Report to Health Facilities Scotland

Royal Infirmary of Edinburgh
Risk of Fire Spread on External Envelope

School of Engineering and Built Environment

Report Date: January 2018

Report to Health Facilities Scotland

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Executive Summary

The Grenfell Tower fire (London, 2017) raised concerns about the potential for combustible external cladding panels, sandwich or rainscreen, to contribute to the rapid spread of fire on the outside of a building leading to rapid fire spread internally on multiple levels. Following a review of cladding systems on NHS Scotland (NHSS) buildings, The School of Engineering and Built Environment of Glasgow Caledonian University was commissioned by NHSS Health Facilities Scotland to undertake a series of fire modelling analyses and to provide a qualitative review with regard to external cladding systems on three hospitals within the NHSS Estate.

The purpose of this study was to evaluate the extent to which the combustible sandwich cladding system would contribute to rapid external fire spread, and potential re-entry, at the Royal Infirmary of Edinburgh in order to inform NHS Lothian decision-making regarding actions/protection measures that might be necessary to ensure the safety of all patients, staff and public in the event of a fire.

A qualitative examination of the materials making up the outer envelope of the Royal Infirmary of Edinburgh (RIE) was carried out. The construction of all of the external envelope elements under consideration, are deemed under the Building (Scotland) Regulations to be at least 'Low Risk'; however they are not deemed to be 'Non-combustible'. There are three types of external sandwich cladding panel installed at RIE, they all have a metal (steel or aluminium) 'skin' and a combustible core.

Computer modelling was carried out using the software Fire Dynamics Simulator (FDS). Fire scenarios that involved the ignition of the combustible sandwich panel cladding from a room fire and from an external vehicle fire close to the external wall at RIE were modelled. These indicated that the cladding was ignited by a fire in both scenarios. However, conditions in the rooms above the fire plume in both cases had become untenable prior to ignition of the cladding. There was no significant lateral spread of fire along the façade, therefore adjacent rooms are unlikely to be affected by the scenarios that have been considered.

It is noted that for the fire modelling to generate conditions for external spread of the fire, and ignition of the cladding, it was necessary for the room fire to assume that:

i) the furnishings in the room did not comply with the requirements of SHTM 87 and that for the room fire the fire load was significantly greater than is realistic in normal operational conditions,
ii) there was no active intervention/action to prevent/mitigate fire growth.

It is the conclusion of this report that in the event of an internal fire, or an external fire close to the envelope, the fire spread associated with the cladding will not contribute significantly to the risk to occupants and their safe evacuation. It is also concluded that a vehicle, or other fire, of sufficient intensity close to the building envelope and windows could rapidly lead to untenable conditions above the fire and present a risk to occupant safety; however the immediate tenability risk is not associated with the combustibility of the cladding panels.

It is also concluded that a vehicle, or other fire, of sufficient intensity close to the building envelope but not in proximity of windows will not significantly increase the risk to occupants but will lead to a loss of a section of the building envelope with business continuity and replacement cost implications.

It is the recommendation of this report that all of the external perimeter, and internal courtyards, should be kept clear of combustible material including vehicles.

This recommendation is made in the context of providing additional precautionary measures for a key regional and national asset.

Content

1 Qualitative Review of Building Envelope Combustibility

Jan 2018

- **Overview**

There is significant concern, following the fire and loss of life at Grenfell Tower (London, 2017) about the potential for external cladding panels, sandwich or rainscreen, to contribute to the rapid spread of fire on the outside of a building leading to rapid fire spread internally, through re-entry, on multiple levels of a building. The detailed analysis of the sequence of events, the dynamics of fire spread and the contributory factors at Grenfell Tower are under investigation. In the interim it is noted that, whilst ACM cladding panels are evidently a contributory factor to the Grenfell Tower tragedy, there are a number of other factors that may have contributed to the fire spread, and rate of fire and smoke spread, through the building.

The other factors include, but are not limited to, the effectiveness of cavity barriers, fire stopping, fire doors, detection and alarm systems and fire load within the building: both contents and forming part of the structure.

The materials used for insulation, or to maintain the rigidity, of combustible cladding panels will burn[1] if they are cellulosic/polymeric. The chemical composition of these materials, which can be modified, will determine ease of ignition and/or ability to sustain combustion in a 'real world' situation. However, these attributes are classified in fire engineering codes and the Building Regulations as the outcomes of standard test(s) and not 'real world' performance of elements of construction[3].

Health Facilities Scotland (HFS) commissioned the University to review the design and construction of the external envelope of three hospitals and to evaluate the implications for fire spread of the use of combustible cladding panels as the external cladding. This qualitative section provides a report to inform the quantitative scenario analysis and the discussions with HFS and decision making by NHS Lothian.

There are three types of external sandwich cladding panel installed at RIE, they all have a metal (steel or aluminium) 'skin' and combustible core. The construction of all of the external envelope elements under consideration, are deemed under the Building (Scotland) Regulations to be at least 'Low Risk'; however they are not deemed to be 'Non-combustible'.

The project brief focusses on the implications, in the event of ignition and external spread of a fire involving the cladding, for the safety of patients, and other occupants, of the hospital. The probability of occurrence of a fire and it's spread, given mitigation provisions in hospital, is therefore not directly considered.

[1] the materials will chemically react in the presence of oxygen and heat and release energy

[3] materials and product characteristics are classified in terms of the results of standardised tests that do not directly represent performance in any 'real' fire or the standard/non-technical definition of words such as 'ignitable, flammable, combustible, fire resistant'.

- **Summary**

1. **Construction**

i. The external perimeter façade and the internal courtyard facades at RIE are of metal composite panels. There are three types of panel:
   a. Hunter Douglas[4]: smooth external aluminium finish, 50mm thick CFC free polyurethane foam core,
   b. Kingspan[5]: profiled steel finish, 45mm thick CFC free polyurethane foam core,

   the Hunter Douglas panels are Aluminium Composite Material (ACM) however the steel faced Kingspan panels have similar performance with a higher melting point for the metal facings of the panel.

   c. A third type of panel has been used in alterations.

ii. The external perimeter is primarily clad with Hunter Douglas panels; the external stair towers are clad with Kingspan panels. The panels clad the building from ground to roof level.

iii. The internal courtyards, the FM Building, HSDU and Energy Centre are clad with Kingspan panels.

iv. The inner element of the exterior envelope of the building is constructed of two layers of 12.5mm thick tapered edge plasterboard with staggered joints providing Fire Resistance (loadbearing and integrity) of 60 minutes and Fire Resistance (insulation) of 15 minutes[6,7].

v. The windows are UPVC with a secondary steel frame, there are no cavity barriers around the windows[8].

vi. There is fire stopping at each floor level[9].

vii. Automatic detection to 'an enhanced' L2 system is installed[10].

viii. Automatic Fire Suppression is installed in the ground floor retail area of the building.

2. **Commentary**

i. The potential for fire spread from a fire in a room to the externa cladding panels is mitigated by:
   a. The inner part of the exterior envelope of the building is constructed of two layers of 12.5mm thick tapered edge plasterboard with staggered joints
   b. SHTM 85, Fire Safety – Precautions in Existing Healthcare Premises which requires: *existing hospitals should have at least 75% of Textiles and Furnishings comply with SHTM 87, Textiles and Furniture: the aim should be 100% compliance. It is reasonable to expect that internal fire spread on textiles and furnishings is mitigated and that initial ignition is difficult[11].*

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[4] University of Edinburgh Test Panel 3
[5] University of Edinburgh Test Panels 1 and 2
[6] from the inside
[7] as specified in the guidance to the Building Standards Scotland Regulations for the building occupancy, height and compartment size
[8] LABC guidance does not require a cavity barrier where there is a suitable steel frame
[9] RIE FM inspections in a number of locations
[10] in accordance with BS5938 Part 1
[11] Confirmed that most furnishings and fabrics conform to SHTM 87 and replacement in progress to ensure full compliance

c. RIE has automatic smoke detection/heat as appropriate. This will alert the staff to a fire incident to intervene before the fire is of a size as to cause failure of glazing or spread from the room of origin by other means.

ii. Glazed windows (closed) would require to be subjected to localised direct flame impingement from fire in a room before failure; the inner pane of the double glazed unit would fail first *(glass fails in fire due to stresses created in a material that is not a good conductor of heat, impurities and constraints caused by differential expansion*). There would be a further period of time to failure of the second pane. The evidence is that failure is typically partial failure of glazing.

iii. The largest internal/ward fire, based on compartment size, has 26 beds. Assuming that all fire compartment walls are appropriately constructed and service/other penetrations are protected this is the maximum extent to which a fire would spread internally and threaten external fire spread. This would only occur if early intervention by staff and/or firefighters, following detection and alarm, failed to contain/suppress the fire.

iv. Upgrading/ remedial work includes installation of self-closing fire doors to each 'room' in the wards. This will restrict the spread of any fire to the room of origin. However, it is noted that there are glazed panels in the wall and the small leaf of the 'penny farthing' door set does not have a self-closer fitted.

v. There is the potential for a wilful fire raising attack or an accidental fire within close proximity of the external cladding, this is mitigated by:

   a. Hunter Douglas panel performance in standard tests[12,13,1415]:
      i. British Standard 476 Part 5 "not easily ignitable",
      ii. British Standard 476 Part 6, index of performance (I): 8.9p Sub-Index (I) : 4.0,
      iii. British Standard 476 Part 7, Class (1) one, surface spread of flame.
   b. limited, if any, combustible material build up to support fire growth after accidental ignition; including ignition by smokers.
   c. CCTV coverage and general security measures reduce risk of deliberate build-up of combustible materials for wilful fire raising.

vi. An accidental vehicle fire, a deliberate vehicle fire or the deliberate ignition of sufficient combustible material or explosives brought to the perimeter of the building would generate the heat release rate to ignite the cladding panels[16].

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[12] the Hunter Douglas panels predominate on the external perimeter that is accessible

[13] the Kingspan panels are steel faced and are therefore less vulnerable

[14] a significant quantity of combustible materials/heat source would be required to produce the heat release required to raise the temperature to ignite the combustible material behind the aluminium/steel outer face of the sandwich panel. Aluminium has a melting point of around 660^{O} C, lower than steel, this temperature, or close to it, would cause the metal facing to 'fail' and expose the combustible core. Heat conducted through the metal facing would raise the temperature of the core material however the test results indicate that prior to facing failure ignition is unlikely.

[15] The University of Edinburgh tests were on small mass samples and not on the installed product. They evidenced that the core material could ignite and release energy in the form tested. This did not provide evidence of time to ignition, the energy required to cause ignition or the performance of installed products 'new' or 'damaged'.

[16] this is primarily a site risk management issue.

- In the event that a fire spreads on the external façade fire spread to inside of the building would be possible through open windows, in the first instance, potentially on all levels.

2 Fire Modelling

This Section of the Report provides a summary of the fire modelling assumptions and outputs for the Royal Infirmary of Edinburgh (RIE) to inform decision-making associated with alternative mitigation measures in the context the risk associated with the contribution of combustible cladding to fire spread, the RIE Fire Safety Strategy and potential changes in regulatory requirements in Scotland.

3 Summary of Fire Modelling Assumptions, Outputs and Conclusions

Key Assumptions

- integrity of specified passive fire safety provisions in situ, these are correctly maintained to prevent/limit internal fire spread
- an internal room fire develops to flashover and sustains a post-flashover fire; a 16MW fire was required to model conditions that supported external fire spread
- no active intervention/action to prevent/mitigate growth to a flashover fire (including failure of/failure to respond to detection and alarm in room of origin)
- an external vehicle/other fire sustains an 8MW fire
- no active intervention/action to prevent/mitigate fire and smoke entry to building

Fire Modelling Outputs

- Room Fire
    - the probability of a flashover fire sustained at 16MW, as predicted by the model to be required to ignite the cladding, is extremely low as this is significantly larger than predicted for the current/actual fire load and requires that there is no active intervention following detection/alarm. The probability of an internal fire leading to ignition of the cladding is therefore very low.
    - in conditions where the combustible cladding became involved due to an internal room fire spreading out through the windows(s) the ignition of the cladding is predicted to occur after the fire had made conditions untenable in the room of fire origin and in the room(s) above. The ignition of the cladding would not have a significant impact on conditions in the upper room or on internal fire spread.

- External Fire
    - an 8 MW vehicle/other fire, a ‘standard’ vehicle fire, is estimated to make conditions untenable in an upper room significantly before the ignition of the cladding.
    - The ignition of the cladding does not have a significant impact on initial tenability conditions in upper room(s) or on internal fire spread. The modelling predicts that an external fire would have similar impacts on tenability in upper room(s) with non-combustible cladding.

- an external vehicle fire close to the building perimeter near windows has the potential to cause the rapid onset of conditions untenable in an upper room.
- a sustained heat source from an internal or external fire is required to maintain combustion of the cladding.

Conclusions

- evacuation of occupants in the event of an internal or external fire and the associated fire and smoke spread would not be significantly affected by involvement of cladding in the fire.
- on the basis of the qualitative analysis and the outputs of the fire modelling it is concluded that the external cladding does not constitute a significant additional life safety hazard in the event of a fire.
- it is recommended that perimeter of the building should be kept clear of vehicles and/or combustible materials

Large Scale Testing of Fire Spread Involving the Cladding

- it is not considered that large scale testing would provide additional information that would materially change the evaluation of the impact of combustible cladding on the fire hazard/risk at the Royal Infirmary of Edinburgh. For large scale testing to provide useful information a number of tests for different scenarios would be required, including internal and external fires and windows open and closed.

Appendix A: Fire Modelling

4 Fire Modelling

4.1 Introduction

The issues we have been asked to address focuses on combustible Aluminium Composite Material (ACM) (panels) used in part, or in total, for the external element of the Royal Infirmary Edinburgh.

To this end, the computer fire model Fire Dynamic Simulator (FDS) has been used to assess three fire scenarios involving the ignition of this cladding and the timeline for further fire spread.

Two scenarios have been selected in which a fire could potentially spread to the external cladding of the building. In the RIE, a fire within the hospital that grows to a sufficient size that the external cladding is ignited has been considered. A timeline has been estimated to consider significant events (e.g. the time to ignition of the cladding, the effects of the cladding fire on the room directly above the room of fire origin).

As there is a concern that a fire originating in a car that is parked adjacent to the building could ignite the cladding and affect the rooms immediately above the fire this has also been modelled.

4.2 Scenarios

4.2.1 Royal Infirmary Edinburgh Room Fire

In order for a fire in a hospital room to ignite the external cladding such a fire would need to be sufficiently large to cause flames to extend beyond the room of fire origin (i.e. out the window). This would require the fire to become ventilation controlled, following flashover and ignition of all combustibles in the room. In order for the fire to become this large, there are several assumptions that must be made:

- The furnishings in the room are not fire retardant
- No first aid firefighting or fire brigade intervention occurs

It should be noted that due to the presence of an automatic detection and alarm system, it is expected that both firefighting intervention and evacuation would begin early in the scenario, however this has not been included in the scenario. As the windows are openable, an open window is included in both the upper and lower rooms, allowing smoke and hot gases to leave and enter the rooms prior to the windows breaking.

4.2.2 Model Input Data

In this scenario, a fire is considered that ignites in a six bed room. A medium growth fire has been used, based on Table 3 of PD 7974-1 (BSI, 2003, p. 26) and the similarity in the fuel load to the furniture found in a hotel room. The fire would continue to grow until it reaches a sufficient size to cause flashover (a sudden transition from a localised fire to the ignition of all exposed flammable surfaces within an enclosure (BSI, 2003, p. 5)) in the room. The size of fire required to cause flashover varies based on both the size of the room and the size of the available ventilation. Thomas's flashover correlation (BSI, 2003, p. 29) has been used to estimate the fire size required for flashover in several rooms in Table 1 below. Then, based on a medium growth fire, the time after ignition for the room to reach flashover is determined.

Table 1 Flashover correlations and time to reach flashover

Room Length (m)	Room Width (m)	Room Height (m)	Window Width (m)	Window Height (m)	Heat Release Rate to cause Flashover (kW)	Time to Flashover (based on a medium growth t2 fire) (s)
10	10	2.7	7	1.5	7182	774
12	10	2.7	7	1.5	7578	795
15	10	2.7	7	1.5	8172	825

It is noted that as pyrolysis is not modelled by Computational Fluid Dynamics (CFD) models, including FDS, this prediction is not possible to make via computer modelling.

After flashover, the fire becomes ventilation controlled (i.e. the size of the fire is limited by the available oxygen). Equation 33 of PD 7974-1 (BSI, 2003, p. 37) Uses the calorific value of the fire load, and the mass burning rate of the fuel to estimate the Heat Release Rate (HRR) of the fire at this stage. The mass burning rate of the fuel is estimated using equation 35 of PD7974-1 (BSI, 2003, p. 38) and the dimensions of the ventilation source. For the purposed of this scenario, it is assumed that there is full fallout of the window in the room of fire origin at the time of flashover. A calorific value of 20 MJ/kg has been assumed based on an average of the values in Table 10 of PD 7974-1 (BSI, 2003, p. 37) in producing Table 2 below, which provides examples of the HRR of ventilation controlled fires.

Table 2 HRR of ventilation controlled fires

Window Width (m)	Window Height (m)	Heat Release Rate of Ventilation Controlled Fire (MW)
5	1.5	16.5
7	1.5	23.1
9	1.5	29.8

It is noted that as the combustion is predominately outside the room at this point in the scenario, the exact HRR is not a critical factor, so long as there is a plume outside the window to ignite the cladding. In order to minimise the computation time (in general, larger fire require longer computation time), a fire of 16MW has been chosen as this will be sufficient to create a fire plume emanating from the window.

The ignition temperature of polyisocyanurate is 445°C (Hasemi, 2016). The aluminium surface would have lost a significant proportion of its strength at this temperature as the melting point of aluminium is in the range 550-600°C and it loses roughly 50% of its strength at 200°C (O'Connor, 2016, p. 3257). It was considered conservative to allow the cladding to ignite while the aluminium would be partly intact, therefore the cladding is considered to ignite at 450°C

There is considered to be a 0.5m wide opening in the windows of both the upper and lower rooms to allow smoke movement via open windows prior to the failure of the glass. The panes of the double glazed window of the upper room are considered to break at 300°C. Cracking of glass is primarily due to temperature differentials across the glass (BSI, 2011, p. 118), therefore it is anticipated that the windows will break due to flame impingement from the external plume and the temperature at which the window would break is not critical to this analysis. The glass is considered to completely fall out to allow the maximum ingress of smoke and hot gases from the fire in the room below.

Conditions in the room above the fire are assessed based on smoke in the room being tolerable to staff, as patients who cannot self-evacuate are expected to be bed bound and below the head height of the staff. Based on a willingness to move through smoke, the room is considered to be untenable if the visibility is reduced below 10m (BSI, 2004, p. 15), or the temperature within the room exceeds 60°C (BSI, 2004, p. 17).

The parameters shown in Table 3 were used in the setup of the FDS Model for the room fire

Table 3 - FDS Model Input Data

Design Fire	16MW
Fire Location	Spread across 6 beds
Ventilation	Window 6m x 1.5m Window considered to break at 300°C, correlating with flame impingement
Run Time	3600 s (1 hour)
Tenability	60°C, visibility 10m
Cell Size	0.25m
Key Events	• Time fire becomes ventilation controlled (taken to be time of flashover) • Time for ignition of cladding • Time for window in upper room to break • Time to untenability of upper room

A general view of the model is presented in Figure 1.

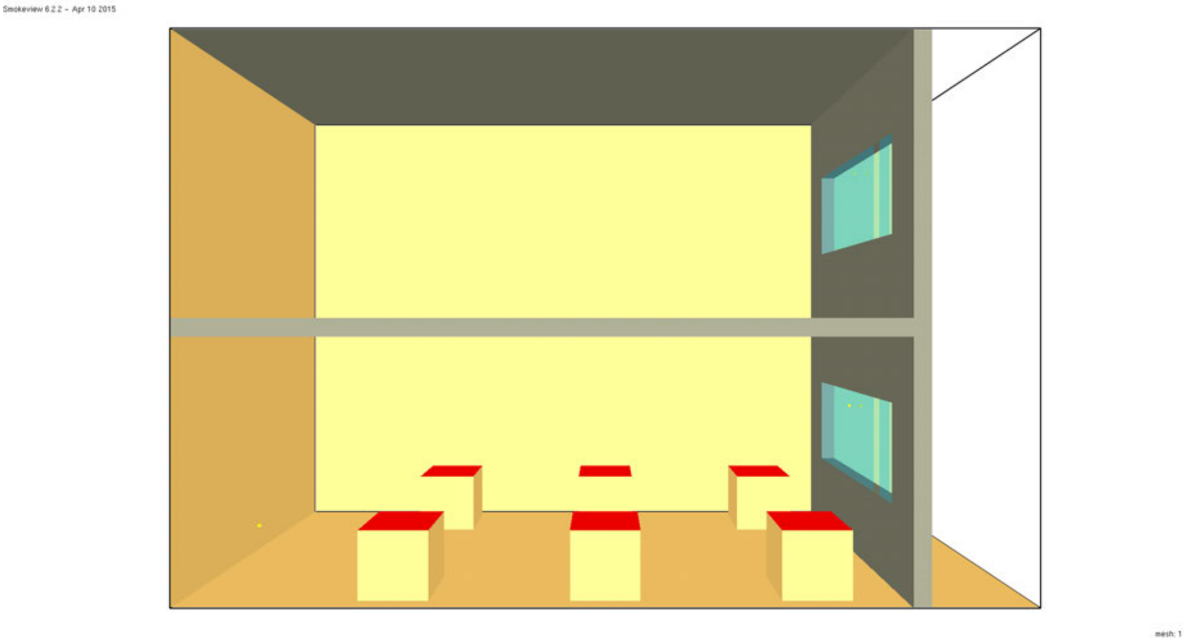

Figure 1 A general view of the model

4.2.3 Model results

As expected, the fire became ventilation controlled and the combustion occurred mainly near and beyond the window of the room of fire origin, as shown in Figure 2 below. The cladding ignited approximately 3 minutes after flashover, as shown in Figure 3 and Figure 4.

Figure 5 shows that the window of the upper room break to due flame impingement at approximately the same time as the fire flashes over in the lower room. However, by this time, conditions had already become untenable in the room above the room of fire origin.

A significant quantity of smoke enters the upper room through the open window and the visibility drops below the tenability limit in approximately two and a half minutes before flashover occurs in the lower room as shown in Figure 6. However, there are not significant hot gases entering the room in the early stages and therefore the temperature tenability criterion is not reached until approximately 15 seconds after flashover (see Figure 7 and Figure 8).

At the end of the simulation time (one hour after ignition), the temperature in the upper room is approximately 400°C, as shown in Figure 9

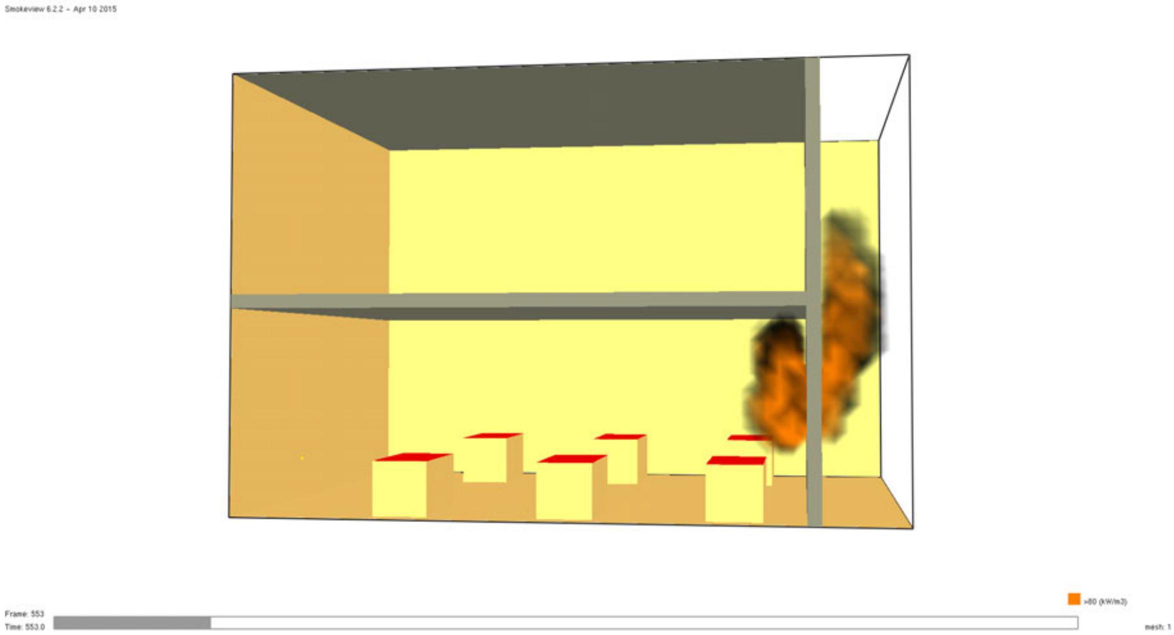

Figure 2 Location of Combustion after the fire becomes ventilation controlled at approximately 6 minutes of simulation

(NB that due to the lack of ability to model flashover, this does not indicate that actual time to flashover expected and as detailed in Section 4.2.2)

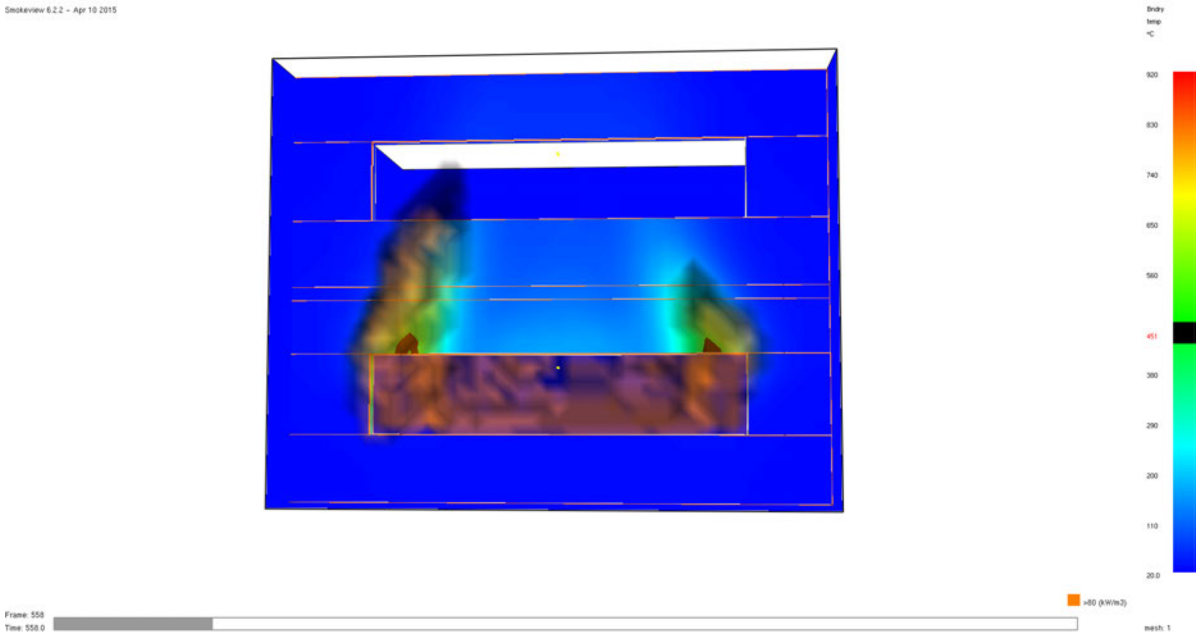

Figure 3 Ignition of the cladding approximately 3 minutes after flashover

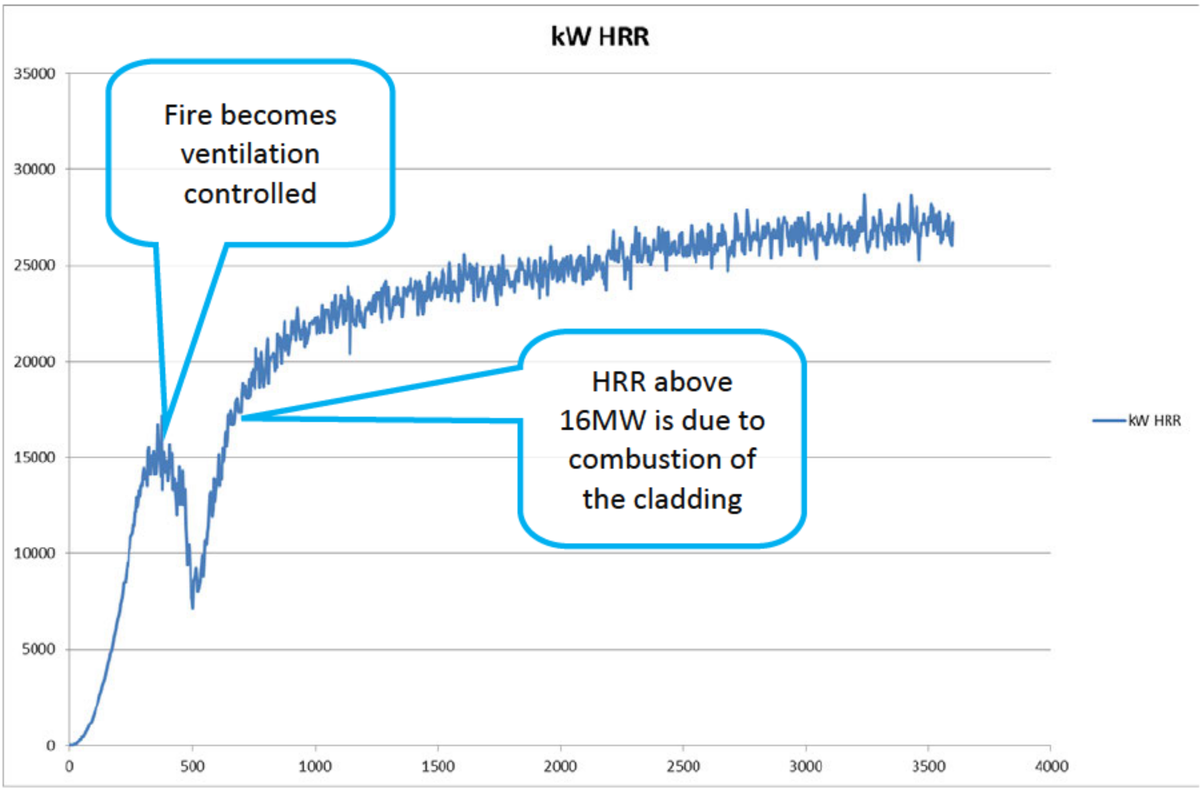

Figure 4 HRR during the simulation

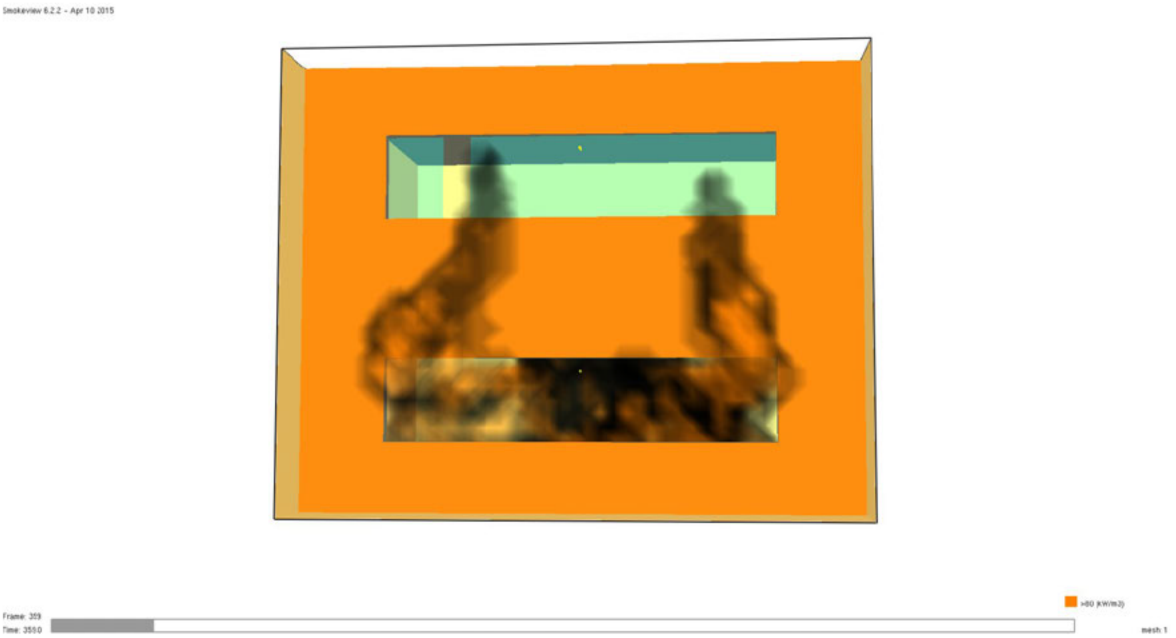

Figure 5 Breakage of the upper room window occurred due to flame impingement approximately the same time as flashover

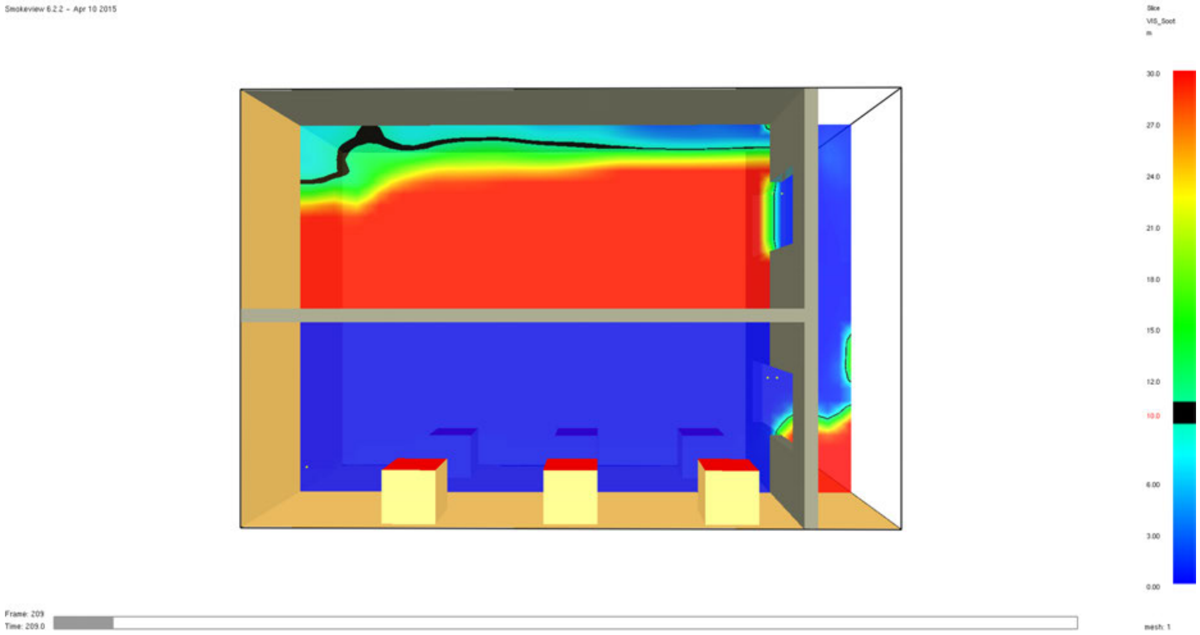

Figure 6 The visibility in the upper room becomes untenable approximately before flashover occurs in the room of fire origin due to smoke spread via the open window

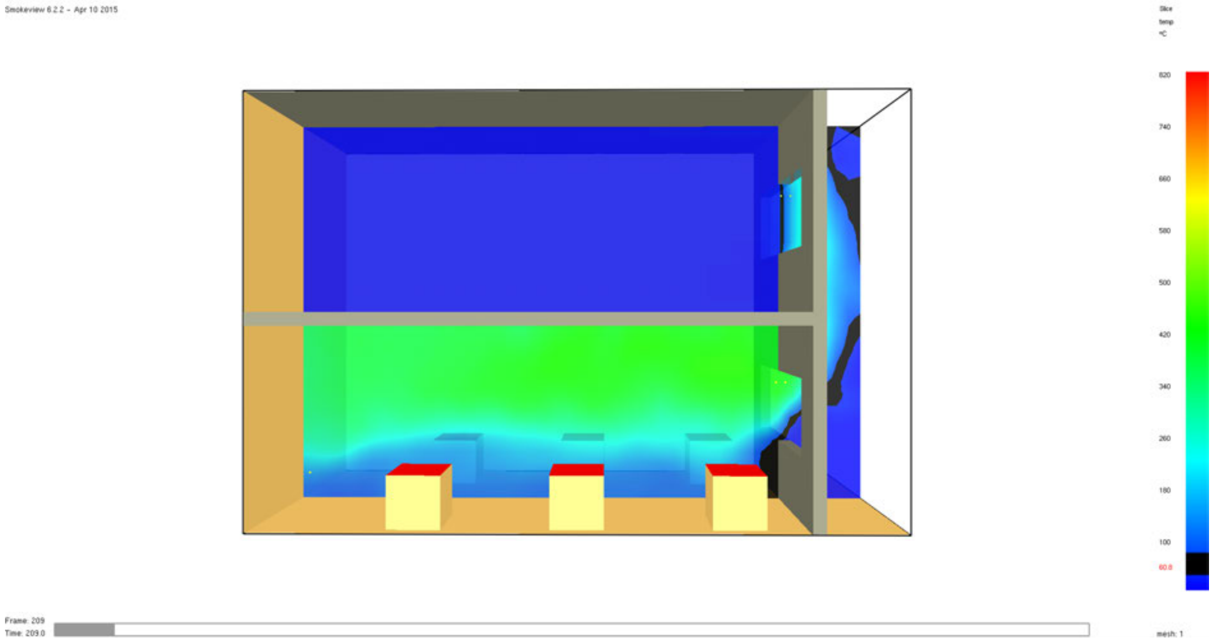

Figure 7 Temperatures within the upper room are still tenable when the visibility becomes untenable

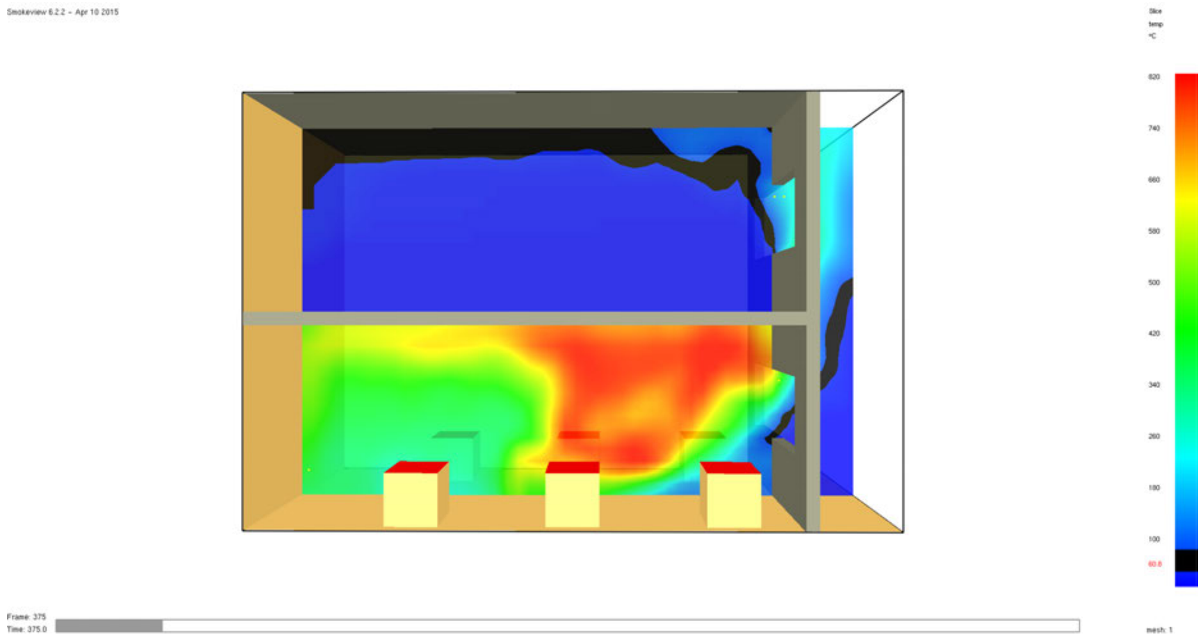

Figure 8 Temperatures within the upper room reach the tenability criterion approximately 15 seconds after flashover

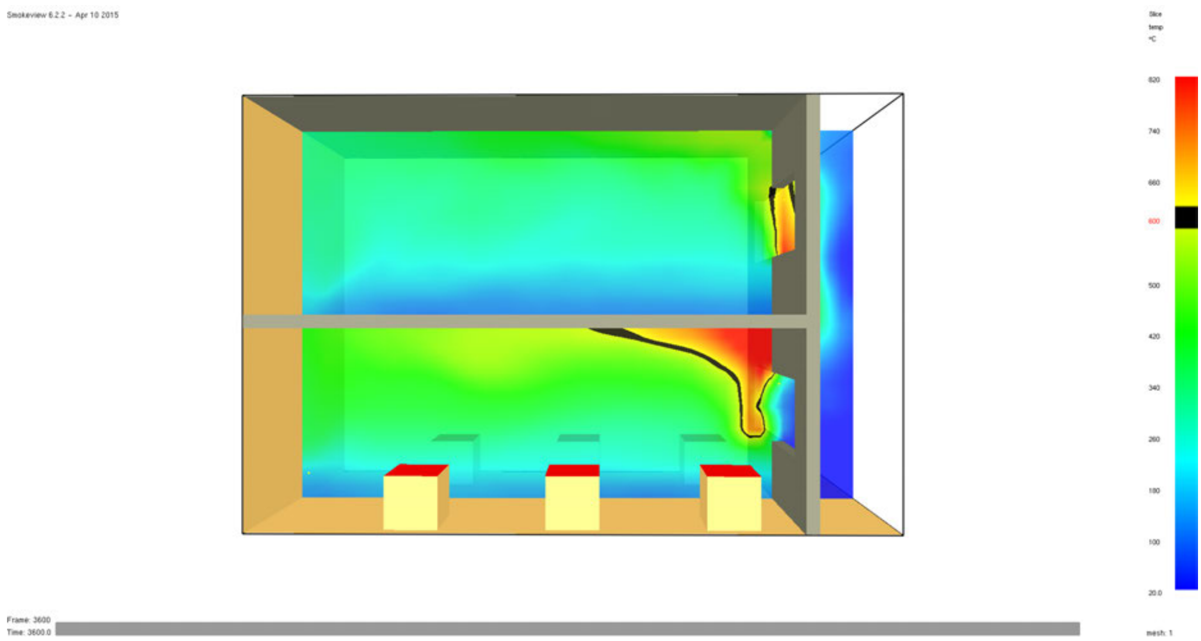

Figure 9 Temperature in the upper room at the end of the simulation period (note that the temperature in the lower room is underestimated due to the focus of the modelling on the external plume)

4.2.4 Royal Infirmary Edinburgh Car Fire

There is a concern that a fire originating in a car that is parked adjacent to the building could ignite the cladding and affect the rooms immediately above the fire. A car parked alongside the building in close proximity (approximately 0.5m) is considered in this scenario.

It should be noted that the presence of an automatic detection and alarm system within the building would not be expected to detect the fire outside in its early stages, as soon as smoke begins to infiltrate the building (especially if the windows are open), then the detection and alarm systems would be activated. Therefore, it is expected that both firefighting intervention and evacuation would begin early in the scenario, however this has not been included in the scenario RIE Room Fire.

4.2.5 Model Input Data

In this scenario, a fire is considered that ignites in a car parked adjacent to the hospital. BS7346-7 (BSI, 2013, p. 12) suggests a steady state fire of 8MW for the design of an indoor carpark without a sprinkler system. This design fire is supported by experiments conducted by the BRE (BRE, 2010, p. 100). As a car adjacent to the building would not be sprinkler protected, this is considered an appropriate design fire for this scenario.

The ignition temperature of polyisocyanurate is 445°C (Hasemi, 2016). The aluminium surface would have lost a significant proportion of its strength at this temperature as the melting point of aluminium is in the range 550-600°C and it loses roughly 50% of its strength at 200°C (O'Connor, 2016, p. 3257). It was considered conservative to allow the cladding to ignite while the aluminium would be partly intact, therefore the cladding is considered to ignite at 450°C

There is considered to be a 0.5m wide opening in the windows of both the upper and lower rooms to allow smoke movement via open windows prior to the failure of the glass. The panes of the double glazed window of the upper room are considered to break at 300°C. Cracking of glass is primarily due to temperature differentials across the glass (BSI, 2011, p. 118), therefore it is anticipated that the windows will break due to flame impingement from the external plume and the temperature at which the window would break is not critical to this analysis. The glass is considered to completely fall out to allow the maximum ingress of smoke and hot gases from the fire in the room below.

Conditions in the room above the fire are assessed based on smoke in the room being tolerable to staff, as patients who cannot self-evacuate are expected to be bed bound and below the head height of the staff. Based on a willingness to move through smoke, the room is considered to be untenable if the visibility is reduced below 10m (BSI, 2004, p. 15), or the temperature within the room exceeds 60°C (BSI, 2004, p. 17).

The parameters shown in

Table 4 were used in the setup of the FDS Model for the car fire

Table 4 - FDS Model Input Data

Design Fire	8MW
Fire Location	A car parked along the building at a distance of 0.5m
Ventilation	Window 6m x 1.5m, with a 0.5m opening at each level Window considered to break at 300°C, correlating with flame impingement
Run Time	3600 s (1 hour)
Tenability	60°C, visibility 10m
Cell Size	0.25m
Key Events	• Time for ignition of cladding • Time for window in lower room to break • Time for window in upper room to break • Time to untenability of lower room • Time to untenability of upper room

General views of the model are presented in Figure 10 and Figure 11.

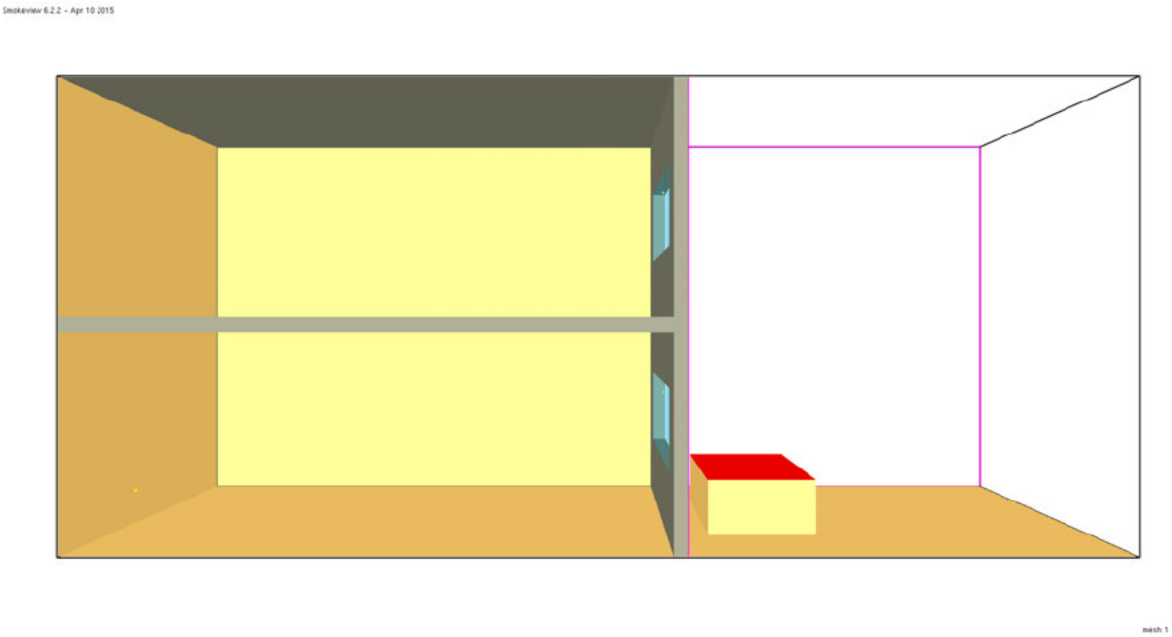

Figure 10 A general view of the model (side view)

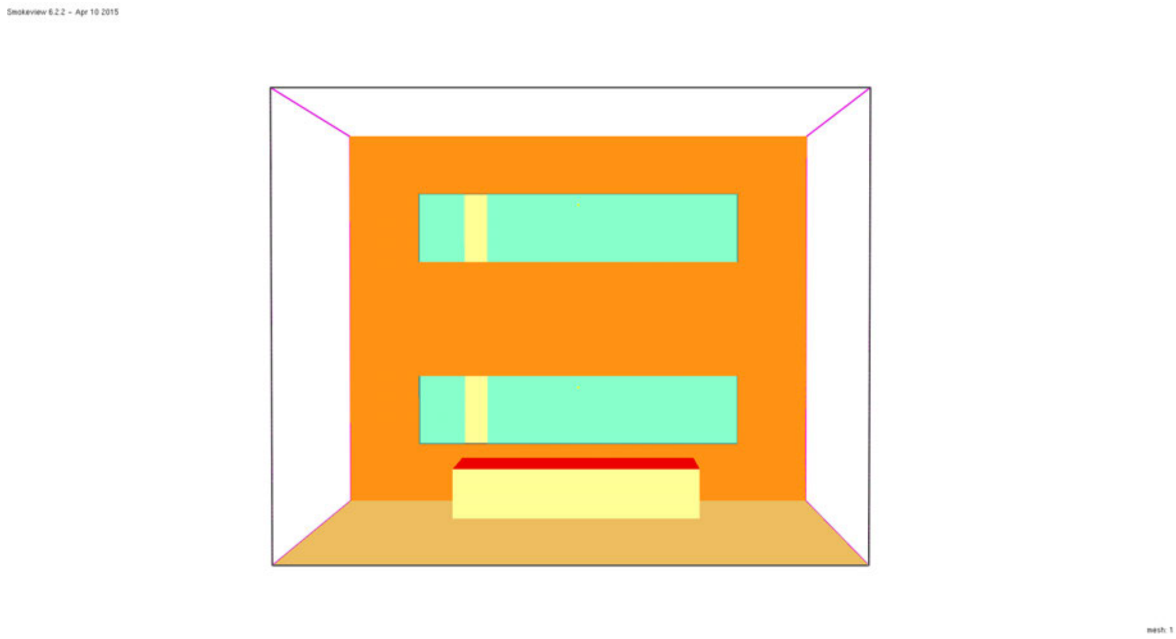

Figure 11 A general view of the model (front view)

4.2.6 Model results

The car fire reaches its peak heat release rate approximately 200 seconds after the beginning of the simulation. The cladding ignited approximately 9 minutes after the car's peak HRR was reaches as shown in Figure 12 and Figure 13.
Figure 14 and Figure 15 show that the window of the upper room breaks to due flame impingement at approximately 20 seconds after the car's peak HRR is reached. Conditions in the upper room become untenable approximately 10 seconds later (30s after the car's peak HRR) as shown in Figure 16. Temperatures in the upper room also rise quickly, and the temperature criterion is reached approximately 1 minute after the car reaches its peak HRR (see Figure 17 and Figure 18)
Figure 19 and Figure 20 show that the window of the lower room breaks to due flame impingement at approximately 5 and a half minutes after the car's peak HRR is reached. Conditions in the lower room become untenable approximately 1 minute later (6 and a half minutes after the car's peak HRR) as shown in Figure 21. Temperatures in the lower room begin to rise at this time and the temperature criterion is reached approximately 2 minutes after the visibility criterion is reached (8 and a half minutes after the car reaches its peak HRR (see Figure 22 and Figure 23)
At the end of the simulation time (one hour after ignition), the temperature in the upper room is approximately 200-300°C, as shown in Figure 24

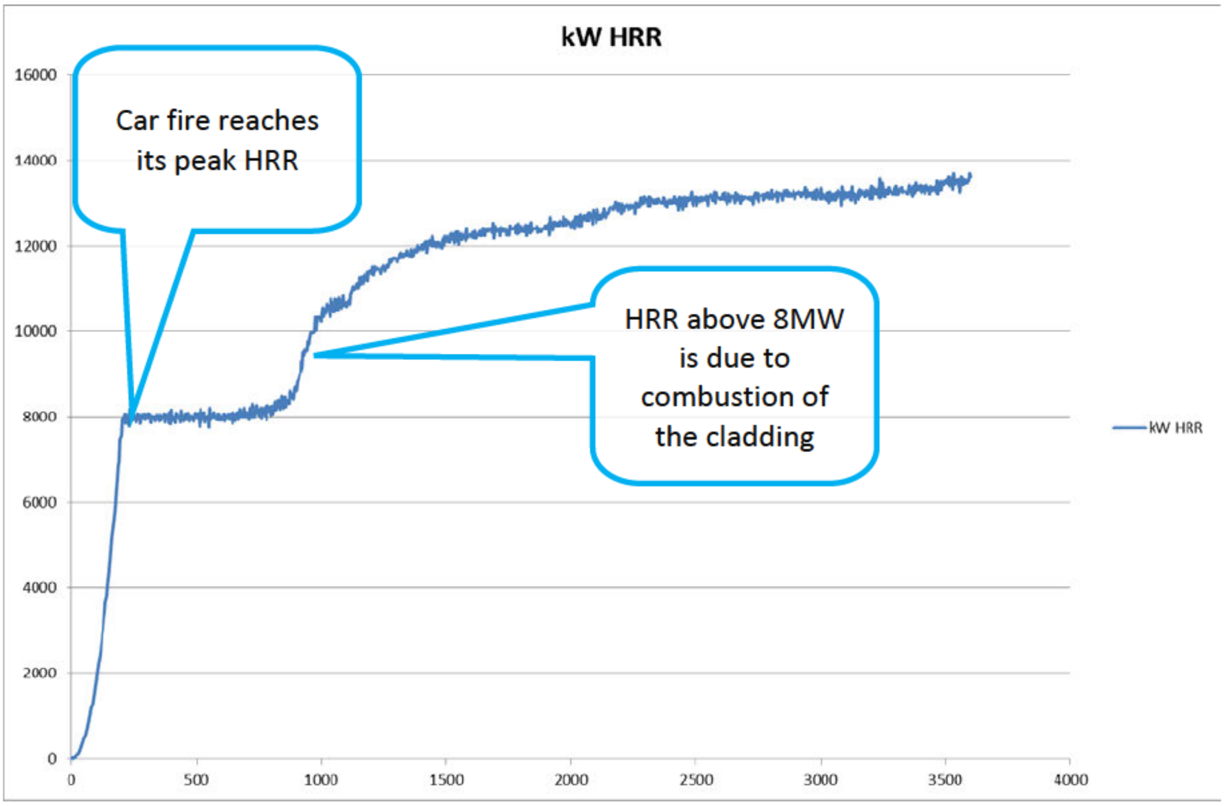

Figure 12 HRR during the simulation

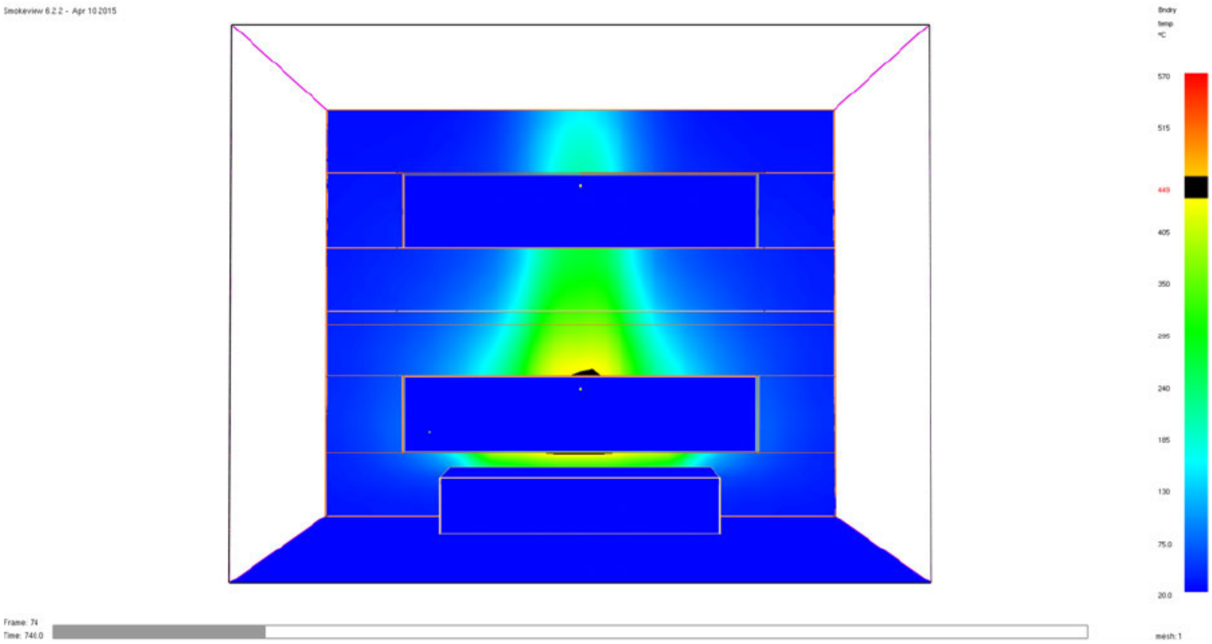

Figure 13 Ignition of the cladding approximately 9 minutes after the car fire reaches its peak HRR

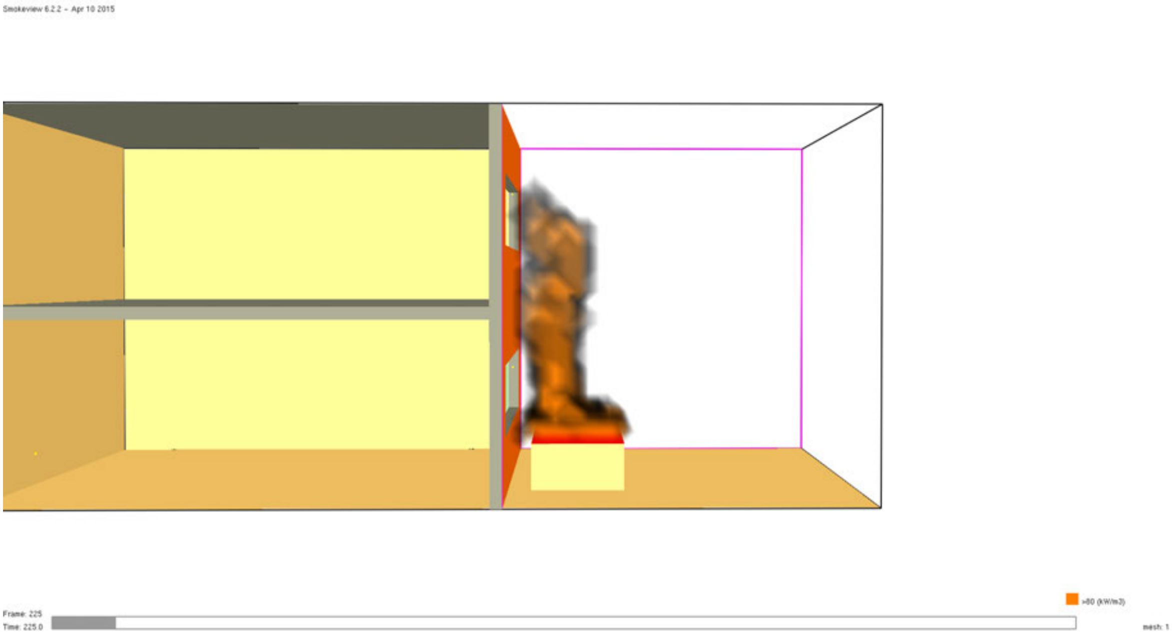

Figure 14 The upper window breaks due to flame impingement about 20 s after the fire reaches its full HRR (side view)

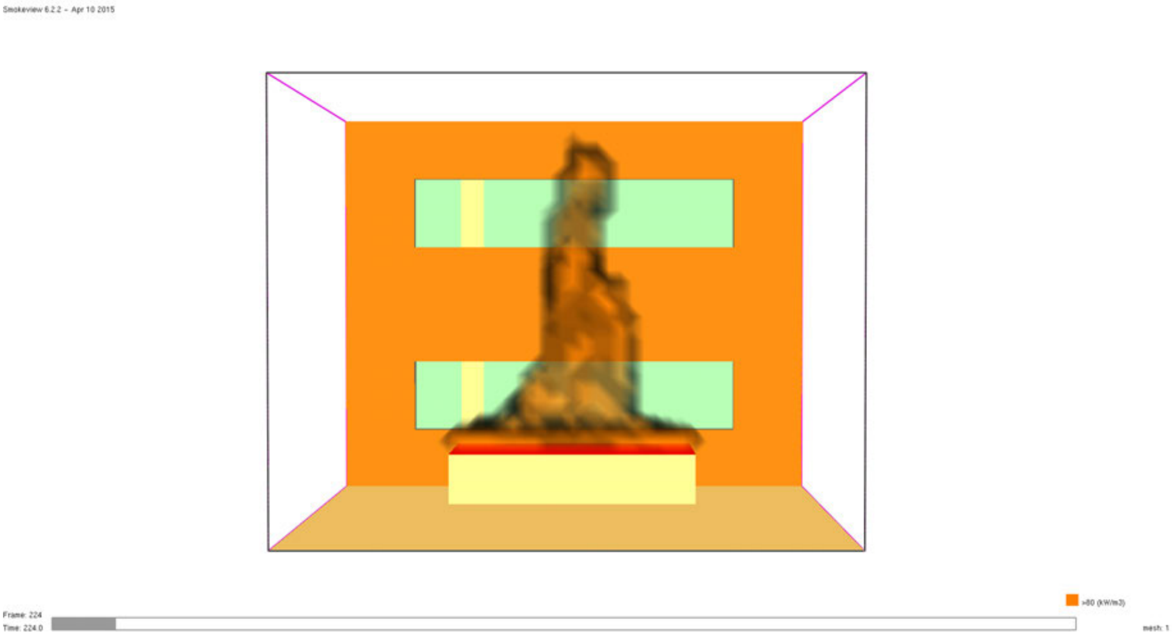

Figure 15 The upper window breaks due to flame impingement about 20 s after the fire reaches its full HRR (front view)

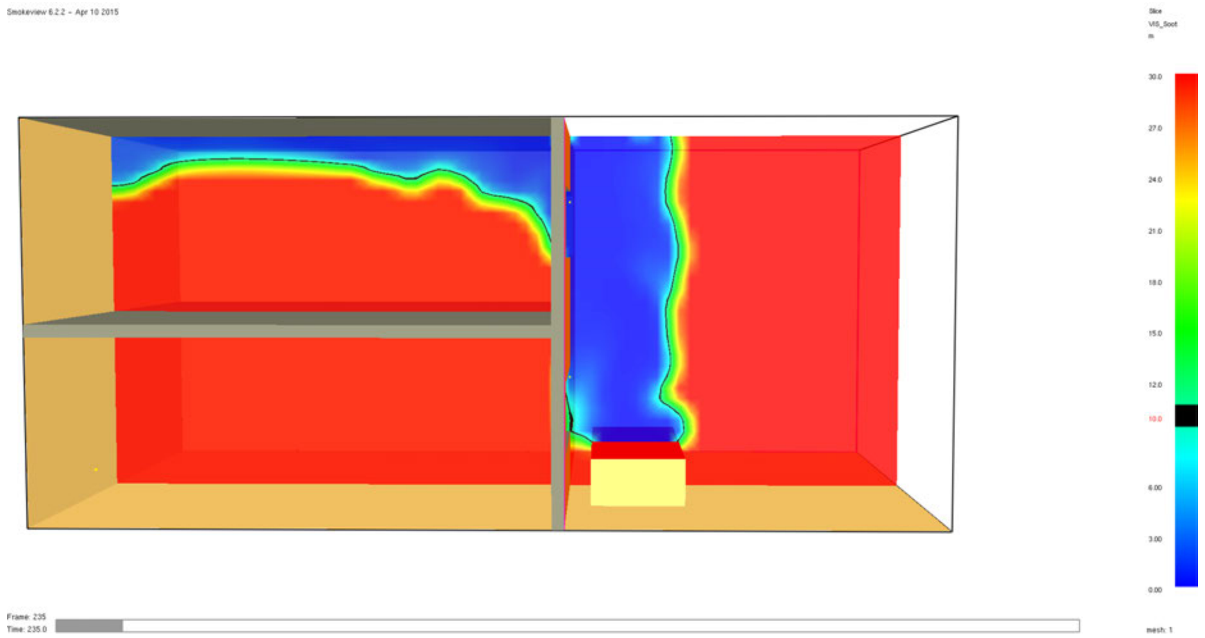

Figure 16 The visibility tenability criterion in the upper room is reached approximately 30 seconds after the fire reaches its full HRR

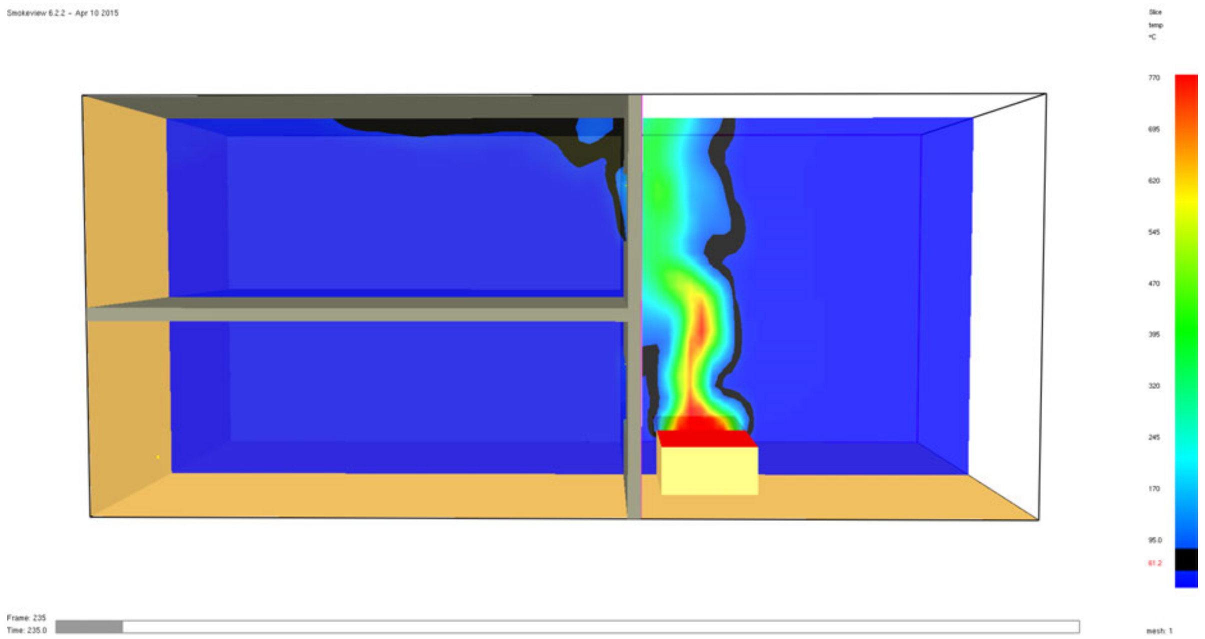

Figure 17 The temperature in the upper room when the visibility criterion is reached

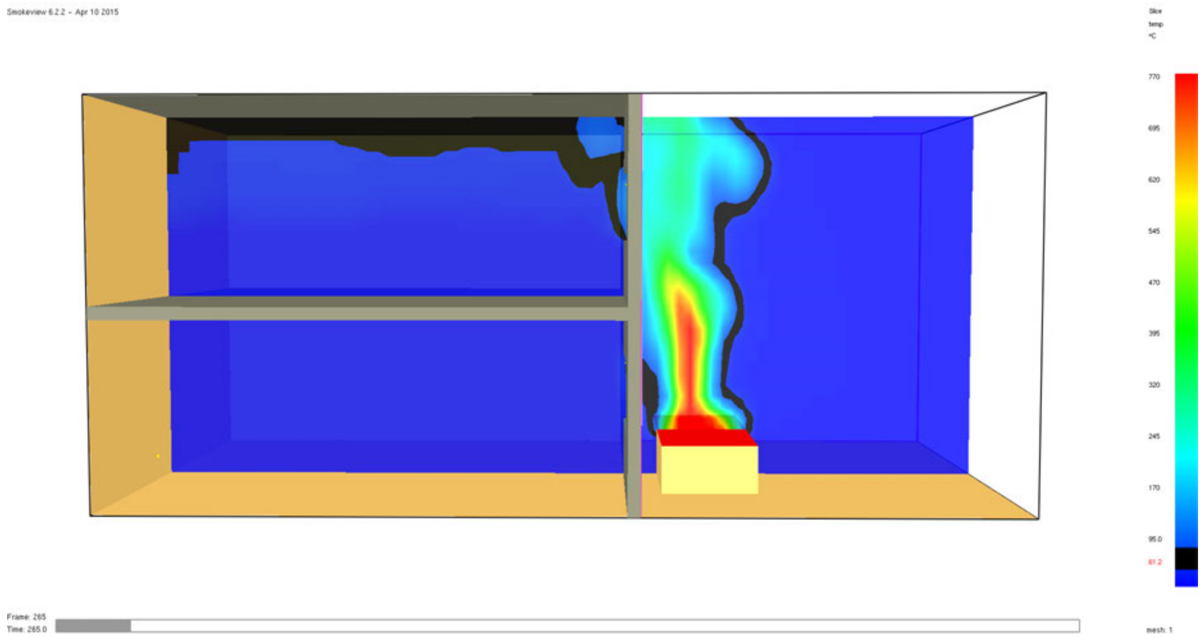

Figure 18 The temperature tenability criterion in the upper room is reached approximately one minute after the fire reaches its full HRR

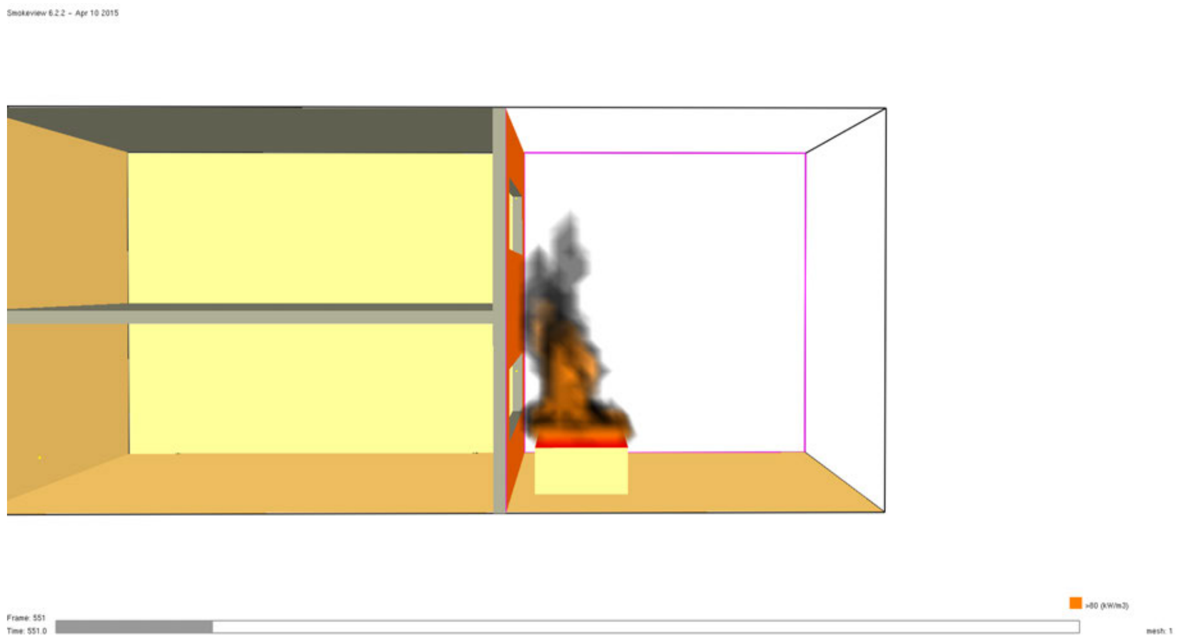

Figure 19 The lower window breaks due to flame impingement about 5 and a half minutes after the fire reaches its full HRR (side view)

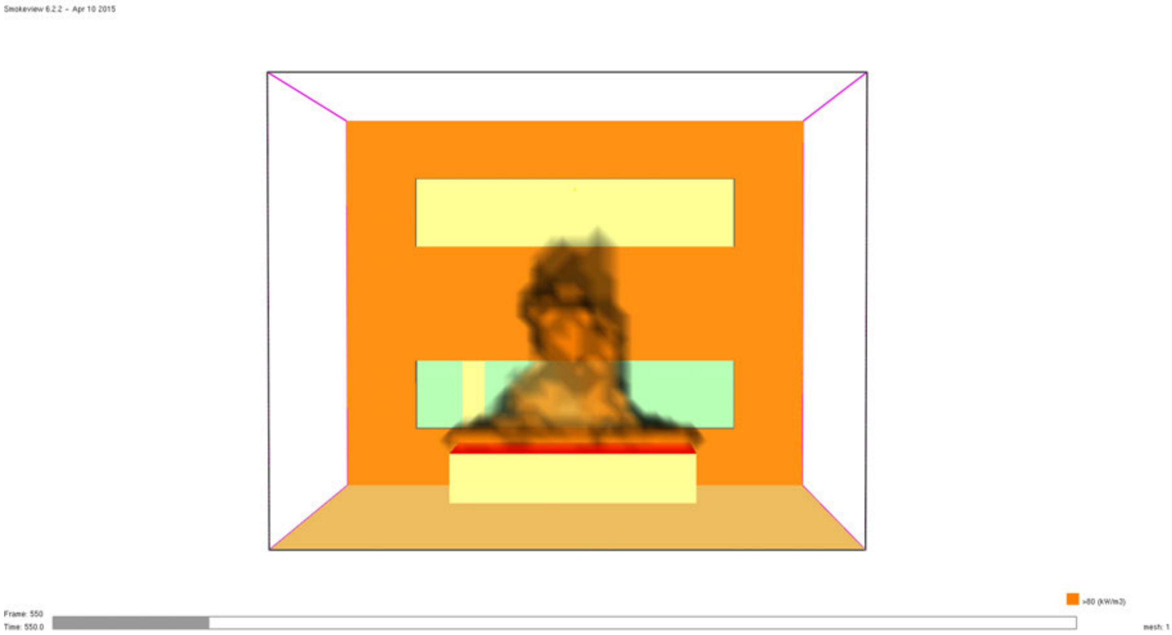

Figure 20 The lower window breaks due to flame impingement about 5 and a half minutes after the fire reaches its full HRR (front view)

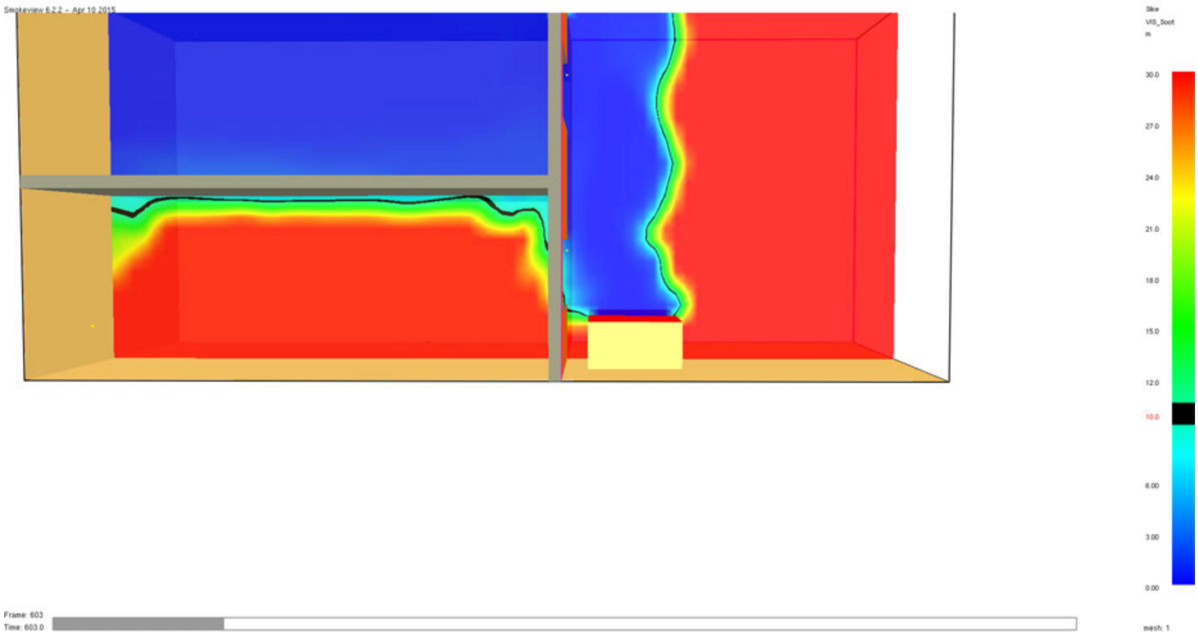

Figure 21 The visibility tenability criterion in the lower room is reached approximately 6 and a half minutes after the fire reaches its full HRR

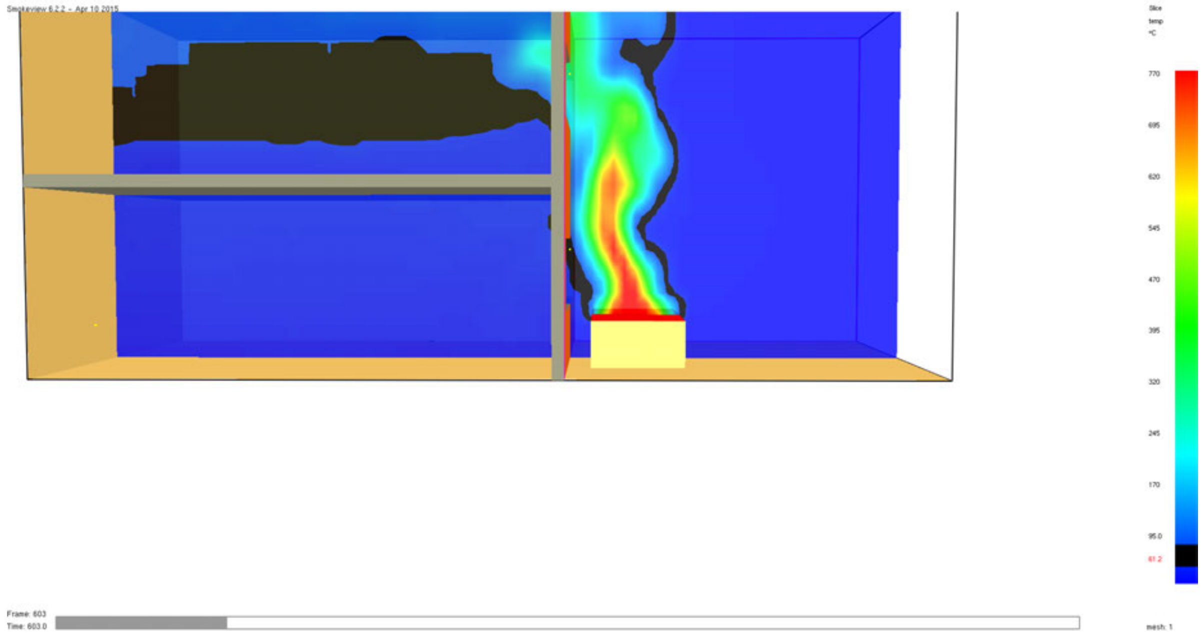

Figure 22 The temperature in the lower room when the visibility criterion is reached

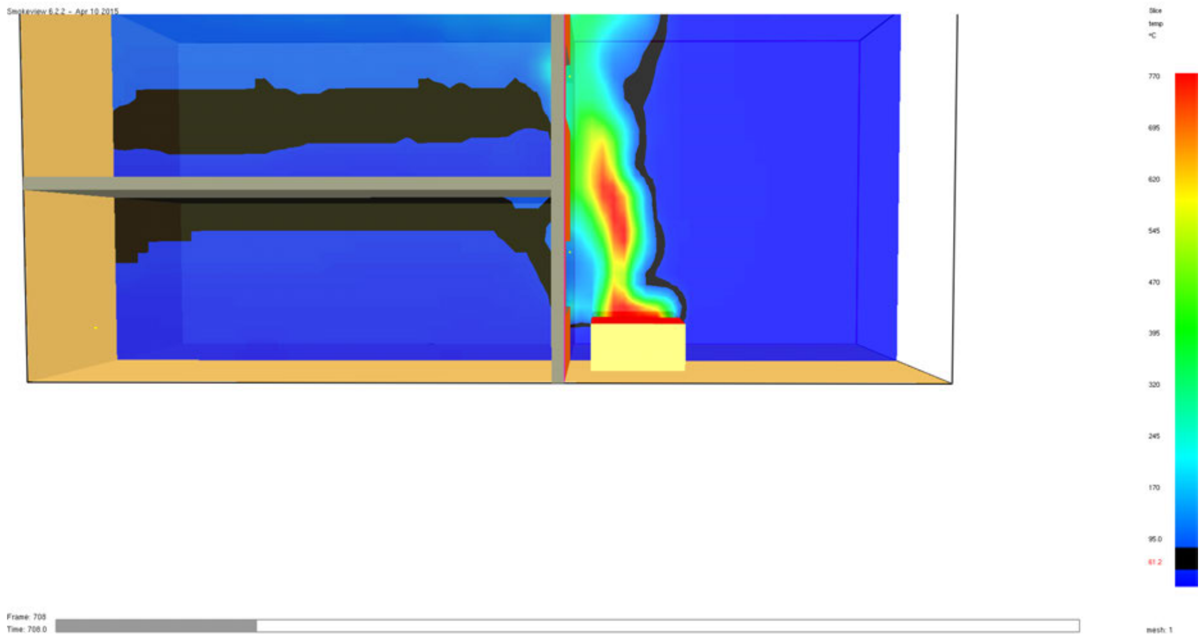

Figure 23 The temperature tenability criterion in the lower room is reached approximately 8 and a half minutes after

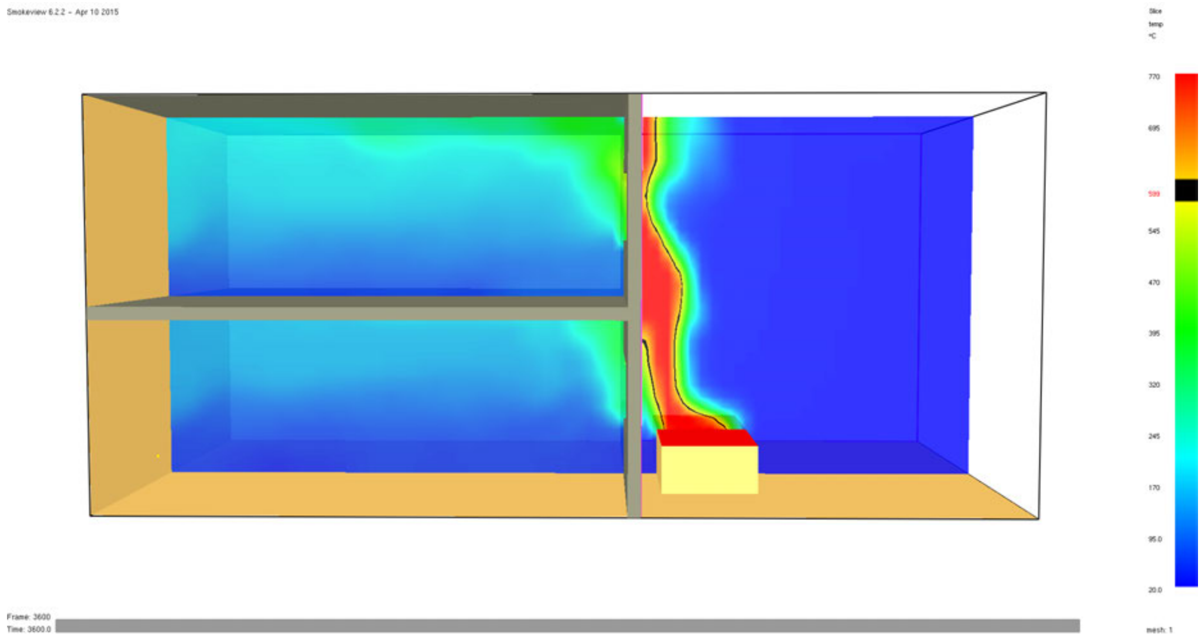

Figure 24 The temperature in the rooms at the end of the simulation

4.3 Discussion

In both scenarios, the cladding was ignited by a fire plume that was external to the building. In scenario 1 the cladding ignited approximately 3 minutes after flashover in the room of fire origin, which resulted in a fire plume being attached to the external wall. In scenario 2, the external fire plume did not become attached to the external wall and the cladding did not ignite until approximately 9 minutes after the car fire reached its peak heat release rate.

In order for a fire to reach flashover (and produce an external fire plume), it is noted that there would need to be sufficient combustible material in the rooms (i.e. the furnishings in the room are not fire retardant) and no first aid firefighting or fire brigade intervention occurs.

In all cases, conditions in the rooms adjacent to the fire plume had become untenable prior to ignition of the cladding. There was no significant lateral spread of fire along the façade, therefore other rooms are unlikely to be affected by the scenarios that have been considered.

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