figure 135: At t = 50 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).



(a)



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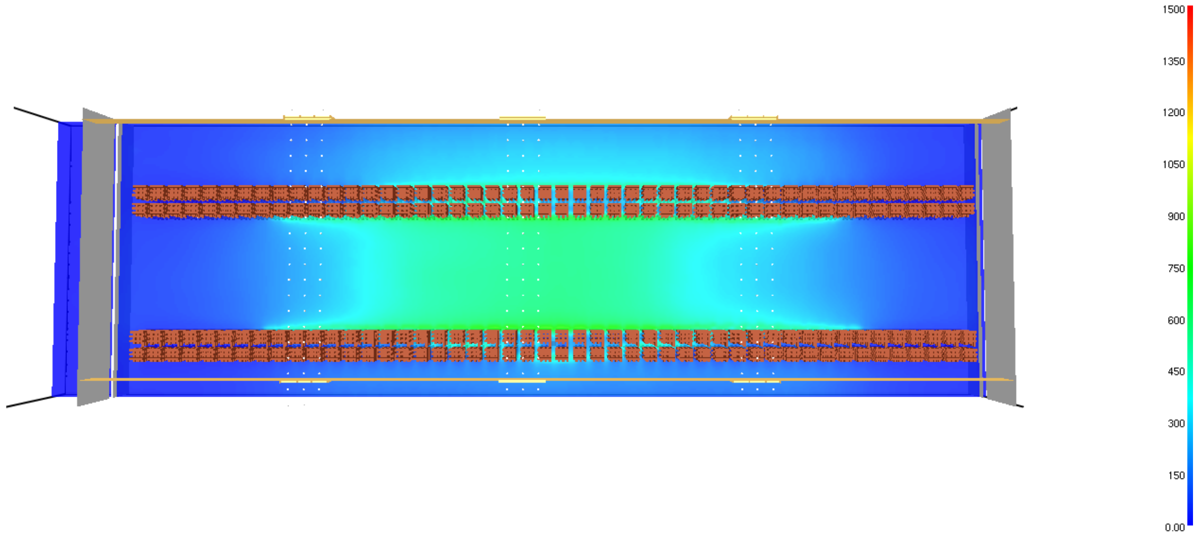
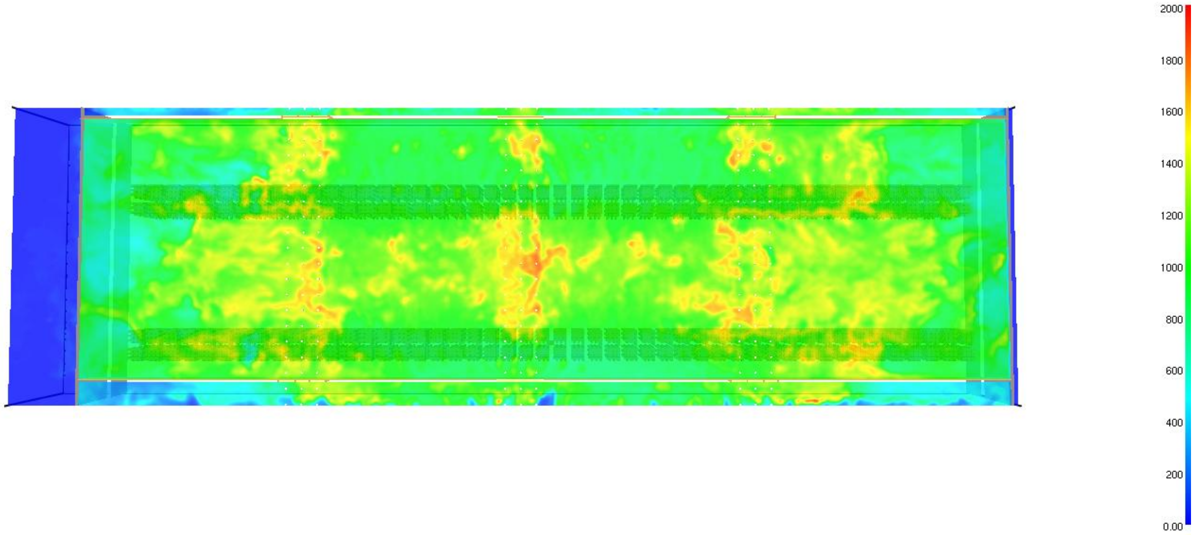


(c)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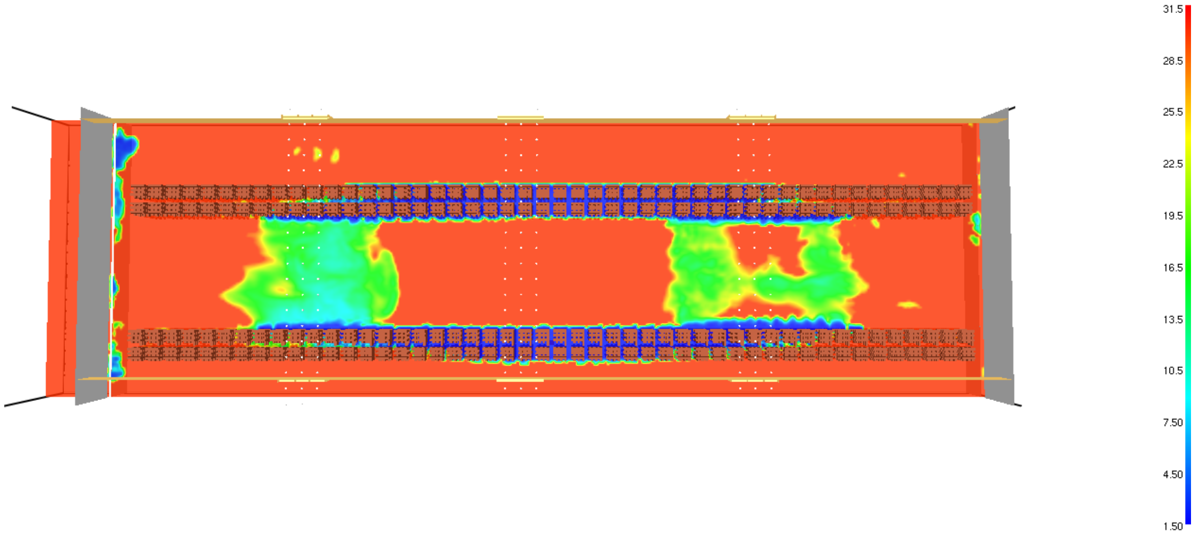
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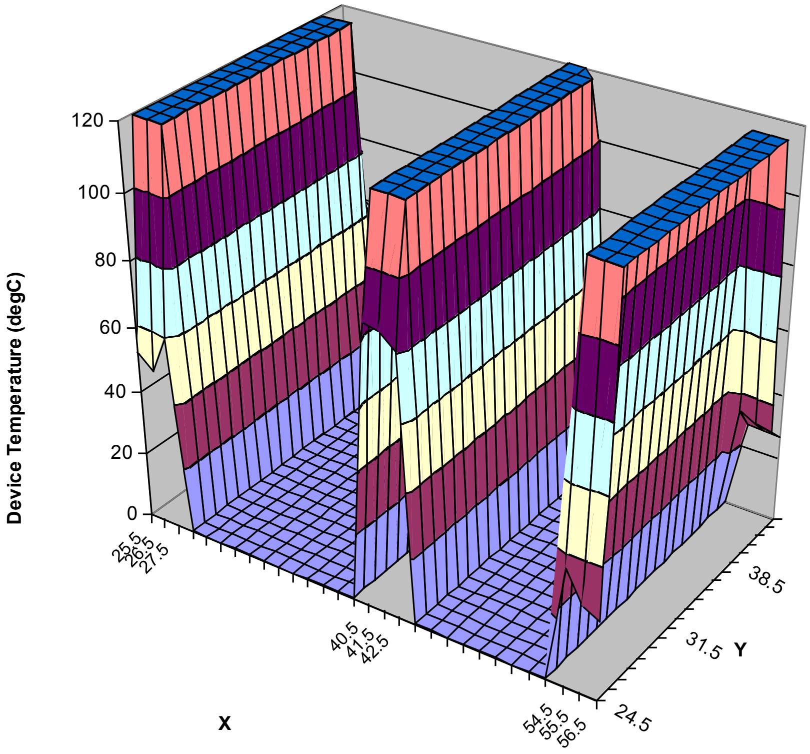
19.5
16.5
13.5
10.5
7.50
4.50
1.50

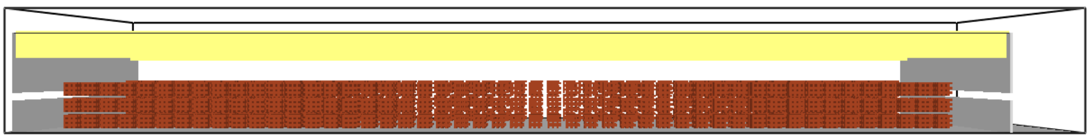
(e)



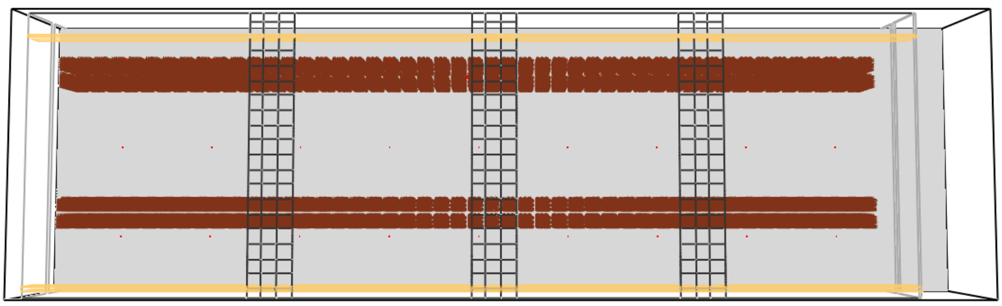
(f)

Figure 136: At t = 60 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, (e) visibility (m) at 2 m above floor height, and (f) device temperatures (°C).

C.4 Scenario 4: Four Smoke Reservoirs and Simultaneous Activation of 68°C Fire Venting in each Smoke Reservoir and Vent Area of 3% Reservoir Floor Area

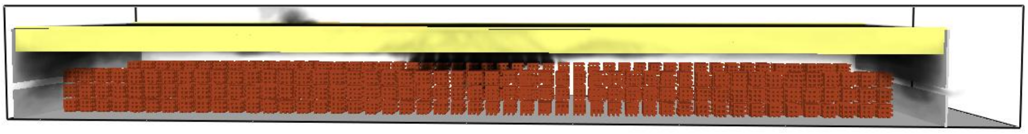


(a)

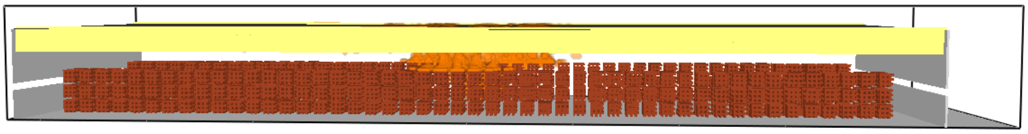


(b)

Figure 137: Schematics of the section of warehouse modelled.



(a)



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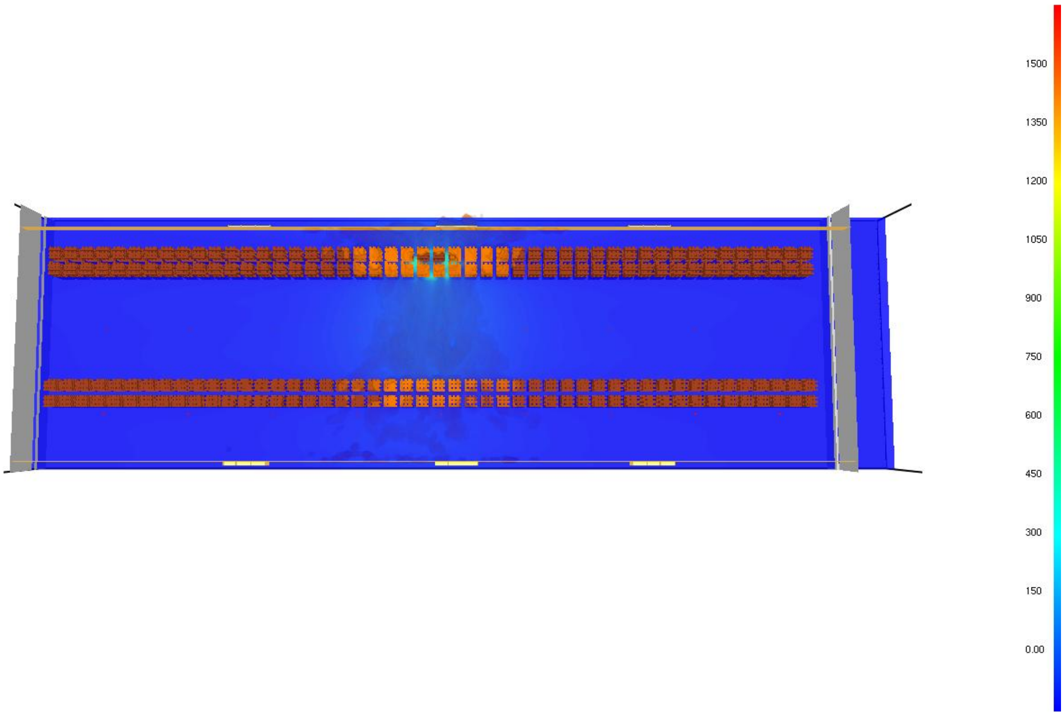
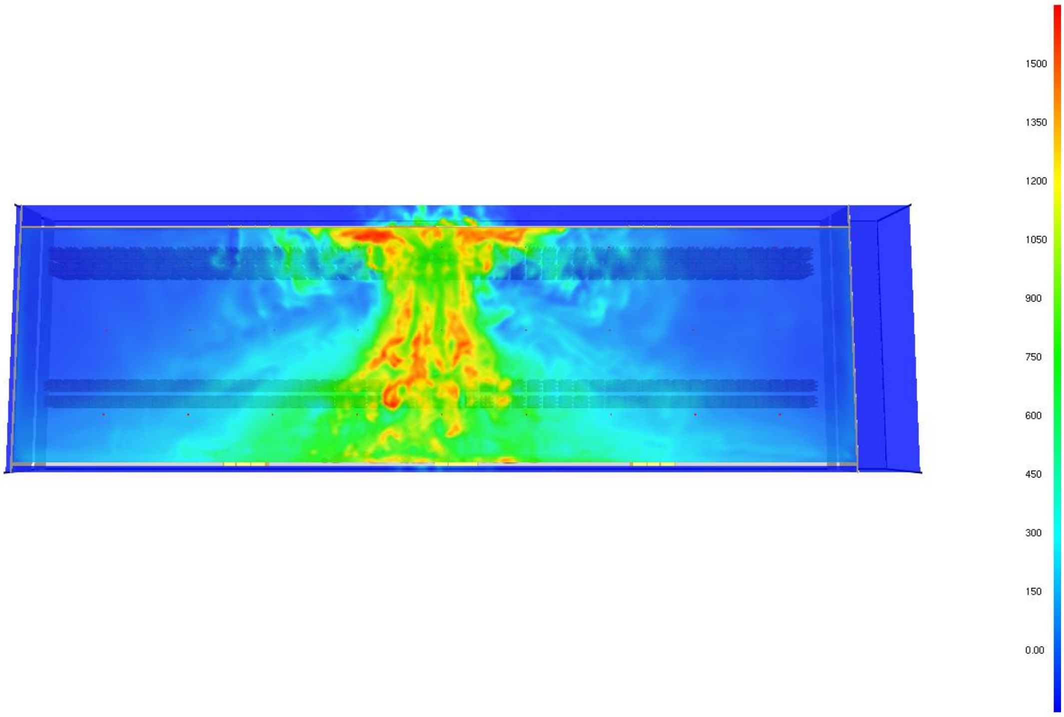
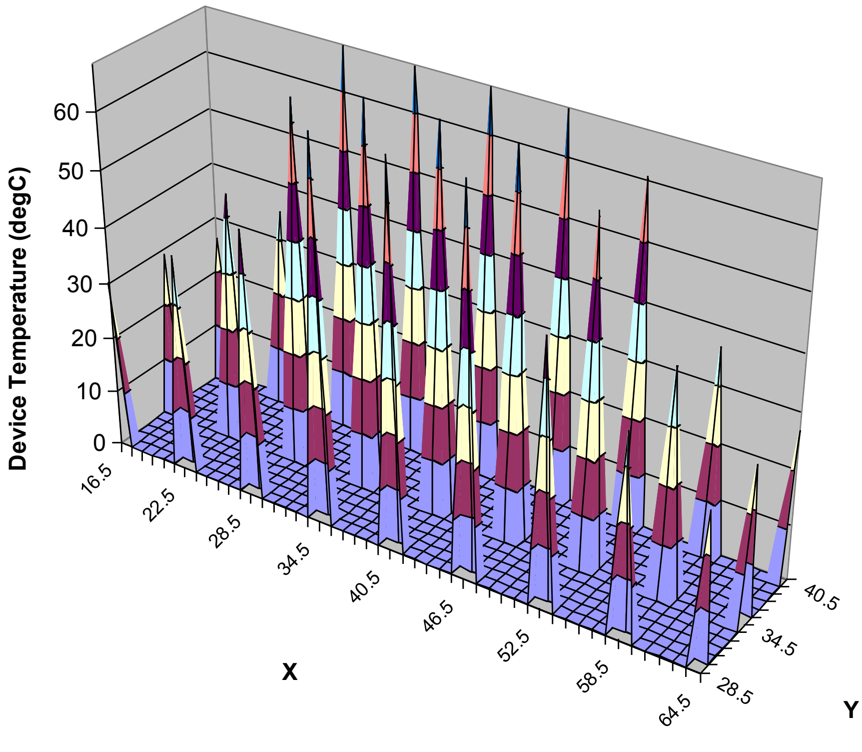


(c)

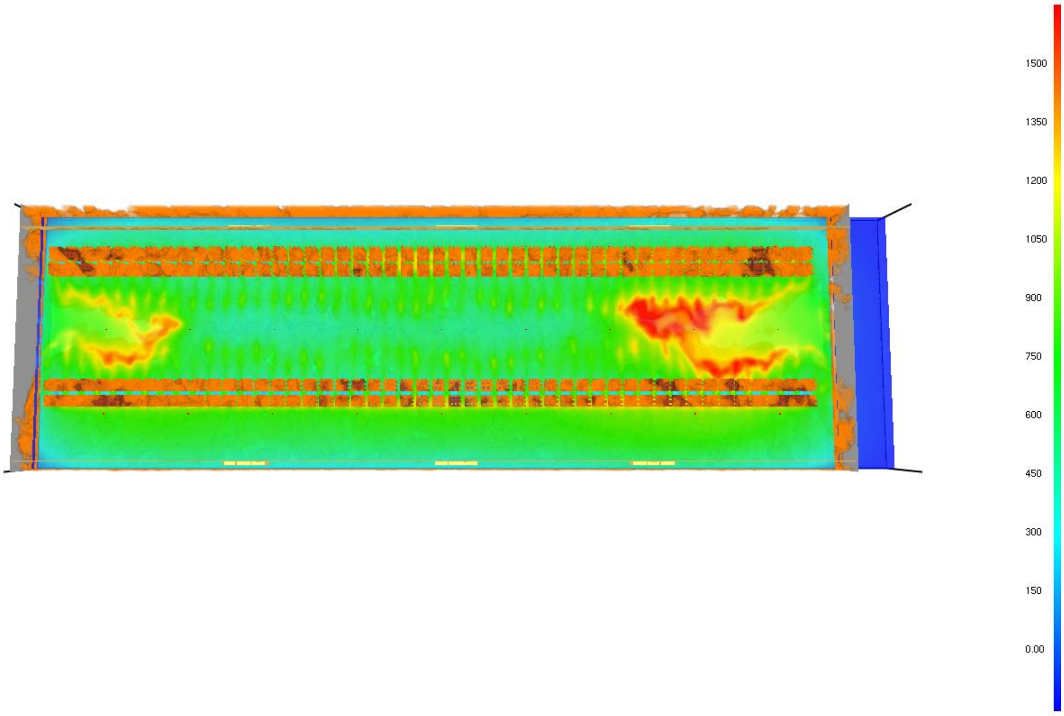


(d)



(e)

Figure 138: At t = 50 s (a) representative soot density, (b) surface where energy density is 190 kW/m³, (c) radiant intensity (kW/m²) at 1.5 m above floor height, (d) gas temperature (°C) at 5.5 m above floor height, and (e) device temperatures (°C).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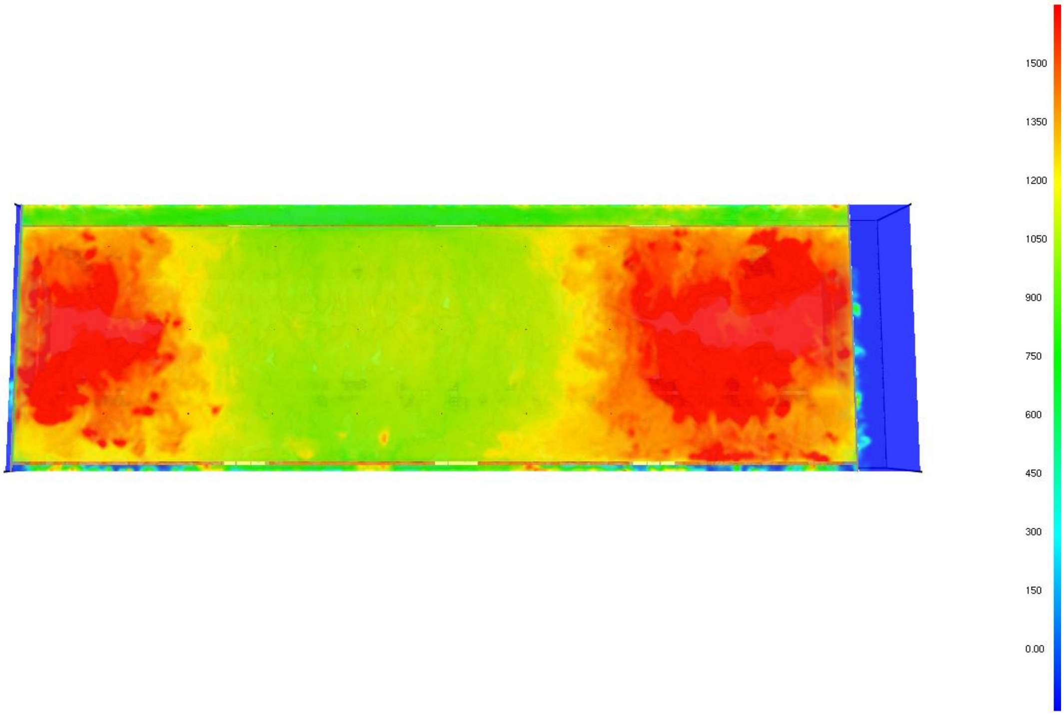
(a)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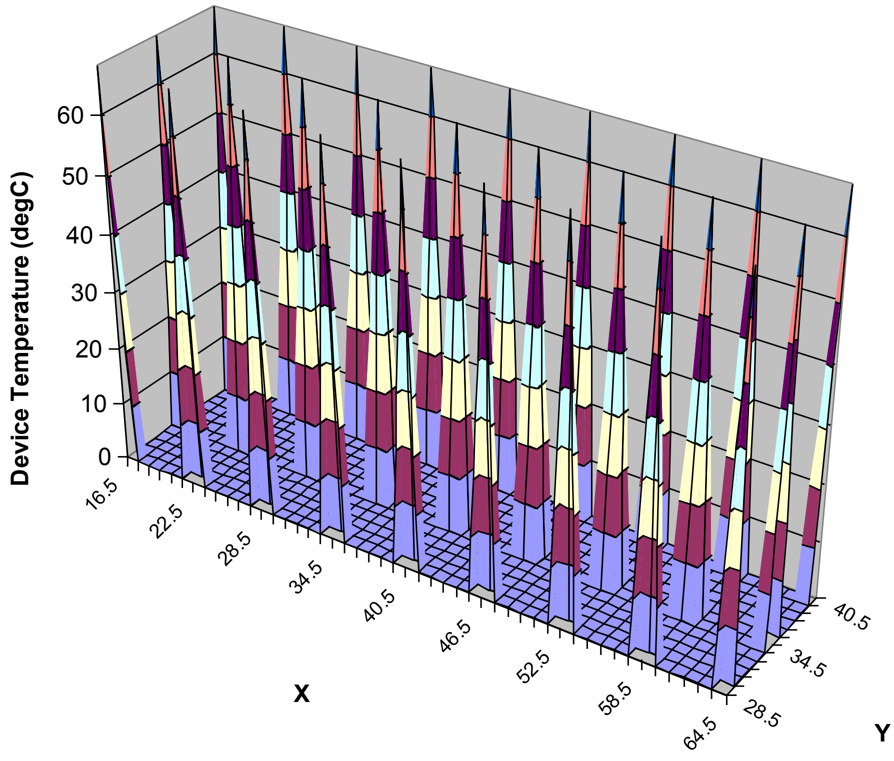
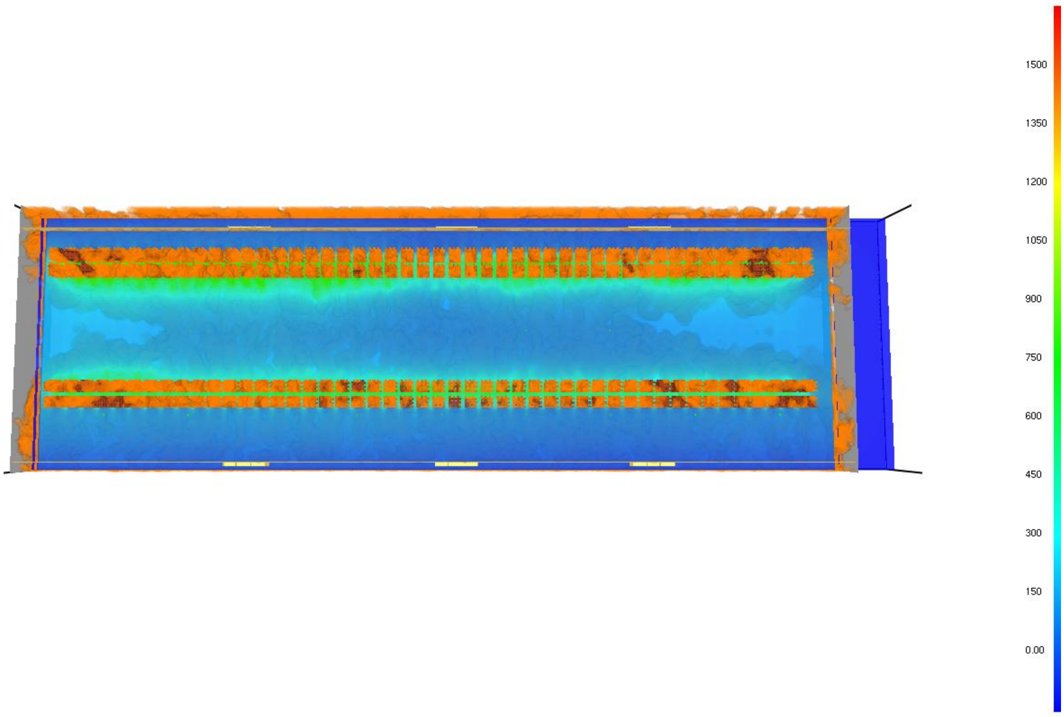
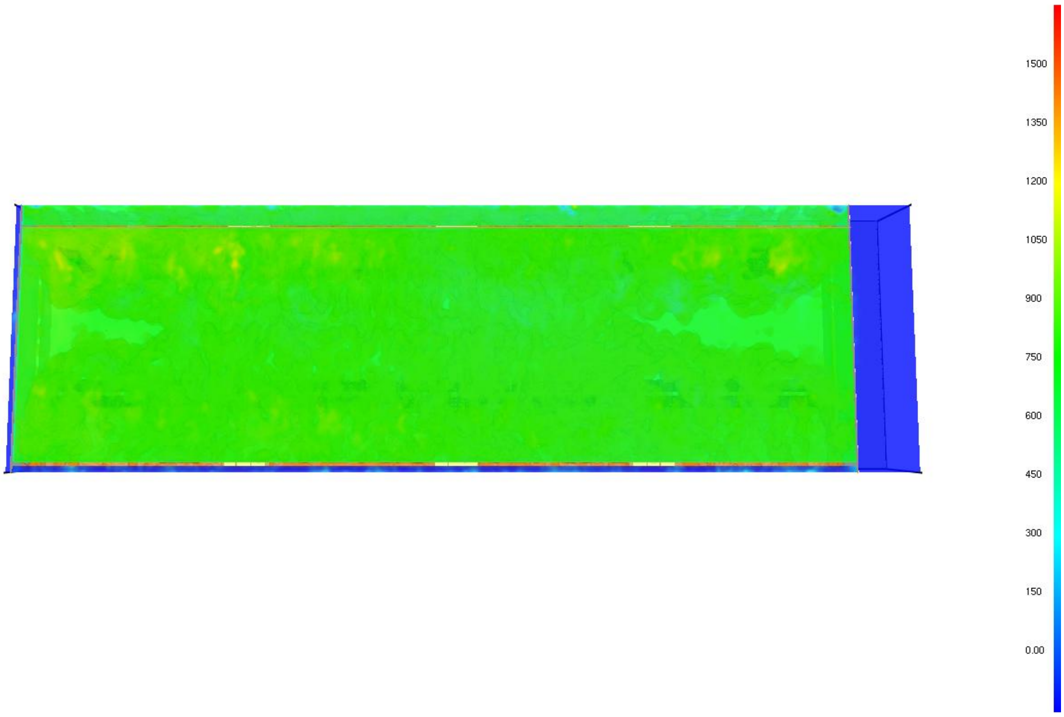


(c)

Figure 139: At t = 100 s (a) radiant intensity (kW/m²) at 1.5 m above floor height, (b) gas temperature (°C) at 5.5 m above floor height, and (c) device temperatures (°C).



(a)



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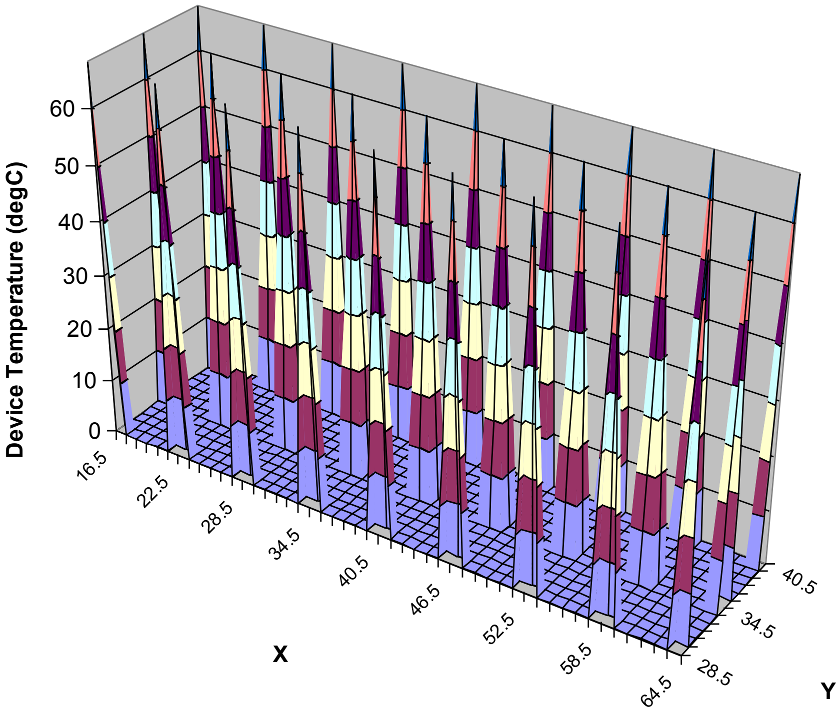


(c)

Figure 140: At t = 500 s (a) radiant intensity (kW/m²) at 1.5 m above floor height, (b) gas temperature (°C) at 5.5 m above floor height, and (c) device temperatures (°C).

APPENDIX.D TIME TO START OF FIRE SUPPRESSION ACTIVITIES

D.1 Fire Brigade Intervention Model - Description & Results

The input values and associated assumed ranges based on the Fire Brigade Intervention Model (AFAC, 2006; Marchant et al 1999, Marchant et al 2001, *International Fire Engineering Guidelines*, 2005) estimations for this study are presented in Table 11.

The example results presented in Table 12 are for a scenario where one set of appliances is called to the incident, although up to 3 sets of appliances may be included in the calculation of estimated time to application of water from time of detection.

The results of the Fire Brigade Intervention Model were used to estimate a conservative time to the application of water from the time of detection, i.e. the spread of the values for the variable labelled '1st appliance begins applying water to fire'. Neither the size of the fire nor the number of appliances called were considered in this part of the study.

The results for the time to application of water from time of detection using the Fire Brigade Intervention Model were estimated for the scenarios where:

- a monitored alarm system is present (Figure 141(a) and Table 13),
- a direct connection to the fire service is present (Figure 141(b) and Table 13), and
- response time (from receipt of the 111 call to arrival at the incident) only is considered (Figure 141(c) and Table 13).

The model was run using @Risk version 4.0.2, with one thousand iterations using Latin Hypercube sampling with expected value calculations and a random generator seed.

The sensitivities are also shown in Figure 142(a), (b) and (c) for the monitored alarm system example, the direct connection to the fire service example, and the response time example respectively. In all cases, the model results were most sensitive to the distance and travel speed between the incident and the fire service.

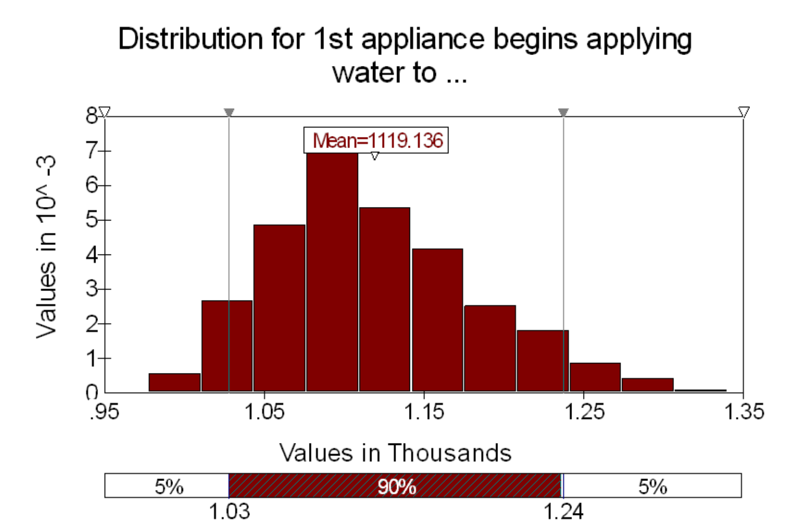
Values for input parameters were chosen based on a combination of estimations, personal communication with Simon Davis (2007), Engineering Manager, NZFS, and comparison with results of statistical analysis (as presented in Appendix D.2).

Table 11: Input values used for Fire Brigade Intervention Model (shaded cells denote user input required)

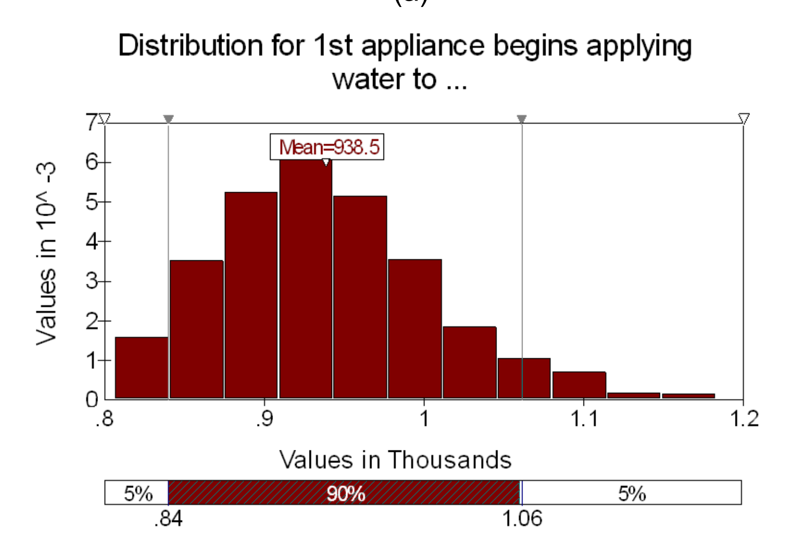
Variable or Parameter Description	Description	min	Unit Rate	max	Unit	No. Units	min	Time (s)	max
Fire Alarm received by brigade									
activation of detection system							110	120	130
monitoring company notifies 111							50	60	70
dispatch time							25	31	40
Dispatch resources and travel to fire scene									
Permanently manned									
permanent - fire fighter preparation		80	92	110	s	1		90	
permanent - urban travel to incident		40	48	60	km/h				
permanent - rural travel to incident		40	48	60	km/h				
Volunteer									
volunteer - fire fighter preparation		450	480	510	s	1		480	
volunteer - urban travel to incident		30	48	60	km/h				
volunteer - rural travel to incident		30	48	60	km/h				
Manning of Fire Stations									
manning of Fire Station of 1st appliance	Permanently manned								
manning of Fire Station of 2nd appliance	Permanently manned								
manning of Fire Station of 3rd appliance	Volunteer								
Location of Fire Stations									
location of Fire Station of 1st appliance	Urban environment								
location of Fire Station of 2nd appliance	Urban environment								
location of Fire Station of 3rd appliance	Urban environment								
Distance from fire station to incident									
1st appliance distance to incident		4.5	5.25	6	km				
2nd appliance distance to incident		9	10.5	12	km				
3rd appliance distance to incident		14	15	16	km				
Determine fire location and investigate									
fire fighter preparation at scene		120	133	150	s	1		134	
OIC assesses situation		1.5	1.6	1.7	m/s	100		64	
Estimate of size of fire at arrival of 1st appliance		6.4	8.0	9.6	MW				
Fire size to water coefficient			0.58		l/MW.s				
Water Capabilities									
capability of 2 man crew		14	15	16	l/s				
capability of pump		49	50	51	l/s				
capability of monitor		24	25	26	l/s				
Capability of appliances									
1st appliance capability	pump + 2 man crew		65		l/s				
2nd appliance capability	pump + 2 man crew		65		l/s				
3rd appliance capability	pump + 2 man crew		65		l/s				
Additional appliances requested									
number of additional appliances requested						0			
OIC requests additional appliances		25	30	35	s	1		0	
Prepare to attack fire									
rate of pumper positioning & connect hoses			8		km/h				
equivalent distance to connect hoses		0.01	0.02	0.03	km/h			9	
flush feed hydrant at booster assembly		50	60	70	s	1		60	
connect & charge hose from hydrant to appliance		90	100	110	s	1		100	

Table 12: Example of the implementation of the Fire Brigade Intervention Model as used for this study

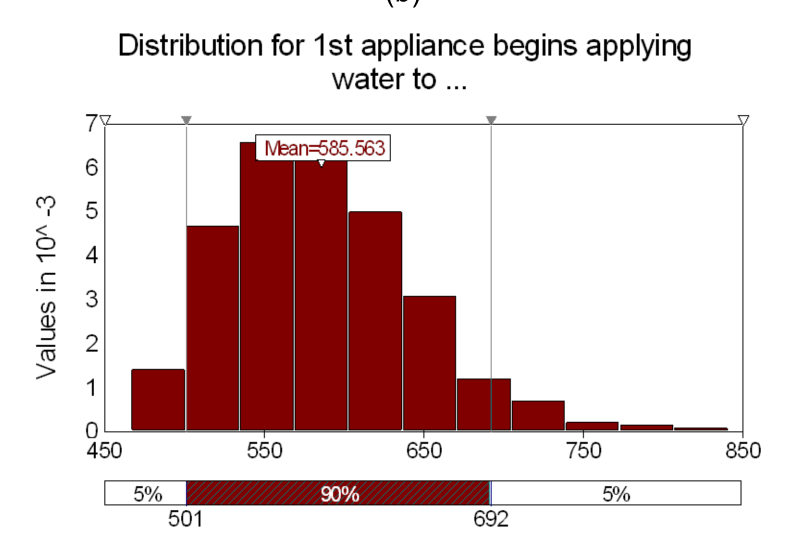
Fire Brigade Intervention Model Results	Unit Rate	Units	No. Units	Time (s)	Activity Time (s)	Elapsed Time (s)	Elapsed Time (s)	Elapsed Time (s)
						1st appliance	2nd appliance	3rd appliance
Activity Description								
Fire Alarm received by brigade						0		
activation of detection system				120	120	120		
monitoring company notifies 111				60	60	180		
dispatch time				30.833	31	211		
Dispatch resources and travel to fire scene								
fire brigade #1 - fire fighters dress, assimilate information and depart station	91.666	s	1	91.666	92	303		
fire brigade #1 - travel to incident	48.333	km/h	5.91666	440.68	441	744		
Determine fire location and investigate								
appliance arrives, fire fighters dismount and don BA	131.66	s	1	131.66	132	876		
OIC assesses situation regarding fire and is met by security or manager	1.5533	m/s	100	64.377	65	941		
Additional appliances requested								
number of additional appliances requested			0					
OIC requests additional appliances	0	s	1	0	0	941		
fire brigade #2 - fire fighters dress, assimilate information and depart station	0	s	1	0	0		-	
fire brigade #2 - travel to incident	0	km/h	11.8333	0	0		-	
appliance arrives, fire fighters dismount and don BA	0	s	1	0	0		-	
fire brigade #3 - fire fighters dress, assimilate information and depart station	0	s	1	0	0			-
fire brigade #3 - travel to incident	0	km/h	15	0	0			-
appliance arrives, fire fighters dismount and don BA	0	s	1	0	0			-
Prepare to attack fire								
position pumper appliance adjacent to booster & connect hoses	8	km/h	0.02	9	9	950	-	-
flush feed hydrant at booster assembly	60	s	1	60	60	1010	-	-
lay, connect and charge hose from hydrant to appliance and await instructions	100	s	1	100	100	1110	-	-
Control and extinguish fire								
1st appliance begins applying water to fire						1110		
2nd appliance begins applying water to fire							-	
3rd appliance begins applying water to fire								-



(a)



(b)

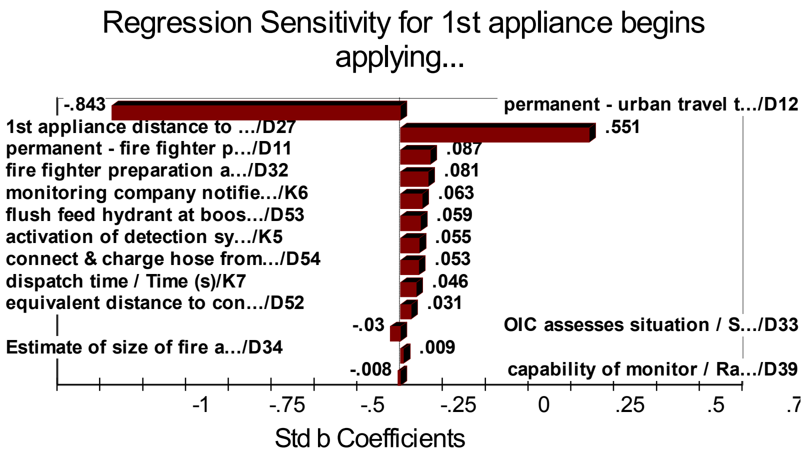


(c)

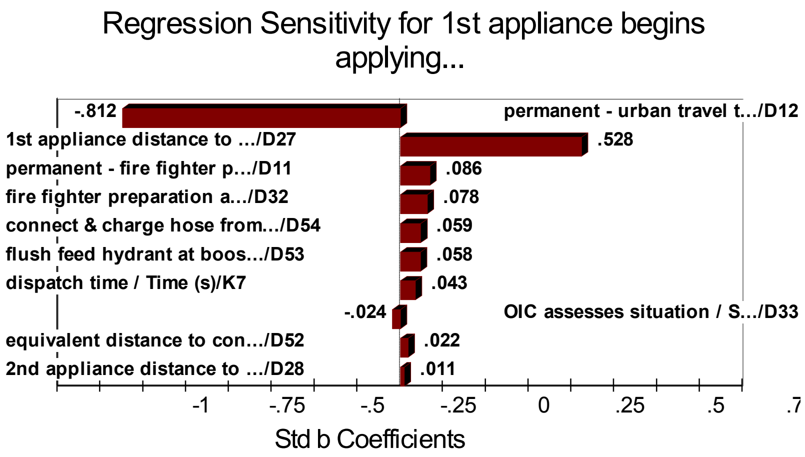
Figure 141: Distribution results for the time to water application on fire from time of detection for the (a) monitored alarm system example, (b) direct connection to fire service example, and (c) response time example

Table 13: Results of estimation of time to application of water to fire from time of detection for a monitored alarm system example and a direct connection to fire service example

Statistical Description	Time to Application of Water to Fire from Time of Detection (s)		
	Monitored Alarm System	Direct Connection to Fire Service	Response Time
Minimum	978	807	467
Maximum	1340	1183	841
Mean	1120	939	586
Standard Deviation	64	66	60
Variance	4090	4420	3590
Skewness	0.51	0.58	0.72
Kurtosis	3.0	3.3	3.7
Mode	1090	887	565
5%	1028	840	501
10%	1042	860	512
15%	1054	871	521
20%	1065	880	532
25%	1073	890	541
30%	1082	900	550
35%	1090	909	558
40%	1097	916	565
45%	1104	923	571
50%	1110	929	579
55%	1118	939	586
60%	1127	948	594
65%	1138	957	604
70%	1146	968	612
75%	1158	979	622
80%	1169	991	633
85%	1189	1006	647
90%	1211	1026	665
95%	1237	1061	692



(a)



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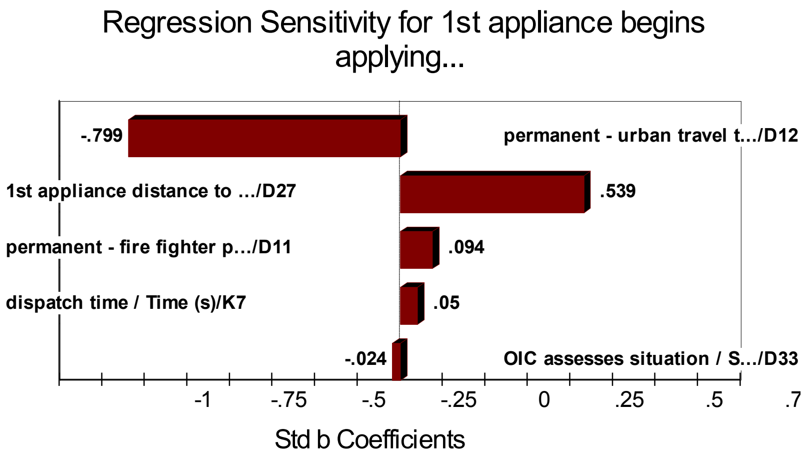

(c)

Figure 142: Distribution results for the time to water application on fire from time of detection for the (a) monitored alarm system example, (b) direct connection to fire service example, and (c) response time example

D.2 Statistics for Response Time for Arrival after Urban Industrial Fire Callout

This simple analysis was performed on NZFS statistics for urban response times to industrial fire incidents, as provided by N. Challands (2007), Fire Safety Information Analyst, NZFS. The response time refers to the time between the initial 111 call and the time of the arrival of the first fire appliance at the incident. That is, the detection time and the time for the investigation of the incident and preparation to attack the fire is not included in the response time.

Table 14 Average response time for urban industrial fire call outs, based on NZFS statistics with outliers included in the data sets (2000 – 2008).

Arrival Condition	**All Conditions**	**Totally Involved Fire**	**Large Fire**	**Small Fire**	**Smoke Only**	**Out on Arrival**	**No fire or smoke**	**Not known**
Average Response Time (s)	**420**	470	453	417	408	416	400	318
Sample Standard Deviation (s)	**190**	384	245	189	133	162	164	129
Minimum (s)	**31**	143	31	71	97	61	214	212
Maximum (s)	**3,509**	3,509	2,318	3,444	937	1,431	1,049	461
95th Percentile	**699**	741	813	668	640	710	686	443
99th Percentile	**957**	1,644	1,340	925	811	947	933	457

Table 15 Average response time for urban industrial fire call outs, based on NZFS statistics with outliers removed from the data sets (2000 – 2008).

Arrival Condition	**All Conditions**	**Totally Involved Fire**	**Large Fire**	**Small Fire**	**Smoke Only**	**Out on Arrival**	**No fire or smoke**
Average Response Time (s)	**416**	433	444	414	408	414	390
Sample Standard Deviation (s)	**156**	142	200	154	129	153	132
Minimum	**81**	222	85	129	109	81	238
Maximum	**1,997**	989	1,624	1,997	913	1,168	791
95th Percentile	**692**	705	806	663	637	704	639
99th Percentile	**921**	858	1,106	896	803	921	752

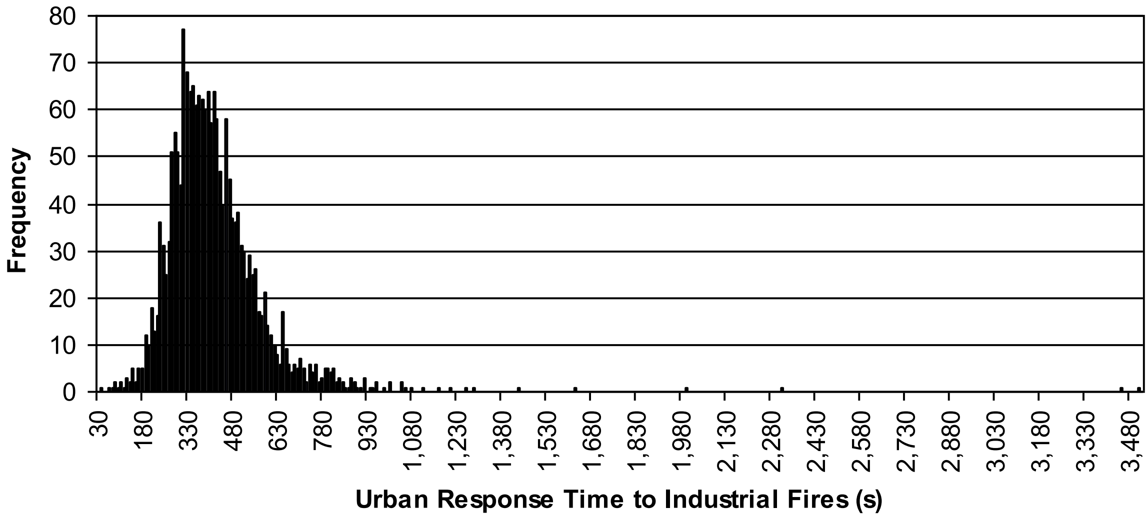

Figure 143: Urban response time to industrial fires, using a bin size of 10 s, for all conditions upon arrival (including outliers in the data set) (2000 – 2008).

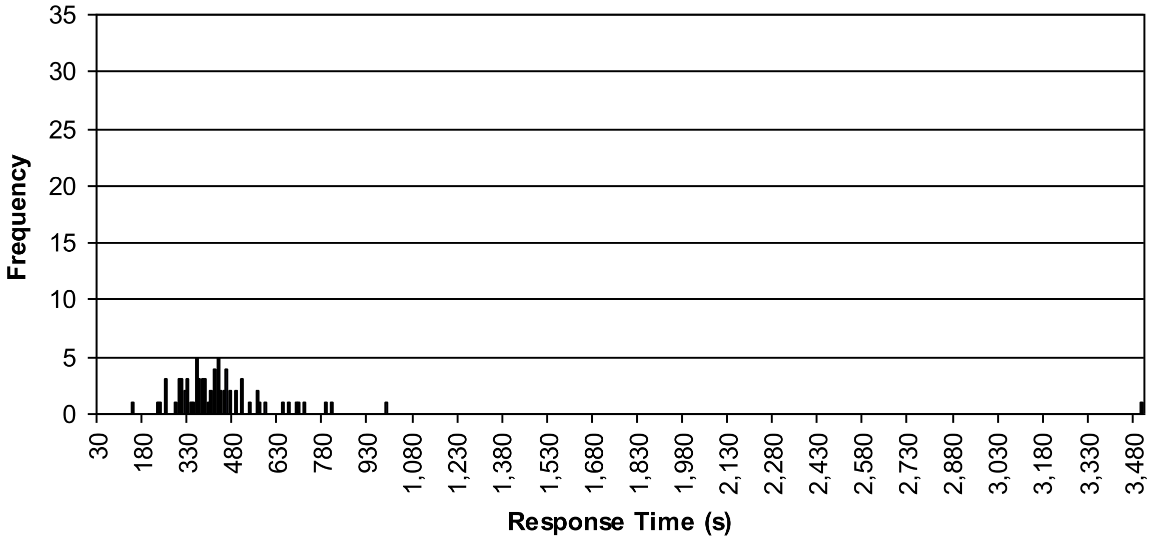

Figure 144: Urban response time to industrial fires, using a bin size of 10 s, where conditions upon arrival at incident were described as 'totally involved fire' (including outliers in the data set) (2000 – 2008).

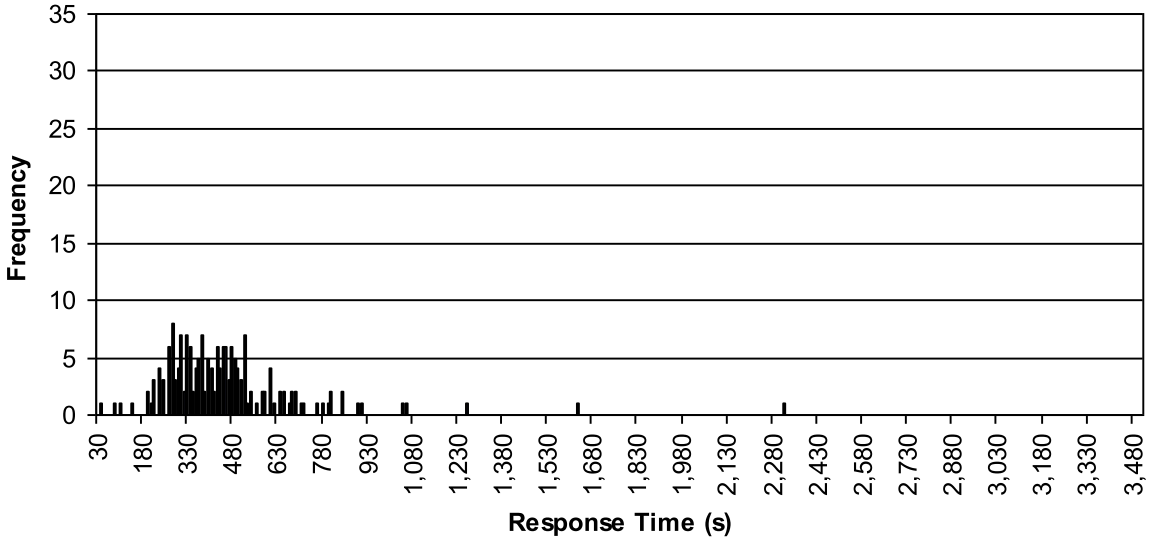

Figure 145: Urban response time to industrial fires, using a bin size of 10 s, where conditions upon arrival at incident were described as 'large fire' (including outliers in the data set) (2000 – 2008).

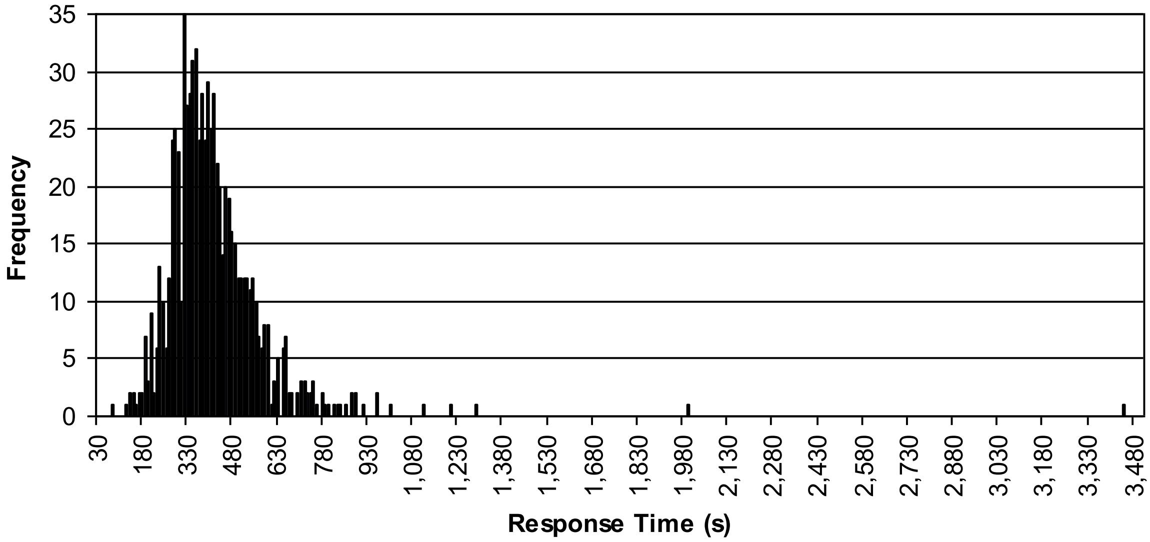

Figure 146: Urban response time to industrial fires, using a bin size of 10 s, where conditions upon arrival at incident were described as 'small fire' (including outliers in the data set) (2000 – 2008).

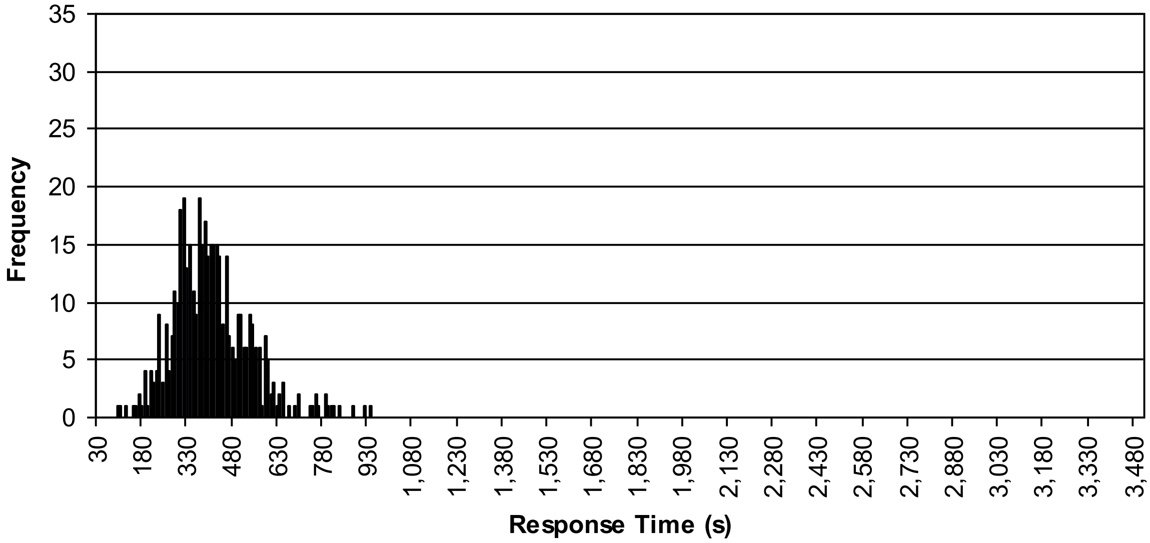

Figure 147: Urban response time to industrial fires, using a bin size of 10 s, where conditions upon arrival at incident were described as 'smoke only' (including outliers in the data set) (2000 – 2008).

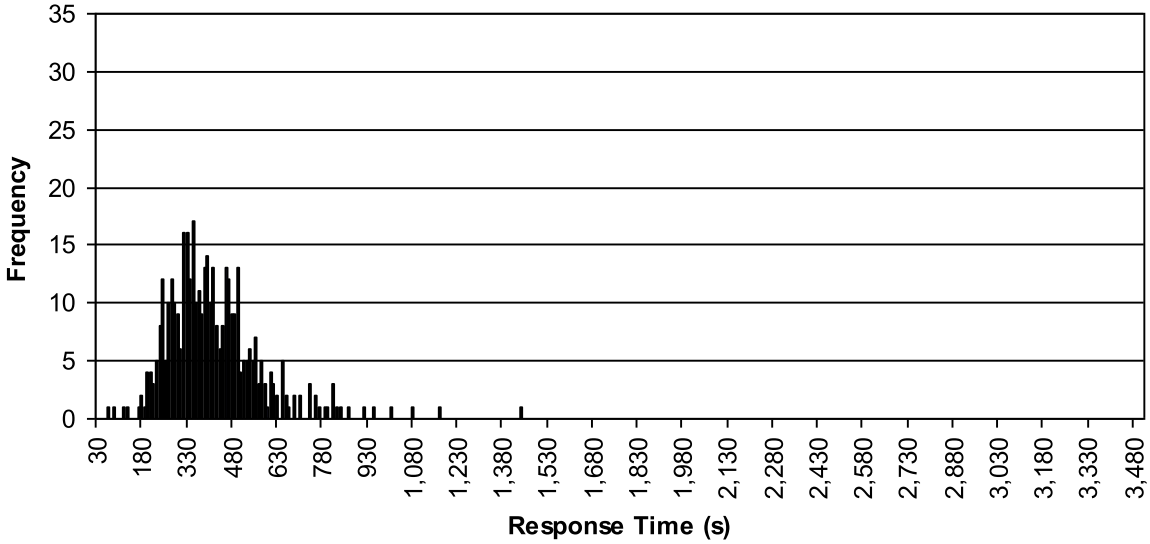

Figure 148: Urban response time to industrial fires, using a bin size of 10 s, where conditions upon arrival at incident were described as 'out on arrival' (including outliers in the data set) (2000 – 2008).

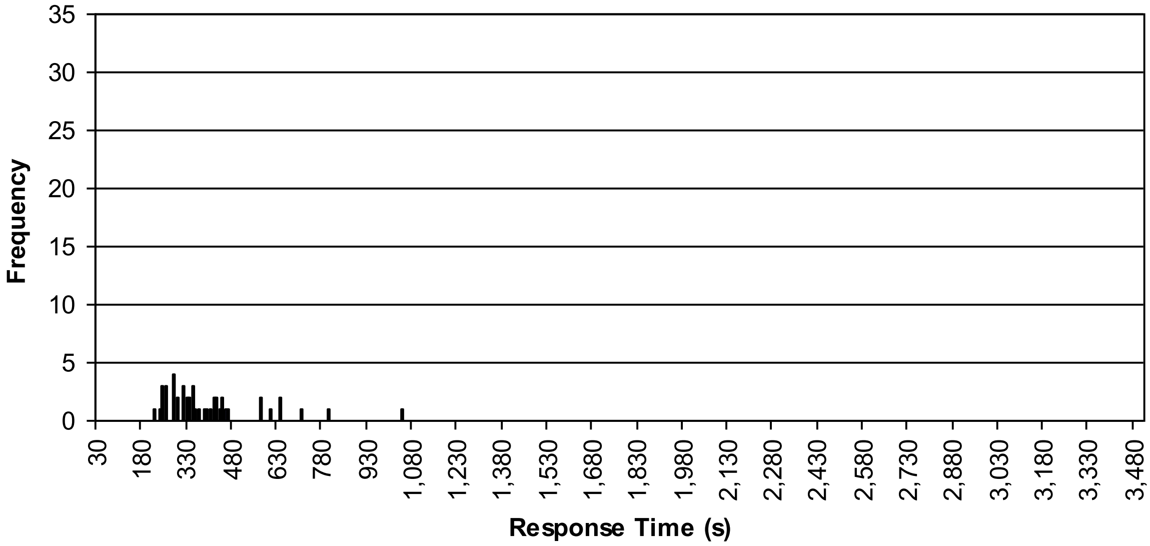

Figure 149: Urban response time to industrial fires, using a bin size of 10 s, where conditions upon arrival at incident were described as 'no fire or smoke' (including outliers in the data set) (2000 – 2008).