# STUDY REPORT

## SR 320 (2015)

## CHARACTERISING FIRE PLUMES FROM OPENINGS IN EXTERNAL WALLS


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The work reported here was jointly funded by BRANZ from the Building Research Levy, whose logos is shown above.





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## Preface

This is the first of a series of reports prepared during a larger parent research project that considered methods of limiting fire spread by design.

## Acknowledgments

This work was funded by the Building Research Levy.

## Note

This report is intended for the MBIE Building and Housing Group, fire engineers and the international fire research community.

# Characterising Fire Plumes from Openings in External Walls

## BRANZ Study Report SR 320


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## Reference


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## Abstract


This literature review is targeted at understanding the development of window fire plumes from openings in the external walls of buildings. The purpose is to characterise the likely thermal exposure conditions for evaluating potential horizontal and vertical fire spread scenarios. Of prime importance is the relative quantity of a compartment's vapourised combustibles that burn outside. This contributes to the external flaming as opposed to the quantity that burns inside the compartment, heating and vapourising the remaining fuel load. Coupled with this is the opening factor of the vent(s) which plays a role in how much heat is retained in the compartment. The opening factor controls the air flow inwards that supports combustion of the fuel as well as the hot exhaust gases outwards that allows heat to escape from the compartment. External flaming and hence fire spread becomes more likel`y when more fuel is being vapourised due to heating within a compartment than can be combusted with the oxygen supplied inside. This excess fuel exits the compartment unburnt and then burns as an external fire when mixed with fresh air.

The challenge is in determining the potential of the external flaming process. Once this is known, probability based values can be assigned to the heat flux on the façade above an opening and on to adjacent buildings using the computational fluid dynamics (CFD) model. Fire Dynamics Simulator (FDS) is by comparison a relatively easy task.

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# 1. INTRODUCTION

The objective of this part of an overall project entitled 'limiting fire spread by design' is to carry out a literature review in relation to characterising the fire plume from openings. The Heat Release Rate (HRR) of the external flame and resultant emitted heat flux is the essential parameter used to calculate the exposure to the façades above and to the adjacent building.

## 1.1 General

The design of construction elements such as aprons and spandrels are intended to limit external vertical fire spread in multi-storey buildings.

The Fire Safety Acceptable Solutions (MBIE, 2012) specify the current minimum dimensions for spandrels and aprons on the external façades of buildings. These are intended to prevent fire spread by leap-frogging from (open) window to window from a lower firecell to an upper firecell. It has been known for over 40 years (Ashton and Malhotra, 1960; and Langdon-Thomas and Law, 1966) that the specified dimensions are not sufficient. Furthermore, no account is taken of the sizes of the windows and the fire load within the compartments – two factors that have influence on the shape of the fire plume exiting windows. High-profile and widely-known fire incidents in the USA (FEMA, 1991; Klem, 1991; FEMA, 1988; Chapman, 1988; Klem, 1989; Morris, 1990; Kim, 1990; anon, 1982; Stone, 1974), the United Kingdom (DoETR, 1999), Brazil (Sharry, 1974; Willey, 1972), Columbia (Sharry, 1974) and Thailand (Hartog, 1999) have highlighted the devastating nature of this fire spread mechanism. It is considered that flames from below deprive fresher air to the flames at the next level and this has the effect of lengthening and adding heat to the flames. This may happen if the windows in the next level above are broken and contents at that level ignite. Then those flames cause breakage and ignition of the next level above and so on. So once the fire has jumped from one level to the next and then mixes with the combustion products from below, lengthening the flames, the potential exists for easier upward spread. Logically, the ideal solution is to prevent spread above the initial outbreak.

Fortunately no serious incidents of this nature have been reported in New Zealand to date. Buildings in New Zealand are getting higher so it follows there is a proportionate increase in the risk of fire spread in this manner.

The Fire Safety Acceptable Solutions (MBIE, 2014) list the current requirements for the prevention of fire spread to adjacent buildings. These are based on traditional incident radiation exposure from the burning building to the adjacent building. For the particular 'risk group' a set of tabulated requirements apply. In the Verification Method C/VM2 (MBIE, 2013) a greater engineering approach is taken. But again the flexibility is limited to pre-specified levels of emitted radiation flux based on the fire load energy density (FLED) on the basis of the activities in the space or room.

The objective for this part of the project is to show 'that a more technically-robust quantification of the external plume can be developed and applied to both vertical and horizontal fire spread. This will lead to improved levels of fire safety'.

For this study, previous research was reviewed focusing on quantifying the thermal exposure and characteristics of flames projecting from openings in external walls. It has identified sufficient verified knowledge to advance those particular aspects of the problem with some certainty.

This review considers the potential of using a Computational Fluid Dynamics (CFD) model such as Fire Dynamics Simulator (FDS) (McGrattan et al, 2009) to confirm the basic trends predicted by the simple equations in the literature. Modelling considered the heat fluxes that the external wall and window above a vent, and an adjacent building, are exposed to for a range of vent fire outputs and vent shapes. The HRR outside the vent was considered to be a more relevant factor than just the flame plume shape.

From the findings of the overall project, risk-based approaches will be developed for the external flame size that allow the probability of fire spread both vertically and horizontally to be assessed.

## 1.2 Current NZBC provisions

The New Zealand Building Code (MBIE, 2012) has the general objectives of:

(a) Safeguarding people from an unacceptable risk of injury or illness caused by fire,

(b) Protecting other property from damage caused by fire, and

(c) Facilitating firefighting and rescue operations.

The relevant clause applicable to the objective of limiting vertical flame spread is C3.2 below.

**C3 – Fire affecting areas beyond the fire source**

**Provisions**

**Functional requirement**

**C3.1** *Buildings* must be designed and constructed so that there is a low probability of injury or illness to persons not in close proximity to a *fire source*.

**C3.2** *Buildings* with a *building height* greater than 10 m where upper floors contain sleeping uses or *other property* must be designed and constructed so that there is a low probability of external vertical fire spread to upper floors in the *building*.

**C3.3** *Buildings* must be designed and constructed so that there is a low probability of *fire* spread to *other property* vertically or horizontally across a *relevant boundary*.

The New Zealand Building Code (NZBC) sets out to limit fire spread (both external and internal) in order to provide occupants with adequate time for means of escape. It also seeks to provide access for firefighters to safely carry out firefighting and rescue operations. The NZBC is not concerned with the protection of the building under consideration. Provisions are intended to ensure a low probability of fire spread to other property under separate ownership. This includes unit titles and places where people sleep.

Although the NZBC contains limited provision for the prevention of fire occurring, relating to fixed appliances only. It does not set out to protect persons in close proximity to or intimate with a fire source.

Compliance with the overall NZBC provisions for fire safety can be demonstrated by adhering to one of the following three design processes in the compliance documents:

- NZBC – Acceptable Solutions C/AS1 to C/AS7
- NZBC – Verification Method C/VM2
- Alternative Solution.

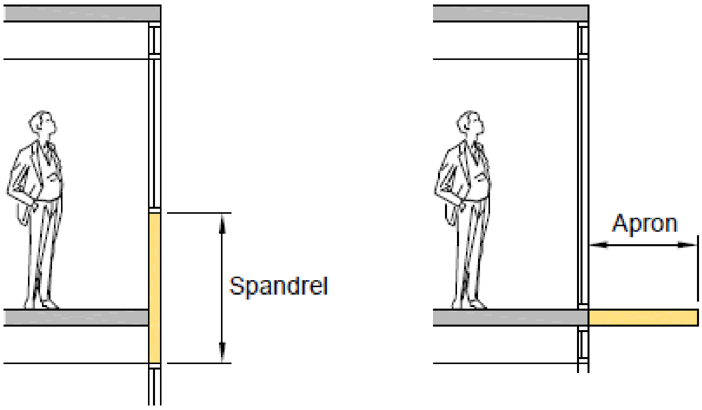
## 1.3 Acceptable Solutions

The NZBC Acceptable Solutions follow a prescriptive ‘cook-book’ type process for use by ‘non-engineer’ building designers.

### 1.3.1 Limiting vertical fire spread

For limiting vertical fire spread Acceptable Solutions C/AS1 to C/AS6 (MBIE, 2013) simply specify the required spandrel height or apron projections in Clauses 5.7.12 and

5.7.13 below. C/AS1 to C/AS6 Table 5.4 specifies combined spandrel and apron dimensions as shown in Figure 1 as follows.




**Spandrels and apron projections**

**5.7.12** Spandrels may be omitted where an apron projecting no less than 0.6 m is *constructed*. Table 5.4 specifies the acceptable combinations of apron projection and spandrel height.

**Table 5.4 Combinations of aprons and spandrels**

| Apron projection (m) | Spandrel height (m) |
|---|---|
| 0.0 | 1.5 |
| 0.3 | 1.0 |
| 0.45 | 0.5 |
| 0.6 | 0.0 |

**5.7.13** Aprons shall extend horizontally beyond the outer corners of the *unprotected area* by no less than the apron projection distance. Aprons and spandrels shall have *FRR*s of no less than that of the floor separating the upper and lower *firecells*. Spandrels shall be rated from both sides. Aprons need only be rated from the underside.

Comment:
The arrangement of windows in each *external wall* is crucial to the prevention of spread of *fire* from floor to floor vertically due to flame projection. The requirements of Paragraph 5.7.11 allow a chess board arrangement, vertical spacing of 1.5 m, or aprons. See also Paragraph 5.3 for application of *FRRs* to *external walls*.

**Figure 1: Relevant clauses from C/AS1 to C/AS6**

### 1.3.2 Limiting horizontal fire spread

For limiting horizontal fire spread Acceptable Solutions C/AS1 to C/AS6 (MBIE, 2013) Clauses 5.1 to 5.6 detail a prescriptive procedure with variations depending on the particular 'risk group'.

New Zealand Fire Service statistics (NZFS, 2005) show a relatively low fire spread to adjacent properties at 3%. The opportunity exists for the application of more technically-robust engineered solutions resulting from a better understanding of the actual fire exposure. This may offer more economical solutions and may improve the level of fire safety.

## 1.4 Verification method

The NZBC Verification Method C/VM2 (MBIE, 2013) sets a framework for the specific fire safety design of buildings. This method is suitable for use by professional fire engineers proficient in the use of fire engineering modelling methods.

### 1.4.1 Limiting vertical fire spread

The provisions of C/VM2 relating to vertical fire spread are listed within Appendix A in Figure 8 and Figure 9. Part B (for non-combustible façade materials) covers the relevant requirements for this study where the role of aprons and spandrels provide the protection. Advice is given on design fires if the designer chooses to use calculation methods. The calculation methods assess the hazard of the projecting fire plume from openings to the unprotected areas on the upper floors where they are within 1.5 m of the vent below. Guidance given on post-flashover design fires (in Clauses 2.3.2 and 2.3.3) states that for uncontrolled fires, the burning rate is assumed to be governed by the ventilation limit or the peak HRR. However, in reality, the burning rate describes the energy released within the compartment and is not indicative of the energy released outside the compartment openings. The pyrolysis rate, if known, may exceed the burning rate sometimes by a considerable amount and it is this excess (unburnt) fuel that appears as an external fire. Guidance is given on calculating the size of the external fire which is the key parameter. It is suggested that the ventilation limit HRR be increased 1.5 times (150%) to determine the total heat release rate if flashover conditions are exceeded. This is deemed to occur if the temperature of the upper layer in the compartment exceeds 500$^{o}$C.

### 1.4.2 Limiting horizontal fire spread

The provisions of C/VM2 (MBIE, 2013) relating to horizontal fire spread are listed in Figure 10 and Figure 11 within Appendix A.

The design fire specified for this scenario is based on the FLED within the fire compartment and from this an emitted radiation flux is assigned. The radiation incident on an adjacent building is calculated using one of the many methods available, such as Law (1963), Grubits (1985), Shields and Silcock (1987), Barnett (1988) and Collier (1996). The VM2 procedure has its limitations, in particular being tied to a selection of just three emitted radiant flux levels from a compartment opening. Characterisation of the fire plume from openings will allow increased flexibility for determining parameters for assessing horizontal spread of fire along the same procedure being sought for vertical fire spread.

# 2. LITERATURE SEARCH

## 2.1 Primary background – compartment fires and external flaming

Drysdale (1999) offers a thorough explanation of post-flashover compartment fires and the conditions required for external flaming (vent fires). The key parameters for this consideration of vertical flame spread externally and fire spread to adjacent buildings are established.

The parameters for internal compartment burning are well established by Kawagoe (1958) where the ventilation factor is determined from the size and shape of the openings. This correlates very well with the fuel burning rate required for the transition between fuel-controlled and ventilation-controlled burning. This well-ventilated burning rate is described in Equation 1.

$$\dot{\boldsymbol{m}}_{\boldsymbol{f}} = \mathbf{0.09}\boldsymbol{A}_{\boldsymbol{w}}\boldsymbol{H}^{\mathbf{1/2}} \qquad \text{Equation 1}$$

Where:

$\dot{m}_f$ = pyrolysis rate of fuel, kg/s

$A_w$ = vent area, m$^2$

$H$ = vent height, m

Equation 1 is based on the burning rate of wood cribs within a compartment. The correlation holds true up to the point where the ventilation factor increases such that the rate of pyrolysis of the fuel is exceeded by the air flow into the compartment. This suggests that the oxygen supplied is in excess of that required for complete combustion and the fire becomes independent of the ventilation factor and is considered fuel-controlled.

Thomas and Bullen (1979) considered the reverse condition where the fuel available, as released by pyrolysis, exceeds that which can burn within a compartment due to a restriction of air entering. Then the excess fuel that is not burnt inside burns when mixed with air that is entrained into the plume once it has exited a vent. This is the condition whereby combustion can resume and external flaming is likely to develop. The size of the external flaming will primarily be determined by an excess fuel factor $f_{ex}$, as it is dependent on the stoichiometric ratio. Secondarily, it is dependent that sufficient oxygen is available in the entrained air to support the combustion.

The excess fuel ratio $f_{ex}$ is defined in Equation 2, the magnitude of which will in turn determine the size of the external flaming.

$$f_{ex} = 1 - \frac{\dot{m}_{air}}{r} \cdot \frac{1}{\dot{m}_f} \qquad \text{Equation 2}$$

Where:

$f_{ex}$ = excess fuel factor

$\dot{m}_{air}$ = mass flow rate of air, kg/s

$r$ = stoichiometric ratio

$m_f$ = pyrolysis rate of fuel, kg/s

Extensive discussion by Drysdale (1999) primarily related to Kawagoe's (1958) original correlation in Equation 1 covers the various parameters that influence whether the compartment fire is fuel-controlled or ventilation-controlled. Some of the influences are outlined in the following passages.

By reducing the ventilation factor (in isolation of other influences) the compartment fire will shift from fuel-control to ventilation-control. At around the transition between the two conditions a maximum temperature is reached coincident with maximum pyrolysis and burning rates. External flaming is more likely where the mean stoichiometric ratio *r* of the fuel combination in the compartment errs on the higher side. This is typically ~5.7 kg of air/kg as for wood and similar cellulosic fuels. The excess fuel factor $f_{ex}$. is likely to increase in accordance with Equation 2. Other fuels in the synthetic polymer category representing more modern materials that are more likely to be found in contemporary contents and linings have a higher stoichiometric ratio *r* (6.9 to 13.2). In this situation there is the potential for an increased excess fuel factor and external flaming.

Figure 2 is reproduced from Drysdale (1999) and is based on small-scale compartment fire experiments by Bullen and Thomas (1979). The graph provides a general indication of the resultant heat flux on the wall above an opening due to flames projecting from the opening. A significant factor is the rapid reduction in the first metre of height followed by a continuing reduction if the excess fuel factor is on the higher side.

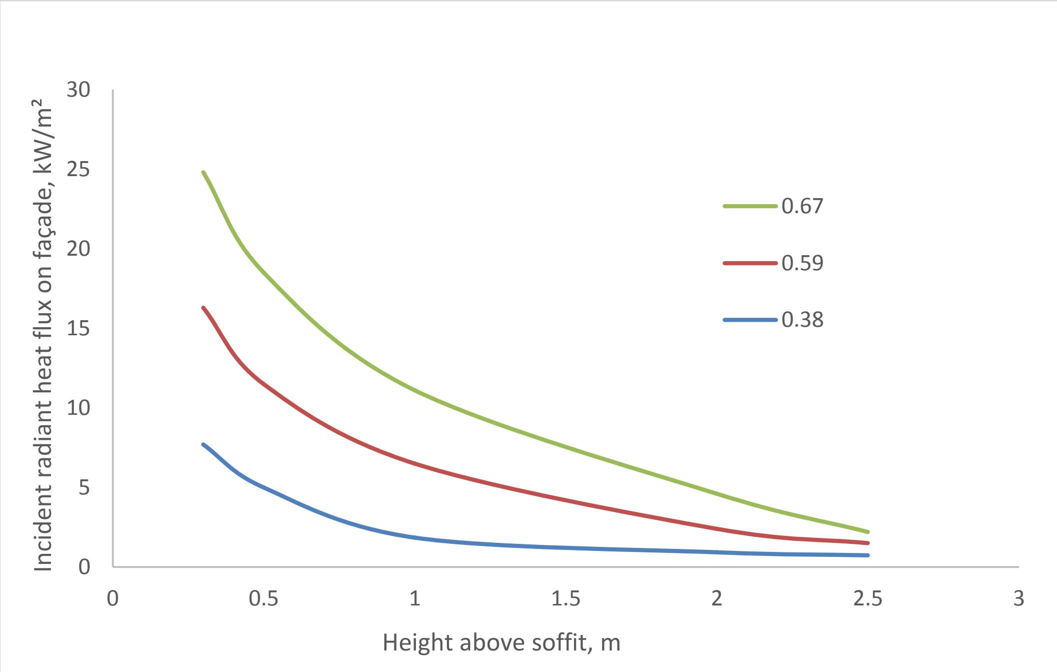



**Figure 2: Variation of radiant heat flux in the plane of the opening of a small compartment as a function of the height above the soffit for external flames as a result of the excess fuel factors of 0.38, 0.59 and 0.67 (extracted from Drysdale, 1999)**

Drysdale (1999) shows that a variety of factors will determine the magnitude of any excess fuel ratio if indeed there is one and these are summarised as:

- Distribution of the fuel load within the compartment
- Distribution of fuel and composition of various elements
- Size and aspect ratio of the compartment (depth and width)
- Ventilation factor, or
- Opening factor, which is the ventilation factor in relation to surface area of the compartment.

Hence the excess fuel ratio will be the prime determinant of external flaming.

The other factors to consider are:

- Temperature profiles in external flames reduce rapidly with height
- There is rapid drop off in heat flux from flames with height
- The tip of the flame is 540°C to 550°C.

Other extensive studies have been conducted over the decades. The SFPE Handbook (Walton and Thomas, 2008) covers the theory of compartment fires with vents, equations for fire within compartments and means of estimating temperatures and HRR. However,there is a relative lack of guidance to enable determination of the flow of unburnt fuel that exits the vents. It is this parameter that is largely responsible for the magnitude of vent fires and subsequent exposure of external walls above vents and to adjacent buildings.

The literature review from here onwards focuses largely on more recent research that attempts to advance the understanding of the heat flux incident on the building façades. The parameters that influence the heat flux were assessed, in particular the size of the vent fire.

### 2.1.1 External flame shape

Thomas and Law (1972) derived the correlation, as shown in Equations 3 and 4, for the external flame shape and projection away from burning buildings. The correlation is based on the data of flame projections by Yokoi (1960), Seigel (1969) and Thomas and Heselden (1972).

The correlation shows that for wider openings the external flames are not projected away from the façade to the same extent and follow closer to the wall above. Under such conditions the incident heat flux on the façade above a vent is greater.

Formula:

$$\boldsymbol{z + H = 12.8(\dot{m}/B)^{2/3}} \quad \text{Equation 3}$$

$$\boldsymbol{x/H = 0.454/n^{0.53}} \quad \text{Equation 4}$$

Where:

$z =$ height of flame (m)

$\dot{m} =$ rate of burning (kg/s)

$H =$ height of opening (m)

$B =$ breadth of opening

$x =$ horizontal projection of flame(m) and

$n = \frac{2B}{H}$ (the 'shapefactor')

The rate of burning $\dot{m}$ can then be determined depending on whether the fire is 'fuel-controlled' or 'ventilation-controlled' in accordance with the following formulae. These were developed by Thomas and Heselden (1972), Law (1982) and Eurocode 1 (2002) Appendix B, such as used by Hao and Hadjisophocleous (2012) and Hietaniemi and Korhonen (2005).

$$\boldsymbol{\dot{m} = \frac{M}{1200}} \quad \text{Equation 5}$$

(fuel-controlled) or

$$\dot{m} = 0.18[1 - e^{-0.036/O}]A_v\sqrt{H}\sqrt{\frac{W}{D}}$$ Equation 6

and

$$O = \frac{A_v\sqrt{H}}{A_t}$$ Equation 7

(ventilation-controlled)

Where:

$M$= compartment fire load (kg/m$^2$)

$O$ = the opening factor (m$^{-1/2}$)

$A_v$ = area of the opening (m$^2$)

$W$ = width of compartment (m)

$D$ = depth of compartment (m)

$A_t$ = total area of compartment enclosing surface (m$^2$)

Equation 5 applies in the case where the fire is fuel-controlled and it is consumed in 1200 seconds at a uniform rate. In the alternative scenario where the fire is ventilation-controlled this is covered by Equations 6 and 7. The selection of which equation(s) to use is determined by which one returns the lower (minimum) rate of burning and that is then used in Equation 3 to determine the flame height.

Further considerations include cases where multiple openings in the same compartment determine the total mass loss rate through those openings. In that case, to determine flame projection the mass loss rate would need to be divided between all of the openings and be considered individually.

Thomas and Law (1972) show that in the following circumstances this model breaks down if:

- There are substantial heat losses from the projecting flame to the façade of the building
- There is wind (the flame will be deflected and projection against the façade [reduced in length])
- The fire is on a lower floor (flames will lengthen due to oxygen depletion by the rising combustion products). Merging of flames from different floors can occur
- The fuel has a very large surface area (the mass pyrolysed will be higher than anticipated and the flames will be longer)
- The fuel is non-cellulosic and has a low value of $L_v$ (latent heat of vaporisation) and high stoichiometric ratio.

The last two circumstances correspond to cases where large excess fuel factors are likely with corresponding increases in flame height and heat flux on the façade.

The effect of the presence of non-cellulosic fuels on the size of the external flames has not been addressed. As hydrocarbon polymers have a much higher air requirement than cellulosic fuels, it is almost inevitable that external flaming will be more significant, all other things being equal. It should also be remembered that thermoplastics will tend to burn as pools in the fully-developed fire, with the potential to produce large areas of burning surface.

Lu et al (2013) show that with a reduced-scale model, the addition of side walls on a façade causes the flame height to increase significantly. This is another instance where previously-developed algorithms and guidance may not apply.

## 2.2 Heat flux on façades

Abecassis Empis (2010) identified the phenomenon of how the geometry and fuel of the internal compartment fire in turn influences the development of external flaming. This then dictates the heat flux to the exterior walls above vents.

Existing correlations are explored, their limitations identified and a simplified methodology proposed. This links the key parameters that are found to govern the internal post-flashover compartment fire to the heat flux potentially imposed on the exterior façade as a result of external flaming. This is considered the crucial relationship.

It is acknowledged (Abecassis Empis, 2010) that the methodology is convoluted and is based on several assumptions, which suggest limits of applicability and consequently a degree of conservatism is justified. Further advice suggests a reduction of unnecessary complexity and the establishment of clear bounds of applicability.

The fundamental problem recognised is that CFD modelling of compartment scenarios of ventilation-controlled conditions is of limited value in determining the vent fire characteristics. So obtaining further experimental results to compare with CFD modelling is recommended.

The findings of the research (Abecassis Empis, 2010) show the characteristics of the fuel load that influence fire behaviour within a compartment and ultimately determine vent fire size. The fuel load characteristics are quite numerous and interrelated as follows:

- The relative location of the different components of the fuel load
- The material properties of the fuel load
- Resultant emissivity of the combustion products
- The effect of having fire load items (or parts of items) with different heat of combustion and critical heat flux for ignition
- Localised rates of burning
- Different areas of fire load
- Different surface orientation
- Varying height of fuel load
- Ventilation factor/opening factor.

A further study by Abecassis Empis (2010) concludes with proposing a *Simplified Model* with clear bounds of applicability.

$$\dot{q}'' = 16\big(1 - Ln(Z)\big) \quad \pm 10 \text{ kW/m}^2 \qquad \text{Equation 8}$$

Where:

$\dot{q}''$ = heat flux on façade, kW/m$^2$

$Z$ = the height above the opening, m

A conservative error bar of $\pm$ 10 kW/m$^2$ is advised for use of the model in design and this takes into account variations in the compartment and vent dimensions. Variations in ambient conditions and the compartment fire load are also allowed for, thus permitting a simple formulation for design purposes. Limitations on the application of Equation 8 restrict the height to between 0.05 and 2.718 m (i.e. not more than a single typical floor height). In the range of 0 to 0.05 m above the soffit unrealistically high values of heat flux may occur that the *Simplified Model* is not validated for.

A further limitation also recommended is that the *reciprocal opening factor* ($A_t/A_vH^{1/2}$) is between 5 and 20 m$^{-1/2}$. In instances where the *reciprocal opening factor* is less than 5

$m^{-1/2}$ the vent size in relation to the compartment surface area is large and the fire is likely to be fuel-controlled. Conversely, for values of *reciprocal opening factor* greater than 20 and up to 40 $m^{-1/2}$, insufficient test data was obtained to validate the *Simplified Model.* The distribution of heat flux is shown in Figure 3 where the graph line at mid height is the value calculated in Equation 8. The upper and lower graph lines are the +/- 10 $kW/m^2$ error bar values.

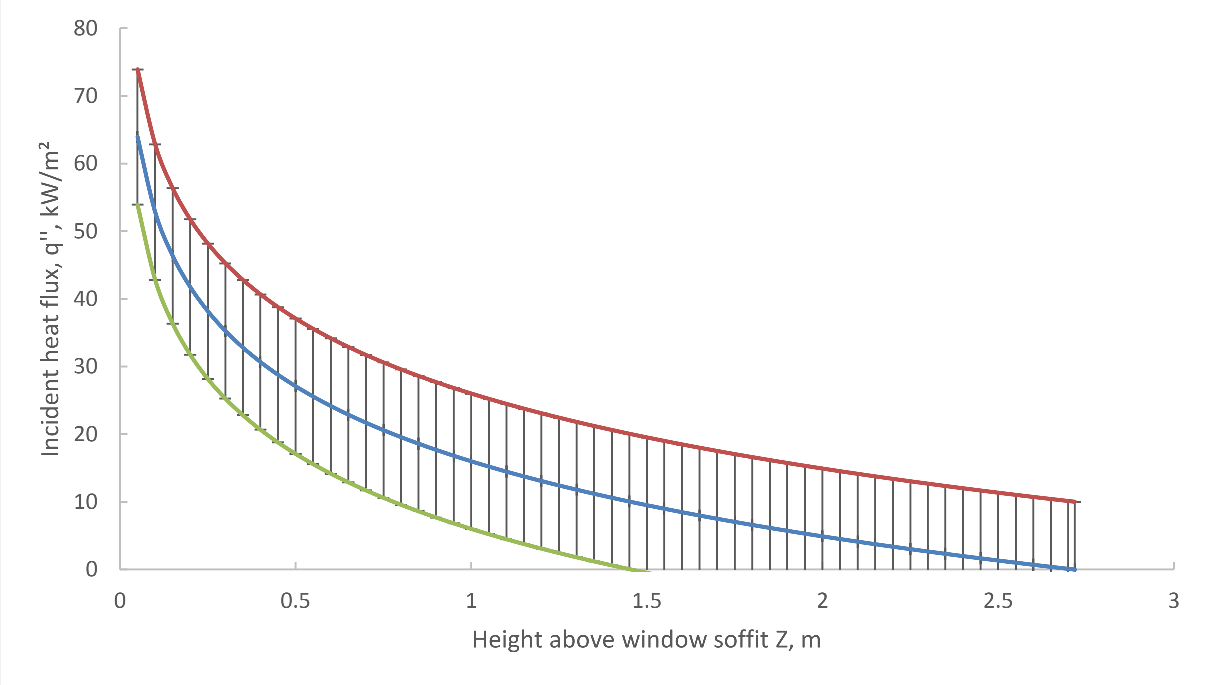



**Figure 3: Vertical distribution +/- 10% of incident heat flux on the façade**

The proposed application of this model is described in the quotation from Abecassis Empis (2010) below.

> *In practice it is likely the Simplified Model will be used to define the heat flux incident on different regions of the façade, such as to select cladding with an appropriate critical heat flux for ignition and to design upper-storey window arrangements that are unlikely to crack and fall out under the heat flux incident in the case of a fire in the compartment below, or even to decide on an inter-storey height to be used between openings. In these cases, the highest heat flux incident on that region should be applied (i.e. corresponding to the lowest height). For the case of the close near-field to the opening soffit, it may be economic to apply a single strip of a different material to the first 0.05 m with a higher critical heat flux for ignition than that of the rest of the façade cladding material (i.e. such as an opening headstone), if the heat flux to that region is significantly higher than that incident further afield.*

This provides a means of using test data with known critical heat flux for ignition of cladding materials or window glass that is not expected to crack at the expected heat flux. Hence spandrel height can be specified accordingly. Unfortunately, Abecassis Empis (2010) does not address this in detail, other than by proposing a conservative solution. Consequently, the problem remains with the relationship of internal/external fire HRR and the ventilation condition that would otherwise determine the vent fire size. Further experimental research would address this and better define a relationship between the influence of compartment fire conditions and external flaming which is the primary relationship required. The resultant heat exposure on the façade would be a better defined relationship for the purpose of design.

Other researchers (K Himoto et al, 2009; Klopovic et al, 1998, 2001A and 2001B; and Lee et al, 2007) similarly characterise the relationship between external flame size or HRR and the heat flux on façades or to adjacent buildings. However, they also stop short of proposing a means of determining the magnitude of the HRR in the external flame.

Hu et al (2012) go a step further and suggest a statistical approach to determining the HRR of the external flame. It is simply demonstrated that an upper-critical value of the external flaming may be as much as 1.32 times that of the ventilation limit, albeit intermittently. It is proposed that there is a probability of 1 that the actual value is less than 1.32 times the ventilation limit. Then that (the probability) reduces linearly down to zero at zero times the ventilation limit as an upper limit.

Tang et al (2012) also base correlations of flame height and temperature at an excess HRR factor of 1.3 based on the small-scale experiments as reviewed in Section 2.4. No definitive advice is given for selecting 1.3 as the excess heat release factor.

Referring back to Section 1.4.1 of this report, NZBC Verification Method C/VM2 (MBIE, 2013) proposes using 1.5 as the HRR factor applicable to the ventilation limit.

## 2.3 Calculation of radiation on façade or to adjacent building

Following on from Section 2.1.1 the formulae presented in Eurocode 1 (2002) Appendix B for the rate of burning also provide guidance for calculating the thermal exposure to external members. Such exposure is based on the flame shape, the varying temperature and other characteristics along its axis.

Specific guidance for calculating the exposure due to the heat flux on the façade or an adjacent building is not specifically included. Although it would be feasible to calculate, by integration, the configuration factors and then heat flux based on the distribution of flame temperatures onto the surfaces under consideration. Such integration would be from the inclined flame (plane) exiting the opening using the formulae provided or deriving formulae specific to the problem.

## 2.4 Small-scale experiments

Ohmiya et al (2000) conducted small-scale experiments investigating the properties of external flames ejected from an opening.

The formulations derived reinforce the long-accepted relationship that $AH^{1/2}$ (the opening factor) is proportional to the critical heat release rate within a compartment above which external flaming starts to occur. In addition, some attempt is made to propose additional relationships for the flame height above an opening of:

$$z=0.65Q_B^{*2/3}B \quad \text{Equation 9}$$

Where:

$z$ = flame height, m

$Q_B^*$ = the dimensionless heat release rate $Q/(\rho_\infty c_p T_\infty g^{1/2} B^{5/2})$

$B$ = the width of the opening, m

A further correction $\Delta z$ takes into account the total heat release rate of the flame ejected from an opening.

$$\Delta z = 0.04 Q_{ef}^{*2} r_o \quad \text{Equation 10}$$

Where:

$\Delta z$ = correction factor for flame height, m

$Q_{ef}^{*}$ = heat release rate of external flame, dimensionless

$r_o$ = equivalent opening radius, $(BH/2\pi)^{0.5}$, m

*H* = height of opening, m

The correlations presented attempt to account for the combustion of the excess fuel ejected from an opening with the expected increase in flame height and temperature. This is achieved with the development of an empirical relationship that fits the data for the small-scale tests. However, the application to full-scale fires is considered (Ohmiya et al, 2000) to require more experiments.

The results that are presented in an empirical nature combine the $z + \Delta z$ relationship and demonstrate a rapid reduction in temperature the higher the flame extends above the opening. No attempt is made to relate this to the incident heat flux on the wall, so this simply reinforces what is already known about the external flame phenomena.

Mizukami et al (2008) show the fuel mass loss rate in a compartment is a function of scale (of the compartment). On further investigation this effect comprises two components – the surface area of the fuel and the thermal effect enhancing the mass loss rate. The thermal feedback to the fuel is from the incident radiation from the heated compartment and the attenuation of the flame radiation. An additional factor noted in the thermal effect is that when the compartment is small the heat is accumulated more easily, perhaps accounting for a more rapid development of a fire event.

Lee et al (2007) conducted small-scale experiments and observed a trend that changes in vent size and shape have an effect on the heat flux above an opening. However, the most significant factor is the amount of excess burning that occurs outside a compartment in a vent fire. This has been repeatedly mentioned and again demonstrated by Delichatsios (2014).

Flammable gases that are ejected from an opening have been preheated in an enclosure in accordance with Equation 11 below.

$$\dot{\boldsymbol{Q}}_{ext} = \dot{\boldsymbol{Q}}_{th} - \mathbf{1500AH}^{1/2} \qquad \text{…Equation 11}$$

Where:

$\dot{Q}_{ext}$ = the heat released outside the enclosure

$\dot{Q}_{th}$ = the heat release rate calculated by the fuel supply

The results of the small-scale experiments (by Lee) with three opening sizes show an indicative value of the heat flux just above the opening in the range of 18-30 kW/m$^2$. This reduces to 10-15 kW/m$^2$ at the flame tip and 2-3 kW/m$^2$ at a height equivalent to two times the external flame height. The shape of the opening was shown to have a discernible influence on the heat flux above it. A tall narrow opening had a lower heat flux ~18 kw/m$^2$, most likely due to the effect of the flame being projected further away from the opening. This is supported by previous experimentally-derived formulations.

Correlations using a CFD model (FDS) to replicate under-ventilated fires including the façade were attempted (Delichatsios, 2014) but these were not wholly successful in predicting the experimental results.

Tang et al (2012) used a small fire compartment with six different window geometries on a façade wall. From this he related flame heights on the façade to the excess fuel heat release rate outside the enclosure. These results were a significant improvement over previous results in the literature. But they still fall short of demonstrating how the magnitude of the external HRR can be determined, other than suggesting an excess fuel factor of 1.3 as discussed in Section 2.2.

## 2.5 Enclosure fires

Delichatsios and Silcock (2002) focus on enclosure fires and in particular when the fire has essentially spread to all of the available fuel and the fire becomes ventilation-controlled. The authors extend previous work by identifying how (the mechanisms of) fuel type (with various stoichiometric ratios), fuel surface area and height, room geometry and opening factor affect the rate of burning. The relationship between pyrolysis rate and air inflow rate was investigated and a key dependence on the stoichiometric ratio was identified.

A series of comprehensive experiments (Ohmiya, Tanaka and Wakamatsu, 1998) were undertaken in cubic-like compartments. The experiments used three different fuel types (methanol, polymethyl methacrylate [PMMA] and wood). Correlations were developed for the rate of pyrolysis, of incoming air flow and of excess pyrolysate. Critical areas for further investigation involving combustion efficiency, heat fluxes and effective fuel area involved in pyrolysis were also suggested.

The key challenge identified in the study was to investigate the relationship that exists between the pyrolysis rate and the air inflow rate. This relationship was of interest for the primary purpose of determining the size of the vent fire resulting from the excess pyrolysates that were not burnt inside the compartment. These excess pyrolysates may be expected to burn externally as a vent fire, heating the façade above the opening.

A relationship based on the stoichiometric ratio (SR) for respective fuels (Table 1) was found to influence the extent of external burning. For fuels with a lower SR ratio such as cellulose and wood-based items there is a tendency for more fuel to burn within a compartment because less incoming air is required. Fuels with a higher SR ratio (e.g. PMMA) where insufficient (returning) air is able to enter a compartment for complete combustion, are more likely to vent. This is because the excess pyrolysed fuel that is unable to burn inside the compartment flows out of the vent and mixes with outside air to result in a vent fire.

**Table 1: Stoichiometric ratio**

| Fuel | Stoichiometric ratio, air-to-fuel |
|---|---|
| Methanol | 6.47 |
| PMMA | 8.28 |
| Wood | 5.7 |

Running counter to this effect is when sufficient air (presumably with a higher opening factor) was able to enter the compartment. In these circumstances, a fuel with a relatively higher SR (greater than ~8) the cooling effect of the additional venting would tend to reduce the rate of pyrolysis of the fuel. This then has an additional effect of reducing the magnitude of the external burning. So the fire would then revert to a fuel-controlled regime. This effect is illustrated in Figure 4 as a generalised representation of the experimental results.

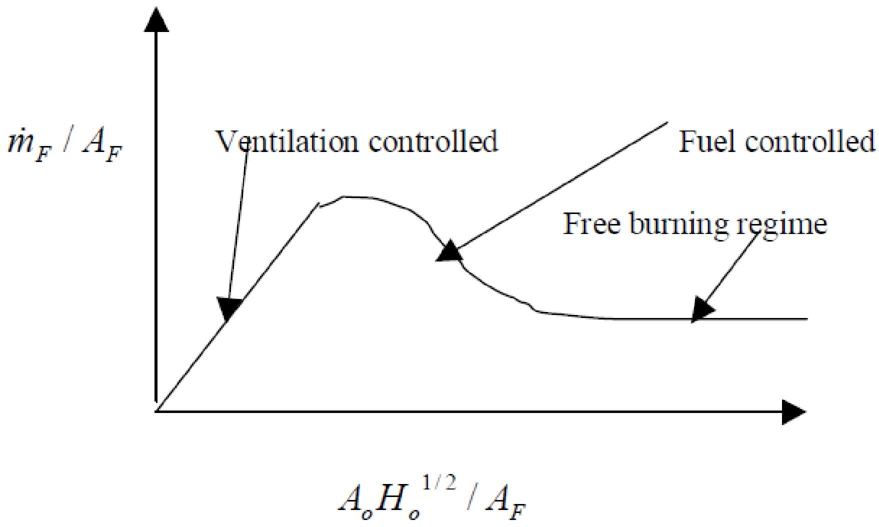



**Figure 4: Expected behaviour of enclosure steady burning rate per unit area versus opening factor per unit area**

To further explain the onset of external flaming consider firstly the far-right-hand-end of the graph in Figure 4. Here the opening(s) is so large the fuel can essentially be considered as burning unrestricted in the open (free-burning) and is essentially fuel-controlled.

If the ventilation is progressively reduced, moving in a leftwise direction on the horizontal axis, the burning is still fuel-controlled but the flow of air is further restricted. As more heat is contained within the compartment, this raises the temperature, increasing the rate of pyrolysis of the fuel ($\dot{m}_f$) and it follows further heat is released by its combustion. Eventually a maximum $\dot{m}_f$ is reached where as much fuel as can be is pyrolysed for the conditions present, the combustion of which is (just) supported by the air supply. Beyond that point as the ventilation factor is further reduced the combustion becomes ventilation-controlled, heat is more effectively contained within the compartment and that maintains the pyrolysis rate to a certain extent. But the excess fuel that cannot be burnt within the compartment is vented and may burn externally when mixed with outside air. Then the reduction of temperature within the compartment may reduce the rate of pyrolysis. In the ventilation-controlled region, external flaming is to be expected to some extent. The magnitude of which will depend on the factors of stoichiometric ratio, heat of combustion, gasification temperature, latent heat of gasification, fire load, its surface area and how it is distributed, including elevation.

### 2.5.1 The influence of stoichiometric ratio

Further analysis of the influence of the stoichiometric ratio on external flaming suggests a critical ratio below which there is most likely sufficient air available for complete combustion within a compartment. As a result there will not be any external flaming.

From the analysis presented, the following formula for the excess pyrolysate exiting the enclosure is derived by Delichatsios and Silcock (2002).

$$\dot{m}_{ex} = \left(0.22 - \frac{1}{s}\right)\dot{m}_a \qquad \text{Equation 12}$$

Where:

$\dot{m}_{ex}$ = mass flow rate of unburnt pyrolysate exiting compartment, kg/s

$S$ = air-to-fuel stoichiometric ratio

$\dot{m}_a$ = mass of air inflow rate to compartment, kg/s

This formulation suggests a stoichiometric ratio below which there will be no excess pyrolysates as shown in Figure 5 as generated by Equation 12. Where the excess of pyrolysates is relative to rate of burning within the compartment.

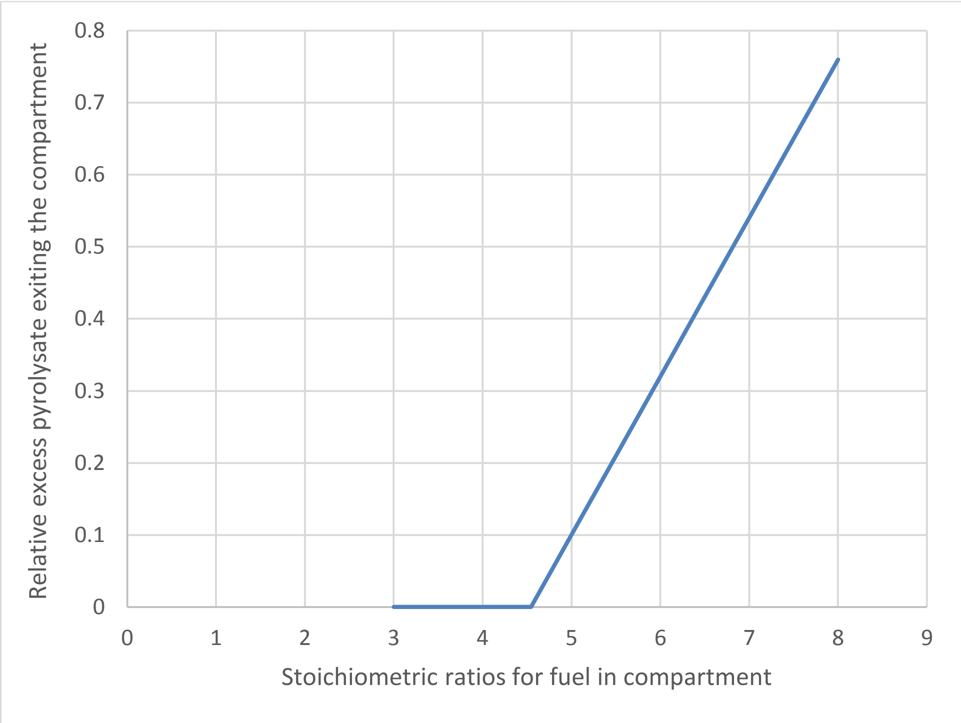



**Figure 5: Excess pyroysate exiting compartment with potential for external flaming**

Such a formulation is an idealised view based on a series of steady-state experiments with a single fuel for which the stoichiometric ratio is known. In reality, a compartment will be filled with a relatively-unknown distribution of fuels with not only a variation of stoichiometric ratios but also a distribution of those fuels. Some portions of the fuel may be predisposed to burn earlier in preference to others due to positioning and ignitability. The question arises, if the stoichiometric ratio is low enough, will this eliminate the possibility of external flaming? But this is unlikely in buildings with modern lining and furniture products, refer to Table 2, as other studies have shown. This will be discussed later.

### 2.5.2 Conclusions on enclosure fires

The authors (Delichatsios and Silcock, 2002) presented a semi-quantitative picture of the vent flows and pyrolysis rates based on a global energy balance for enclosures which acknowledged its limitations. They concluded that:

- In ventilation-controlled conditions, all incoming air is consumed
- The air inflow rate dependence on the ventilation factor changes as the temperature distribution in the enclosure changes from a uniform distribution such as in a rectangular room to a layered distribution. A layered distribution may be found in a corridor or a an enclosure with two opposite, opposed openings, meaning it is unknown what the outcome will be

- In an enclosure, two temperature regions exist – a higher one near the combustion volume and a lower one in the rest of the enclosure. Heat fluxes will depend on the temperature and smoke concentration fields. A conservative estimate for radiative heat fluxes can use the higher-temperature and optically-thick conditions
- The pyrolysis rate dependence on the air flow rate changes as the temperature distribution in the enclosure changes from uniform to layered
- For some fuels depending on the mass air-to-fuel stoichiometric ratio (low end) no excess pyrolysate exists, in which case no flames extend outside the enclosure
- The air inflow rate when the mass pyrolysis rate is at a maximum, varies significantly with the heat flux from the flames and the effective area of pyrolysis. This is identified as the weakest link in the current analysis that requires further investigation
- For ventilation-controlled, fully-involved enclosure fires, that is those likely to result in vent fires, the heat release rate of flames outside of the enclosure is due to the burning of excess pyrolysate. This is given by the difference between the total pyrolysate that is produced by the heat flux exposure on the fuel and that which can burn within the enclosure. Burning within the enclosure is limited by the incoming air that is available to support that combustion. The stoichiometric ratio plays a part whereby for lower values (of S) less air is required for complete combustion reducing the likelihood of vent fires. Conversely, higher values of S require more air. In the cases where the rate of incoming air is unable to meet demand, the remainder of the pyrolysate burns outside of the enclosure when coming into contact with fresh air.

$$\boldsymbol{HRR_{ex}} = \left(\boldsymbol{\dot{m}_f} - \frac{\boldsymbol{\dot{m}_a}}{\boldsymbol{S}}\right)\Delta\boldsymbol{H_c} \qquad \text{Equation 13}$$

Where:

$HRR_{ex}$ = heat release rate of flames outside enclosure, W

$\dot{m}_f$ = total fuel mass pyrolysis rate (dependent on fuel area $A_F$ and heat flux), kg/s

$\dot{m}_a$ = mass of air inflow rate to enclosure (dependent on opening factor $AH^{1/2}$), kg/s

$S$ = air-to-fuel stoichiometric ratio (dependent on type of fuel burning)

$\Delta H_c$ = heat of combustion per unit fuel mass (dependent on type of fuel burning), kJ/kg

This ($HRR_{ex}$) heat release rate determines the flame height of emerging flames and affects the heat fluxes to the external wall.

### 2.5.3 Relationship to fuels in compartments

By way of putting the above into perspective, Table 2 lists a selection of fuels. The stoichiometric ratios (S) were obtained from Table 2-5.1 in the SFPE handbook (Gottuk and Lattimer, 2008) and Tables F.1 and F.2 in the ISO 9705 Standard (ISO, 1993). Fuels that are based on wood products have an S around 5. Fossilised fuels derived from wood are ~8 to 11, while those based on plastics or petroleum products range from 8 to 14.

It could be surmised on the basis of the theory presented above that those fuels with an S < 4.54 are less likely to result in vent fires when burning within a compartment. However, it will be shown later that this is not necessarily the case.

**Table 2: Selected stoichiometric ratios**

| Fuel | Estimated stoichiometric ratio (S) |
|---|---|
| Wood (ponderosa pine)* | 4.83 |
| Wood (spruce)* | 3.87 |
| Polyurethane foam* | 8.78 |
| Poly(methyl methacrylate) (PMMA)* | 8.23 |
| Polyethylene** | 14.78 |
| Cellulose** | 5.11 |
| Cotton** | 4.94 |
| Newsprint** | 5.93 |
| Corrugated cardboard** | 5.05 |
| Lignite** | 8.16 |
| Coal, bituminous** | 11.25 |

Source *Gottuk and Lattimer (2008), **ISO (1993)

## 2.6 CFD modelling

The following selection of studies explored the validity of using CFD modelling (FDS3) to predict the results of experiments and compare these with empirical formulations.

Hietaniemi and Korhonen (2005) consider the heat exposure generated by external flames. They vary the HRR within the limits of -20% to +50% (uniform distribution) to allow for variabilities of various factors such as amount, properties and positioning of fuel within the compartment. This concept is supported by Harmathy (1980/81) who compiled data and studied their variability. Breakage of windows above a vent fire is assumed to occur at exposures of ~35 kW/m$^2$. Three minutes at the exposure level equates to the heat energy required of 6.3 MJ/m$^2$. But three minutes at a flux of 10 kW/m$^2$ is too weak to break a window with indefinite exposure (Hietaniemi and Korhonen, 2005).

Luo et al (2011) use a CFD model to demonstrate that a 500 mm horizontal projection (apron) offers more protection than a 900 mm spandrel to a façade above an opening. It was assumed that the window covering the room of fire origin was fully-dislodged (broken and fallen out) in the fire event. Useful pictures of the external fire plumes (generated from the CFD model) for apron and spandrel cases show the relative temperature exposure on the glazing above of 275-330$^o$C and 330-385$^o$C respectively.

AbdRabbo et al (2013A, 2013B) apply the CFD model, Fire Dynamic Simulator (FDS) and SmokeView (NIST, 2009) to the problem of external flaming from an opening with and without horizontal projections. The model results are compared with experimental results and demonstrate that the well-known effect that the vent shape has on flame projection away from a wall is replicated in the model. The basis of the comparison was the heat flux incident on the façades above the vents. The value of horizontal projections in reducing the heat flux above openings is also demonstrated by the model.

Goble (2007) conducted extensive experiments with a scaled-down compartment. The internal HRR was by a gas burner with stepped outputs up to a 300 kW max and a range of vent sizes. Video footage of the flame shape was analysed to determine the flame height and averaged. Then vertical two-dimensional contour maps perpendicular to the centre width of the vent were produced at the various HRRs and vent sizes. FDS was used to model the experimental results but with limited success, in particular for small ventilation areas. The focus was on finding a correlation between the flame shape of the experiments and the FDS model. This was not shown to be as successful as the comparison of heat fluxes by AbdRabbo et al (2013A, 2013B). It is also noted the comparisons were made using an earlier version of FDS(3) as opposed to the later version (FDS5) used by AbdRabbo.

Cao and Guo (2003) use FDS to demonstrate the effectiveness of horizontal projections in deflecting flames away from a façade and also reducing the heat flux thereon. These results support the findings of Ashton and Malhotra (1960) and Oleszkiewicz (1989, 1990 and 1991).

Some preliminary trials with FDS are included in Appendix B for purposes of ascertaining the model's effectiveness in addressing the tasks in the ongoing phases of the larger project. These trials focused on the heat flux incident on the façade rather than the flame shape.

## 2.7 ISO room size simulations of external flaming

Several case studies of ISO room-scale tests conducted at BRANZ that involved considerable external flaming are examined as follows.

### 2.7.1 Maori heritage building example of external flaming

A BRANZ study (Whiting et al, 2004) considered the fire protection of New Zealand's traditional Maori buildings. As part of the case presented for better protection of these, an authentic reconstruction using four traditional materials was assembled in the BRANZ ISO 9705 room (ISO, 1993). Prior to this, these four materials were tested in the cone calorimeter to ISO 5660 (ISO, 2002) to determine the reaction to fire properties on an individual basis.

From the cone calorimeter data for the four materials tested, estimates were made of the stoichiometric ratio in the range of 2.6 to 3.3. This range suggests that in accordance with Figure 5 there is unlikely to be any external flaming from the ISO room. However, this was not the case as there was significant flaming clearly indicating other factors determine such an outcome.

In the Maori building simulation the four different materials are illustrated in Figure 6 showing details of the construction. The linings were the only fuel source in the compartment apart from the 100 kW gas burner in the corner. Because the entire fuel load is in the surface lining this is a significant factor, compared with more realistic cases where the fuel load is a mixture of surface linings and objects. The ready availability of the fuel is critical to the potential pyrolysis rate and hence higher HRR responsible for the significant flaming observed.

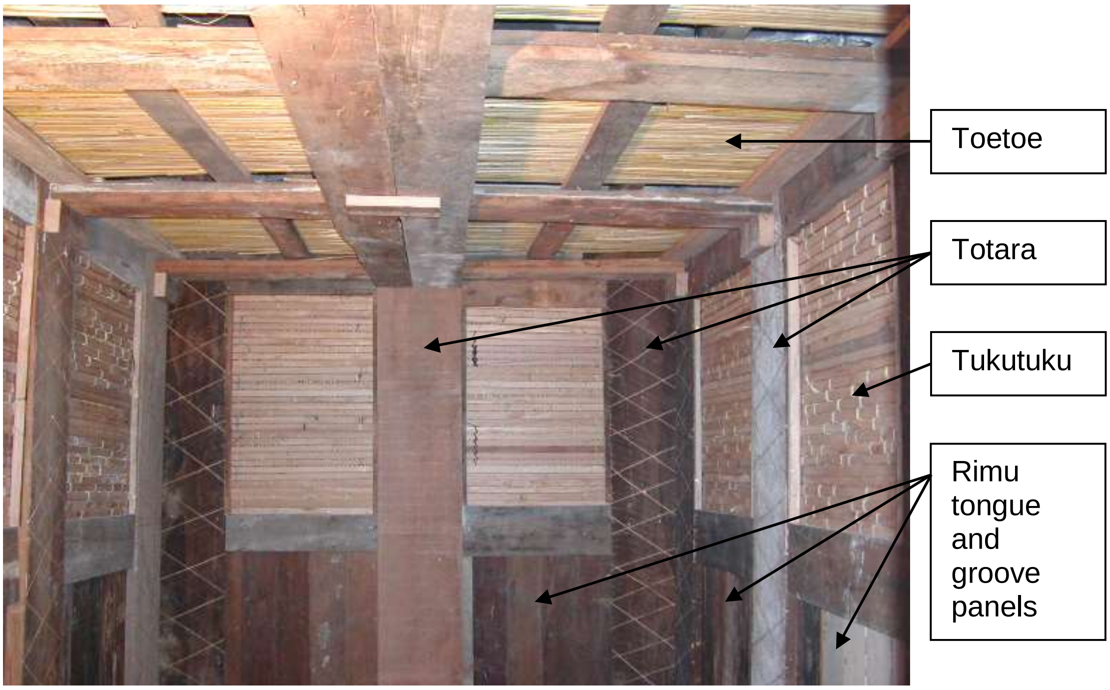



**Figure 6: ISO room fire test construction of Maori building internal linings**

Cone calorimeter results for the four materials are listed in Table 3. Totara and rimu are timber species with measured densities of 561 and 564 kg/m3 respectively.

The tukutuku is described as woven wall panels. The panels comprise 20 mm x 100 mm x 8 mm thick rimu slats thatched horizontally using flax to stems of toetoe orientated perpendicular to the rimu slats. The completed specimen nominally measured 100 mm x 100 mm x 20 mm thick, with a mean density of 204 kg/m$^3$.

Toetoe is essentially a tussock grass, the circular shafts of which were used to line the ceiling with a mean density of 182 kg/m$^3$.

The results of the cone calorimeter testing also produced the heat of combustion for each material in Table 3 and calculation of the likely FLED in Table 4.

**Table 3: Properties of materials in Maori building study**

| Fuel | Time to ignition @ 50 kW/m$^2$, sec | Calculated heat of combustion, MJ/kg | Density, kg/m$^3$ |
|---|---|---|---|
| Totara | 28 | 8.9 | 561 |
| Rimu | 21 | 10.0 | 564 |
| Tukutuku | 10 | 10.7 | 204 |
| Toetoe | 9 | 9.9 | 182 |

In the ISO 9705 test, considerable external flaming was observed with a peak HRR of ~5 MW as measured by the oxygen consumption calorimetry. Predictions of HRR inside the compartment for a vent 0.8 x 2.0 m high at the point of flashover are well below 5 MW as follows in Equation 14.

$$\boldsymbol{HRR} = \mathbf{1500}\ \boldsymbol{A_w H^{1/2}}, \mathbf{kW} \quad \text{Equation 14}$$

$$= 1.5 \times 2 \times 0.8 \times 0.8^{1/2}$$

$$= 3.4 \text{ MW}$$

The calculated HRR of approximately 3.4 MW is significantly less than the 5 MW measured. Therefore if it is assumed 3.4 MW was burning within the compartment then the external flame accounts for the remaining 1.6 MW or 47% (excess fuel). This is comparable with an excess fuel factor of 0.47 and fits within the family of three curves (0.38, 0.59 and 0.67) in Figure 2. Therefore the visual observation (Figure 7) could be considered representative of what would be expected in terms of incident radiation above the door opening due to the flaming.

**Figure 7: The extent of external flaming**

In Figure 7 the height of the opening is 2000 mm and the concrete panels are 600 mm in height, so the flame exiting the doorway is approximately 800 mm high. This means that 1200 mm is external flame and 800 mm below is air being drawn into the compartment. This is a ratio of 60% to 40%, a typical neutral axis for a well-established fire.

The significant point is that external flaming can occur if the fuel conditions are suitable, illustrating that it is difficult to predict what the extent of that flaming might be. In this case the excess fuel ratio was close to 50% on the basis of the predicted ventilation-controlled condition and the HRR actually measured.

This supports the case that some creditable upper-bound fractile (in this case 50%) for the magnitude of the external flaming is specified. This is required before any predictions of the flame size and ultimately its upward reach, and then the relatively easy task of assigning the incident heat flux can be proposed.

### 2.7.2 Other BRANZ studies with external flaming

Three other studies conducted at BRANZ, by Whiting (2003), (Nyman, 2002) and Brown (2007), saw outside experiments (seven in total) set up based on an ISO room size compartment. The compartment was filled with a range of fire loads entailing predominantly wood cribs with, in some cases, polyurethane foam chairs added. The range of FLEDs was nominally 400, 800 and 1200 MJ/m$^2$ to simulate equivalence to building types that require 30, 60 and 90-minute fire resistance rating (FRR) (DBH, 2012). The purposes of the experiments included examining fire spread downwards through timber floors, characterising time-equivalent fires and the heat transfer to steel members.

The HRR was not measured as the exhaust gases were not captured for analysis. However, in three tests (Nyman, 2002) the whole room structure was sitting on load cells to measure the rate of weight loss to gain some information on the rate of pyrolysis.

In all seven experiments, some degree of external flaming was visually noted and was also observed to be pulsating quite significantly, especially for the higher HRR and larger flame sizes. Typically, as a burst of flaming peaked it would then die down as the inflow of air through the lower portion of the vent marginally cooled the flaming. Before a fresh supply of oxygen, in the incoming air, supported increased combustion of the pyrolysed fuel leading to another surge of external flaming. This continued until the wood cribs had burnt back from the opening. The results are summarised in Table 4.

**Table 4: Fire loads and duration of external flaming**

| Reference | Test # | Fire load, MJ | FLED, MJ/m$^2$ | Vent fire duration and (height), mins, m | Vent H x W, m |
|---|---|---|---|---|---|
| Whiting (2003) | 1 | 6500 | 752 | 17 (3 m) | 2 x 0.8 |
| Nyman (2002) | 1 | 6800* | 787* | 10 (3 m) | 2 x 0.8 |
| Nyman (2002) | 2 | 9288* | 1075* | 22 (3 m ) | 2 x 0.8 |
| Nyman (2002) | 3 | 6551* | 759* | 13 (2.5 m) | 2 x 1.2 |
| Brown (2007) | 1 | 3637* | 456* | 1 (1 m) | 2 x 1.2 |
| Brown (2007) | 2 | 7152* | 828* | 16 (1 m) | 2 x 1.2 |
| Brown (2007) | 3 | 3529* | 408* | 9 (1 m, weakly pulsating) | 2 x 1.2 |

*Fire load comprised wood and polyurethane foam

A typical observation to a greater or lesser degree, depending on the fuel layout and location of ignition point, was recorded as follows. Generally, if the fuel was ignited at a location away from the opening, the fire would develop locally until sufficient heat flux had built up in the upper layer. Then the next (adjacent) wood crib or other item would ignite followed by other items in the direction of the vent opening until the item closest to the vent was burning. Then, with the greater availability of incoming air, the burning item closest to the vent burnt preferentially. The fire then rapidly developed to a stage in combination with the remainder of the compartment such that the fire became ventilation-controlled and external flaming developed. This was assisted by the close proximity of the burning item to the vent and the shorter time for completion of the burning of the pyrolysed products. The seat of the fire was then observed to burn back deeper into the compartment as fuel near the vent was consumed. Eventually the external flaming reduced due to a combination of fuel having been consumed and the longer time for pyrolysed products to burn given their greater distance from the vent.

## 2.8 Research in Australia and the United Kingdom

Most of the research on fully-developed fires has been conducted in relatively-small spaces with near-square floor plans. In such cases, the conditions (temperature of the smoke and incident heat on the enclosure) are relatively uniform throughout the upper portion of the space. However, Thomas and Bennetts (1999) and Welch et al (2007), have documented differences in that behaviour for ventilation-controlled fires in long, thin spaces or in large areas. In such cases, the burning occurs in the fuel nearest to the supply source of air. Temperatures are also observed to be greatest nearest to the supply source of air.

This research by Thomas and Bennetts (1999) in Australia has demonstrated with reduced-scale models this mechanism. In enclosures where there is a depth from the vent opening (e.g. broken windows) to the actual fuel this can produce specific conditions. These conditions are characterised by a large portion of the vaporised fuel burning at a point removed from the location of the solid fuel (combustible material) source. The researchers' experiments used fully-involved spaces where the depth from the vent opening was at least twice the width of the test space. In these experiments, the air supply drawn into the test space by the fire was insufficient to burn all of the available fuel. Fuel once vapourised was transported to the openings and burned there, producing an unexpectedly-high heat flux on the elements at and near the vent opening. The importance of the researchers' work is it demonstrates that, in many fires, the reality is the fire exposing the structural elements is not necessarily a constant in either time or space.

## 2.9 Conclusion

In the above experiments the magnitude of external flaming is relatively independent of where a fire starts in a compartment or the shape of the compartment or the distribution of the fuel. The worst-case scenario is excess fuel in a ventilation-controlled regime. It is quite probable that irrespective of where a fire originates it will at some stage migrate towards an opening(s) where the supply of oxygen is more plentiful. In such a conditions the HRR and heat flux on the façade is likely to be a maximum. Thus, further investigation is suggested by several of the authors to focus on combustion efficiency, heat fluxes and effective fuel area.

Ultimately what is required is a likely distribution of HRR for the compartment fires, based on a range of input parameters, some of which will result in external flaming. Depending on the risk to the façade above and/or adjacent buildings a statistical distribution is established. Then an appropriate fractile for the magnitude of the external flaming can be used for assessing a proposed design.

# 3. PREVIEW OF FDS TRIALS

Some preliminary FDS trials in Appendix B show the feasibility of modelling external flaming scenarios.

A series of trials were undertaken on a façade 8 m high with seven different vent sizes connected to an approximate 3 x 3 x 3 m fire-generation compartment behind. These trials demonstrated increasing heat fluxes on the façade above the vent, generally in proportion to the size of the vent fire (external flaming) and the opening factor of the vent. The FDS code showing grid size and fuel ramping for the 2 x 1 m vent example are detailed in Appendix C. The heat release rate per unit area (HRRPUA) of the fire source was varied so as to ramp the fire from 25% to 150% of the ventilated limited condition in increments of 25%. The threshold of the appearance of a vent fire as viewed in SmokeView was evident once 100% was exceeded. This approach was taken primarily to trial FDS as a means of modelling the heat flux from a known size of external flame.

The magnitudes of the heat fluxes modelled on the façade were in general agreement with that shown by the methods proposed in the literature review.

The FDS model is also set up for monitoring of the flame shape by means of recording the temperatures at strategic locations in front of the façade.

Furthermore heat flux monitoring locations can be included at selected distances from the building façade and at a range of heights. These monitor what the incident heat flux would be on an (imaginary) adjacent building in the first instance and then what safe distance is found by actually putting a receiving façade there.

The pulsating flaming in the vent fire that was observed in the BRANZ trials (Whiting et al, 2004) was replicated in the FDS trials. When the fire size within the compartment increases beyond the transition point the fire becomes ventilation-controlled and a vent fire (external flaming) is established. The pulsating flame is clearly visible in SmokeView under ventilation-controlled conditions.

It is anticipated that this strategy of modelling is suitable for firstly verifying that experimental data (full and reduced-scale) is replicated and secondly that an empirical relationship can be established. Variations to the vent size and reasonable upper-bound estimates of the likely external flaming based on an overdrive percentage such as 150% of the fuel/vent limited fire condition are recommended starting parameters.

## 3.1 Further FDS modelling of multiple levels and adjacent buildings

The capabilities of FDS also permit multiple levels (floors) to be modelled for the effects of external flaming. This offers possibilities of testing theories such as:

- Breaking of windows at levels above the initial fire compartment, and then
- The entrainment into the flames above of partially-oxygen-depleted, hotter gases with less oxygen meaning longer flames stretching to the next level above. But this may not be relevant if the temperature of the flame and resultant heat flux is reduced below the critical level. Even though the length of the flames may extend to a greater height,
- The inclusion of an adjacent building to monitor incident heat flux.

## 3.2 Zone modelling

Most models (zone) do not have a pyrolysis model, rather, the user is required to specify either the HRR or mass loss rate versus time. Therefore, one solution is to incorporate a pyrolysis model into a conventional zone-type model by allowing the excess fuel in the flow leaving the opening to be tracked (Utiskul and Quintiere, 2008).

The FDS trials suggest that specifying the pyrolysis rate within the fire compartment is key to how much external flaming results. If this is the case, then the same approach could be trialled with a zone model to verify the same results as the incident heat flux on the façade are achieved. If this proves to be the case then this facility could be added to a zone model such as B-Risk (Wade et al, 2013).

# 4. CONCLUSION

The majority of the literature reviewed focuses on the flame size (vertical and horizontal projection) exiting a vent, based on the vent width and height. There was considerably-less literature that considered what the contributing factors are to vent fires, such as the HRR and pyrolysis rate within the compartment. Virtually none of the literature provided any useful guidance other than in broad probabilistic terms.

The mechanism of external vertical fire spread as a result of external flaming from vents is governed by a multitude of factors. However, these may be combined to just two key parameters as follows:

- The HRR and shape of the external flame exiting from the opening, which in turn influences;
- The incident heat flux on the wall (spandrel) above the opening or on an adjacent building.

The first parameter is the more difficult to determine as it depends on a range of factors, many of them inter-related, of which the most significant is the excess fuel ratio. This is simply stated as the balance of the pyrolysed fuel that does not burn within a compartment due to the ventilation limit so burns externally. However, once the probable extent of the external flaming is established, it follows that determining the incident heat flux over the height range is relatively straight forward by comparison.

The prescriptive means of determining the HRR, temperature and shape parameters that is described in Eurocode 1 and is discussed in this study report provide an alternative and readily-applied method. Some judgement in the use of this method is recommended as discussed earlier. This may be by way of checking the magnitude that the calculated HHR exceeds the ventilation limit (HRR), then deciding what is realistic in terms of the excess fuel ratio.

Once the extent of external flaming is established, there are still other considerations that may alter the incident heat flux on the wall above or on a neighbouring building such as:

- The influence of windy conditions will tend to deflect flames from travelling vertically and aid mixing fresh air in the entrainment, assisting combustion of fuel and shortening the flame length
- If there is flaming from windows below, the rising air containing combustion products is likely to be partly oxygen-depleted and this will be entrained into the flames above, thus lengthening the flames
- In the event that flames are lengthened, it may be more likely that the windows into the compartments above will be broken, thus increasing the likelihood of upward fire spread. This may be countered by a lower concentration of combustion and thus lower the temperature of the flaming.

A key solution to the problem of upward fire spread by external flaming is in preventing the windows on the immediate level above from breaking and thus inhibiting any upward spread. So it follows that if the risk of fire spread can be quantified it can be reduced by:

- Limiting the size of vents
- Increasing the spandrel height
- Including aprons/projections
- Using fire resistant glass that will reduce the likelihood of external flaming.

The essential unknown is how much (as a percentage) of the total pyrolysed fuel will be available for burning outside of a compartment and contribute to the heat flux above an opening. The most practical way of dealing with this, considering the extent of the unknown parameters, is to simply propose a suitable value of excess fuel factor, relative to the ventilation limit. This will be based on an appropriate fractile of a worst-case scenario. For example, it could be proposed that the external HRR and thus flame size is based on a pre-determined excess fuel factor. That excess fuel factor could be representative of say 95% of all likely scenarios for a given fuel load within a compartment and the vent size (ventilation factor).

Another approach could be choosing to accept an excess heat release factor of 1.3 to 1.5. This would represent the maximum of the peaks of the intermittent flaming resulting from an excess fuel factor by relating closer to the average external heat release rate.

An alternative and more practical approach at this stage, in the absence of definitive advice on determining external HRRs, is to simply prepare some tables or graphs of external heat flux results. Then, based on a likely range of external HRRs, it is left to the end user to decide the likely magnitude of the external flaming applicable to the building design under consideration. Such a solution is proposed in future work below.

# 5. FUTURE WORK

Proposing a future direction for this study can be separated into two parts. Firstly, confirming a rationale for determining the likely magnitude of the HRR of external flaming for design purposes. Secondly, applying this to a method of determining the heat flux on façades and adjacent buildings.

## 5.1 Assigning values for the external HRR

The findings of the literature review offered some workable guidance, albeit with some qualifications, for determining the likely magnitudes of the HRR of external flaming.

A practical approach to resolving this challenge would be by preselecting a likely range of external flaming HRRs. This would be based on likely excess fuel ratios and/or the provisions of Eurocode 1 that exceed the ventilation limit for particular vent dimensions. The selected range of HRRs would then be modelled in FDS in a similar process to that presented in Appendix B. This preliminary modelling demonstrated that the external flame size need not be known precisely in advance.

This can be used to generate a series of graphs of incident heat fluxes on a façade above a vent (or onto an adjacent building) for a range of external HRRs. Using these, a reverse approach to design could (theoretically) be taken. For a given vent (size and shape) and for a limiting heat flux at a specified height above it, the maximum permitted external HRR (excess fuel ratio) can be determined. This HRR will be a ratio of the ventilation-limited condition (100%). It then follows that design judgements can be based on a probability distribution of likely external HRRs.

Furthermore, a set of empirical relations may be developed that replace or supersede the series of graphs generated by FDS.

If at some time in the future better tools are available for predicting what the HRR of the external flaming is likely to be, then the reverse design approach as suggested will not be required.

## 5.2 Validation of FDS modelling for external flaming

Once confidence that FDS is a reliable predictor of the heat flux on a façade is demonstrated, a small-scale test apparatus could be constructed. This could be perhaps a 50%-sized façade around the BRANZ ISO room gas burner with a 300 kW maximum HRR output. Alternatively the BRANZ vertical channel test rig could be adapted to perform a similar function. In either event, trials could be conducted with a range of input parameters such as vent size/shape and fire size related back to opening factors and actual vent fire size. Such trials could be used to confirm and develop existing theory and test the potential of FDS to validate or predict results.

Further on, an additional development could be to add a pyrolysis submodel to a zone model (e.g. B-RISK) to enable more accurate prediction of the potential fuel burning at the vent. Then the simple external flame height and heat flux relationships or correlations developed for the vent fire as a function of time could to be added to the model output.

Such a modelling approach can be used to develop flexible design options for external wall elements to limit vertical fire spread, based on probabilistic approaches.

If extending the same process to develop flexible design options for horizontal fire spread, then the heat flux emitted from the opening in a fire compartment is again the key parameter.

Some considerations for possible design application are:

- A major unknown will be the contents/furnishings which will contribute to the challenge of assessing or estimating the HRR
- Methodology must therefore be suitably conservative as suggested above
- A recommended factor needs inclusion that relates to a worst-case scenario such as a 95 percentile.

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# APPENDIX A C/VM2 SOLUTIONS

## A.1 Limiting vertical fire spread, C/VM2

### 4.6 Design scenario (VS): Vertical fire spread involving external cladding

| Scenario in brief | A *fire source* exposes the *external wall* and leads to significant vertical *fire* spread. |
|---|---|
| Code objectives | ***C1(a)*** *Safeguard people from an unacceptable risk of injury or illness caused by fire.*<br>***C1(b)*** *Protect other property from damage caused by fire.* |
| What you must satisfy | The performance criteria of C3.5 (ie, if *buildings* are taller than 10 m or have upper floors that are *other property* or contain people sleeping, *fire* shall be prevented from spreading more than 3.5 m vertically) so that:<br>• tenable conditions are maintained on *escape routes* until the occupants have evacuated, and<br>• vertical *fire* spread does not compromise the safety of firefighters working in or around the *building*.<br>***C3.5*** *Buildings must be designed and constructed so that fire does not spread more than 3.5 m vertically from the fire source over the external cladding of multi-level buildings.* |
| Required outcome | Demonstrate that the *building's* external claddings do not contribute to excessive vertical *fire* spread using one of the methods described. |

**Scenario description**

This *design scenario* applies to:

a) All *buildings* with a *building height* of more than 10 m, and

b) Any other *buildings* with upper floors where people sleep or are defined as *other property*.

**Comment:**
This scenario is not concerned with *building*-to-*building fire* spread across a *relevant boundary*, as this is addressed in the *design scenario*: HS (see Paragraph 4.5).

The *design fire* for this scenario shall be a *fire source* that is either:

a) In close contact with the façade (eg, in a rubbish container/skip) that could ignite and spread *fire* vertically to higher levels in the *building*, or

b) Adjacent to an *external wall*, such as a *fire* plume emerging from a window opening or from an *unprotected area* of the wall burning.

There are two considerations in this scenario:

**Part A:** External vertical *fire* spread over the façade materials, and

**Part B:** *Fire* plumes spreading *fire* vertically up the *external wall* via openings and *unprotected areas*.

**Comment:**
Part A addresses concerns regarding the contribution of *combustible* claddings to vertical *fire* spread, while Part B looks at the role of aprons, spandrels or sprinklers in preventing external *fire* spread (due to projecting window *fire* plumes) between openings at different levels in the *building*.

For Part A, the *design fire* exposure is:

a) Radiant flux of 50 kW/m² impinging on the façade for 15 minutes for *buildings* in *importance levels* 2 and 3, or

b) Radiant flux of 90 kW/m² impinging on the façade for 15 minutes for *buildings* in *importance level* 4.

The intention is to prevent façade cladding materials from contributing to significant flame spread propagation beyond the area initially exposed. Some damage to the area initially exposed is expected.

**Figure 8: Vertical fire spread. Clause 4.6 from C/VM2 (a)**

This can be achieved by:

a) Limiting the maximum *HRR* from a cladding material when exposed to the design event to no more than 100 kW/m², or

b) Limiting the extent of the vertical flame spread distance (on the façade) to no more than 3.5 m above the *fire source*. This accepts that *fire* spread via the façade materials may occur to the floor immediately above, but not two floors above.

For Part B, the *design fire* exposure is a *fire* plume projecting from openings or *unprotected areas* in the *external wall*, with characteristics determined from the *design fire* as described in Part 2 for the applicable occupancy. The intention is to prevent *fire* spread in unsprinklered *buildings* from projecting *fire* plumes to *unprotected areas* on upper floors where they are within 1.5 m vertically of a projecting plume *fire source*.

**Method**

For Part A, follow the requirements of Part 5: Control of external fire spread of the relevant Acceptable Solutions (C/AS2 to C/AS6) and use:

a) Large or medium-scale 'façade type' *fire* tests (eg, NFPA 285, ISO 13785-1 or Vertical Channel test) demonstrating the extent of vertical flame spread is no more than 3.5 m above the *fire source*, or

b) Small-scale testing using ISO 5660 or AS/NZS 3837 (cone calorimeter) for homogeneous materials, demonstrating the maximum *HRR* from a cladding material is no greater than 100 kW/m² when exposed to the design event to ensure propagating flame spread over its surface is unlikely, or

c) Use *non-combustible* materials.

**Comment:**
Validated flame spread models could be used for some materials.

The requirements given in Acceptable Solutions C/AS2 to C/AS6 Paragraph 5.8 for *fire* properties of external claddings are acceptable means of demonstrating compliance with Part A above for *buildings* with an *importance level* not higher than 3.

For Part B:

a) *Construction* features such as aprons and/or spandrels designed to the specifications given in C/AS2 to C/AS6 Part 5 or the installation of an automatic *fire* sprinkler system designed to a recognised national or international Standard can be used to satisfy the requirements of this scenario.

b) Should calculation methods be used instead, then *fire* plume characteristics and geometry shall be derived from the *design fires* as described in Part 2 for the applicable occupancy.

**Figure 9: Vertical fire spread. Clause 4.6 from C/VM2 (b)**

# A.2 Limiting horizontal fire spread, C/VM2

## 4.5 Design scenario (HS): Horizontal fire spread

| | |
|---|---|
| Scenario in brief | A fully developed *fire* in a *building* exposes the *external walls* of a neighbouring *building* or *firecell*. |
| Code objectives | *C1(b) Protect other property from damage caused by fire.* |
| What you must satisfy | The performance criteria in C3.6 and C3.7. This will require calculation. C4.2 is to be considered in relation to horizontal *fire* spread across a *notional boundary* to sleeping occupancies and *exitways* in *buildings* under the same *ownership*.<br>***C3.6** Buildings must be designed and constructed so that in the event of fire in the building the received radiation at the relevant boundary of the property does not exceed 30 kW/m² and at a distance of 1 m beyond the relevant boundary of the property does not exceed 16 kW/m².*<br>***C3.7** External walls of buildings that are located closer than 1 m to the relevant boundary of the property on which the building stands must either:*<br>*a) be constructed from materials which are not combustible building materials, or*<br>*b) for buildings in Importance levels 3 and 4 be constructed from materials that, when subjected to a radiant flux of 30 kW/m², do not ignite for 30 minutes, or*<br>*c) for buildings in Importance levels 1 and 2, be constructed from materials that, when subjected to a radiant flux of 30 kW/m², do not ignite for 15 minutes.*<br>***C4.2** Buildings must be provided with means of escape to ensure that there is a low probability of occupants of those buildings being unreasonably delayed or impeded from moving to a place of safety and that those occupants will not suffer injury or illness as a result.* |
| Required outcome | Demonstrate that the criteria in C3.6 and C3.7 are not exceeded by calculating the radiation from *unprotected areas* in the *external wall* to the closest point on an adjacent *boundary* and at 1.0 m beyond an adjacent *boundary*, and specifying exterior cladding materials with adequate resistance to ignition<br>Control horizontal *fire* spread across a *notional boundary* to sleeping occupancies and *exitways* in *buildings* under the same *ownership*. |

**Comment:**
NZBC C3.6 applies to all *buildings* except those with an automatic sprinkler system with two independent water supplies, one of which is not dependent on town mains and not used for storage above 3.0 m.

The performance requirements of C3.6 are also to be applied to limit the radiation at the *notional boundary* to sleeping occupancies and *exitways* in *buildings* under the same *ownership*. This partially contributes to the achievement of the functional requirement C4.2.

### Scenario description

A fully developed *fire* in a *building* exposes the *external walls* of a neighbouring *building* (*other property*) or *firecell* (sleeping occupancy or *exitway*).

This scenario addresses a *fire* in a *building* that leads to high levels of radiation heat exposure across a *relevant boundary*, potentially igniting the *external walls* of a neighbouring *building*.

The potential for any *firecell* to expose *other property* shall be evaluated. However, the area beneath a canopy roof does not need to be assessed as a source of external *fire* spread if all the following conditions apply:

a) The nearest distance between any part of the canopy and the *relevant boundary* is not less than 1.0 m, and

b) The average *FLED* applying to the area beneath the canopy is not greater than 400 MJ/ m², and

c) The canopy has at least 50% of the perimeter area open to the outside.

The *design fire* for this scenario comprises an assumed emitted radiation flux from *unprotected areas* in *external walls* of the *fire source building* (assuming no intervention). This shall be taken as:

d) 83 kW/m² for *FLED* $\leq$400 MJ/m²

e) 103 kW/m² for *FLED* between 400 and 800 MJ/m², and

f) 144 kW/m² for *FLED* greater than 800 MJ/m².

**Figure 10: Horizontal fire spread. Clause 4.5 from C/VM2 (a)**

Emissivity of *fire* gases shall be taken as 1.0.

For unsprinklered *buildings*, the width of the enclosing rectangle need be no greater than 20 m for *FLED* up to and including 800 $MJ/m^2$, or no greater than 30 m for *FLED* greater than 800 $MJ/m^2$. The actual width of the enclosing rectangle shall be used if it is less than 20 m.

If a *firecell* is not used for storage above 3.0 m and with an automatic sprinkler system supplied by two independent water supplies, one of which is not dependent on town mains, there are no restrictions on the amount of *unprotected area* and the *fire* engineer does not need to assess the external *fire* spread to the *boundary*.

In other *firecells* with an automatic sprinkler system, the maximum *unprotected area* permitted for an unsprinklered *firecell* can be doubled. Alternatively, if the *firecell* is not used for storage, you can consider:

a) The height of the enclosing rectangle as the vertical distance between the floor and the ceiling level beneath which the sprinklers are installed in the area adjacent to the *external wall* facing the *relevant boundary*, and

b) The width of the enclosing rectangle as the square root of the design maximum area of sprinkler operation (the actual width of the enclosing rectangle may be used if it is less).

The *fire* engineer only needs to consider one *firecell* at a time as a potential source of thermal radiation.

*Unprotected area* shall include both unrated *external wall construction* as well as any unrated window/door assemblies and other openings. Areas of the *external wall* that are not designated as *unprotected area* shall have a *fire resistance rating* (meeting both *integrity* and *insulation* criteria) sufficient to resist the full *burnout design fire* described in Paragraph 2.4. Furthermore, the structural system supporting those parts of the *external wall* not permitted to be unprotected must also have sufficient *fire* resistance to resist the full *burnout design fire*, and keep the *external wall* in place.

*Unprotected area* is not permitted within 1.0 m of a *relevant boundary*, except for a combination of small *unprotected area* and/or *fire resisting glazing* as described in Acceptable Solutions C/AS2 to C/AS6 Paragraph 5.4 or in the commentary document for this Verification Method.

**Method**

Calculate radiation from *unprotected areas* in the *external wall* to the closest point on an adjacent *boundary* and at 1.0 m beyond an adjacent *boundary*. The calculations must take into account:

a) The distance to the *boundary*, and

b) The size/shape of the *unprotected area* in the *external walls*, assuming the emitted radiant heat flux specified above for the applicable *FLED* range.

Alternatively, use the tabulated values of the maximum percentage of permitted *unprotected area* directly from Acceptable Solutions C/AS2 to C/AS6 as appropriate, or as provided in the commentary for this Verification Method.

The tables in the commentary document along with additional tables for *fire resisting glazing* and return and/or wing walls have been produced in accordance with this Verification Method. These tables can be used directly for unsprinklered *firecells* as long as *external walls* are parallel to, or angled at no more than, 10° to the *relevant boundary* and are no closer than 1.0 m to the *relevant boundary*.

For *external walls* at greater angles to the *relevant boundary*, appropriate calculations shall be undertaken to demonstrate that the performance criteria are achieved and minimum dimensions shall be specified for return and/or wing walls as necessary or use tables as provided in the commentary document.

To demonstrate that NZBC C3.7 is achieved, it is expected that relevant *fire* test results for the selected cladding system will be provided. Engineers may also choose to comply with Paragraph 5.8 of the relevant Acceptable Solutions C/AS2 to C/AS6 to satisfy the performance criteria of this clause.

**Figure 11: Horizontal fire spread. Clause 4.5 from C/VM2 (b)**

# APPENDIX B FDS MODELLING

A series of FDS trials were conducted to determine the heat fluxes above a range of vent sizes as shown in Table 5. A sample of the FDS code is presented in Appendix C for the 2(H) x 1 m vent case.

**Table 5: FDS trials**

| Trial | Vent size* H x W, m | Opening factor, $m^{5/2}$ | Fire size**, MW | Max temp in compartment, $^oC$*** |
|---|---|---|---|---|
| 1 | 2 x 1 | 2.828 | 4.242 | 1000 |
| 2 | 2 x 0.5 | 1.414 | 2.121 | 650 |
| 3 | 1 x 2 | 2 | 3 | 700 |
| 4 | 1 x 1 | 1 | 1.5 | 600 |
| 5 | 1.5 x 1.5 | 2.756 | 4.13 | 900 |
| 6 | 1 x 0.5 | 0.5 | 0.75 | 350 |
| 7 | 2 x 2 | 5.66 | 8.48 | 1200 |

*vent soffits all at 3 m elevation

**fire size is that required for flashover in accordance with $1500AH^{1/2}$

***max temperature modelled in compartment ~proportional to the opening factor

A series of FDS trials were conducted for each vent size and fire within the compartment of size 2.5 x 2.5 x 3 m high with bounding walls/floor/ceiling 0.25 m thick. The fire size was initially 25% of that required for flashover (or for the fuel/ventilation-controlled threshold to be crossed) for 60 seconds and thereafter increased in increments of 25% up to 150%. That is 25, 50, 75, 100, 125 and 150% each for 60 seconds.

The results of each trial are shown in Figure 12 to Figure 18 below. The values plotted are the mean heat flux at heights above the opening where 3 m is at the soffit and so on. The legend shows the fire size in MW from 25% to 150% of the fire size listed in Table 5 in increments of 25%.

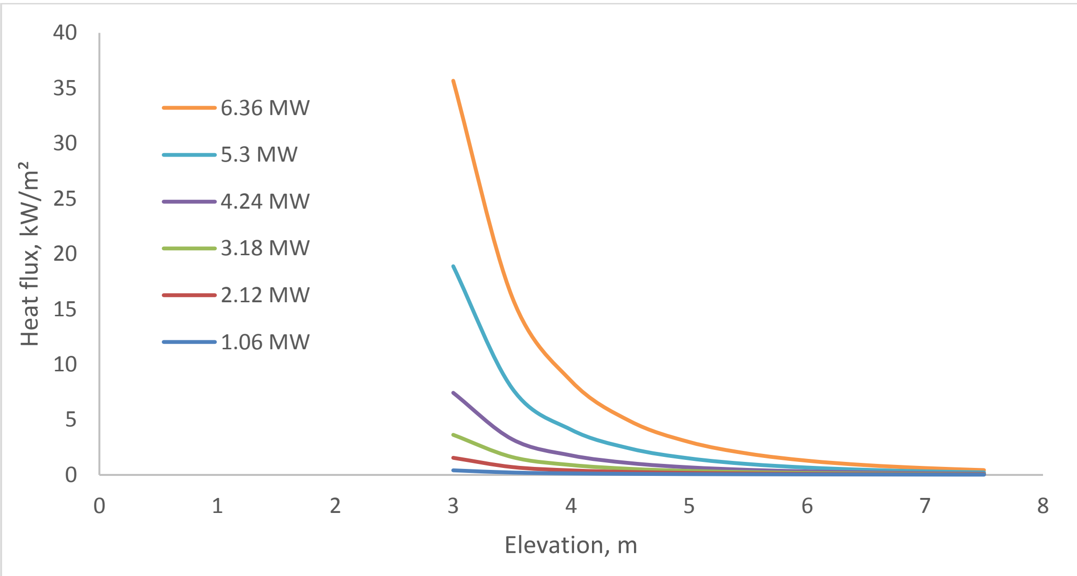


**Figure 12: Heat flux above a vent size 2(H) x 1 m, vent fire transition 4.24 MW**

What was noted as being significant when comparing the family of curves for the increasing fuel supply rate, is that the heat flux significantly increases once the 100% limit is exceeded. This is because any excess over the 100% is seen as external flaming contributing to the heat flux on the wall rather than heating inside the compartment.

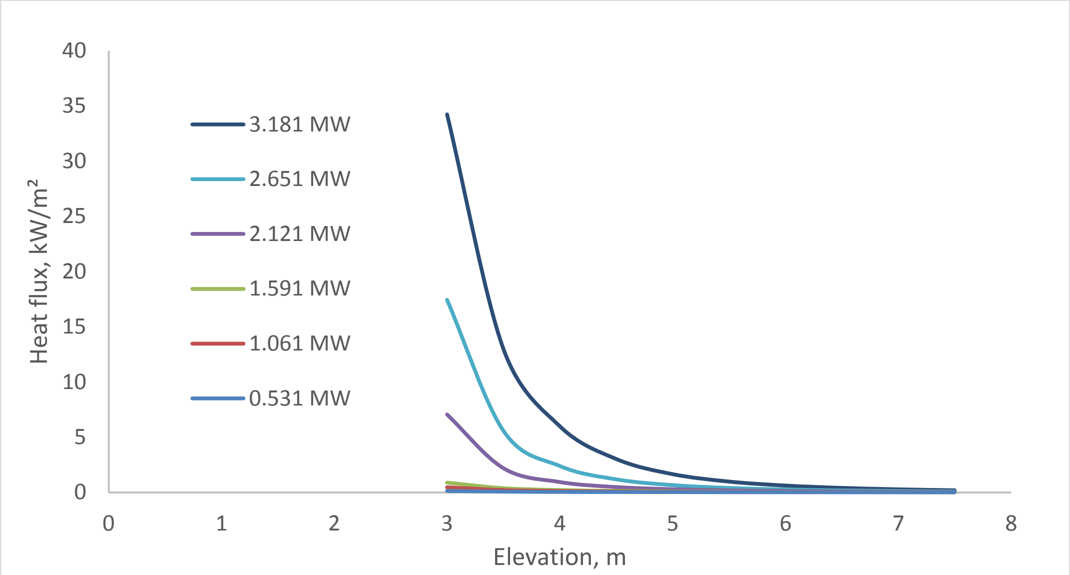


**Figure 13: Heat flux above a vent size 2(H) x 0.5 m, vent fire transition 2.12 MW**

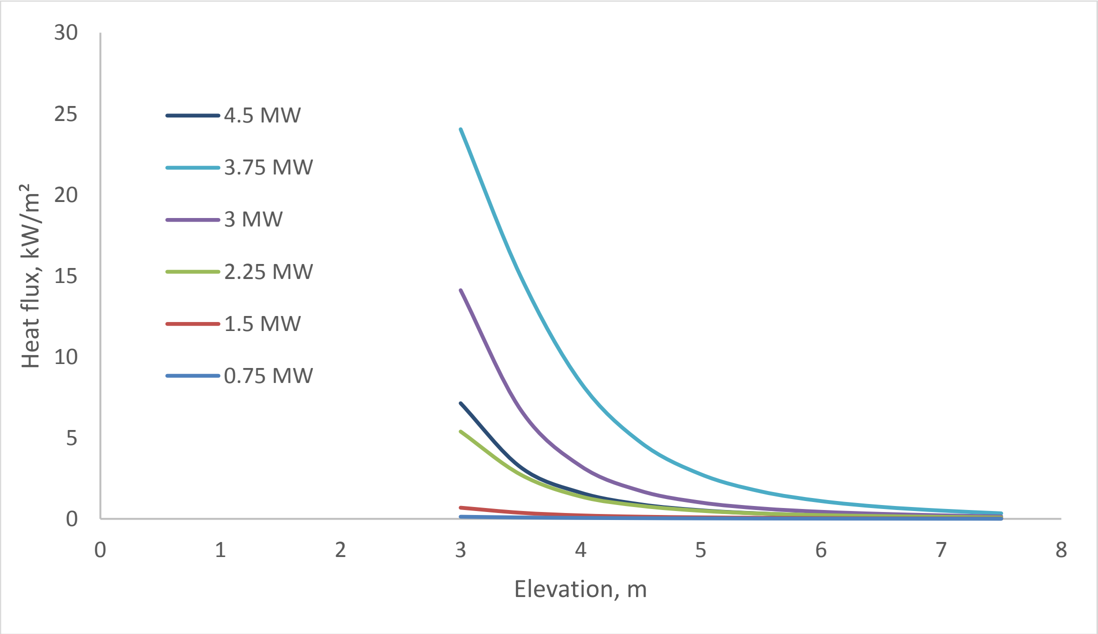


**Figure 14: Heat flux above a vent size 1(H) x 2 m, vent fire transition 3 MW**

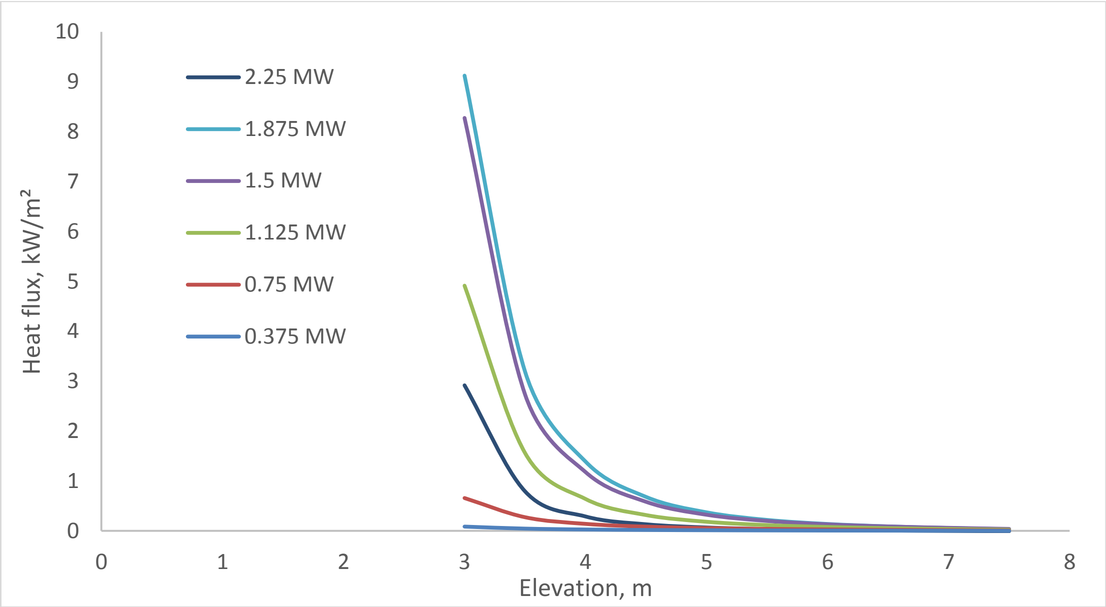


**Figure 15: Heat flux above a vent size 1(H) x 1 m, vent fire transition 1.5 MW**

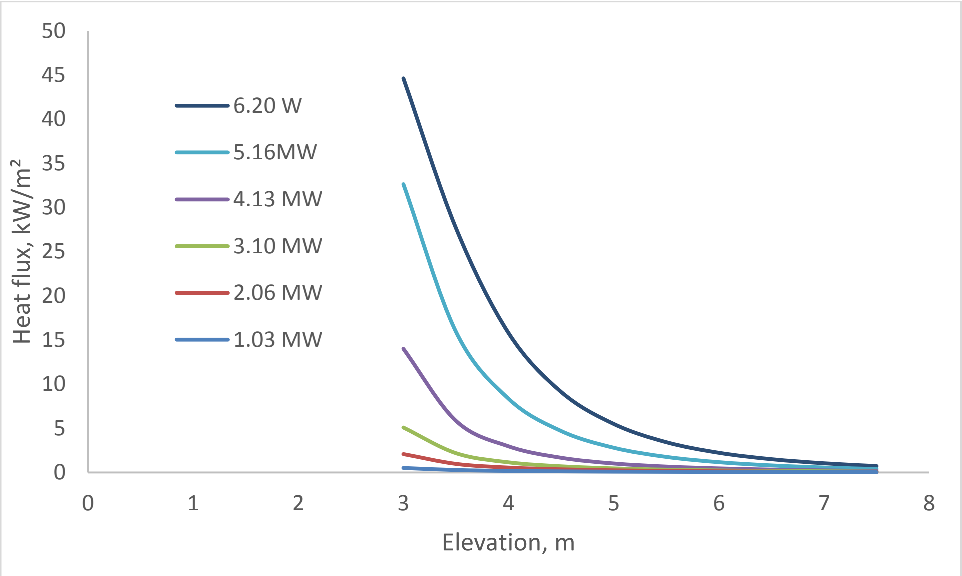


**Figure 16: Heat flux above a vent size 1.5(H) x 1.5 m, vent fire transition 4.13 MW**

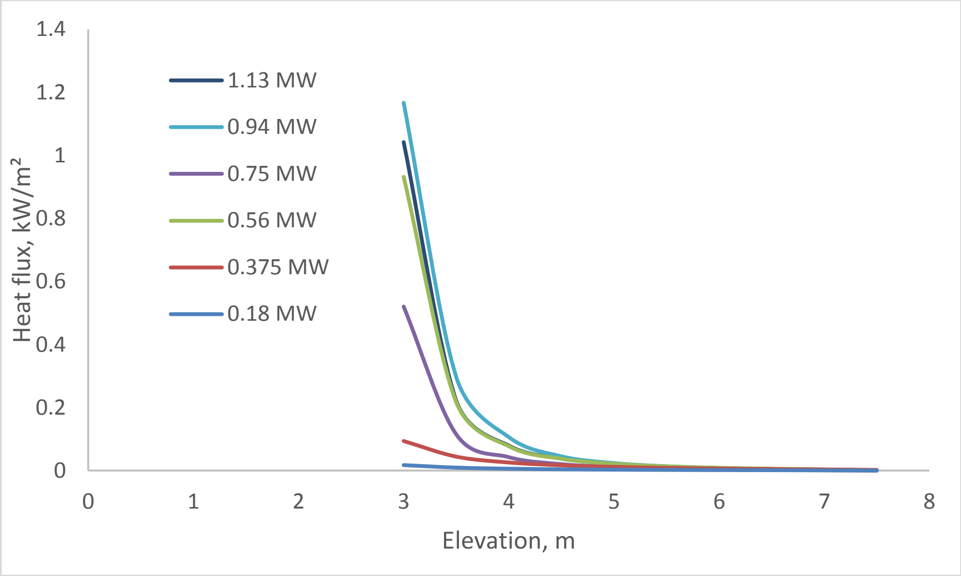


**Figure 17: Heat flux above a vent size 1(H) x 0.5 m, vent fire transition 0.75 MW**

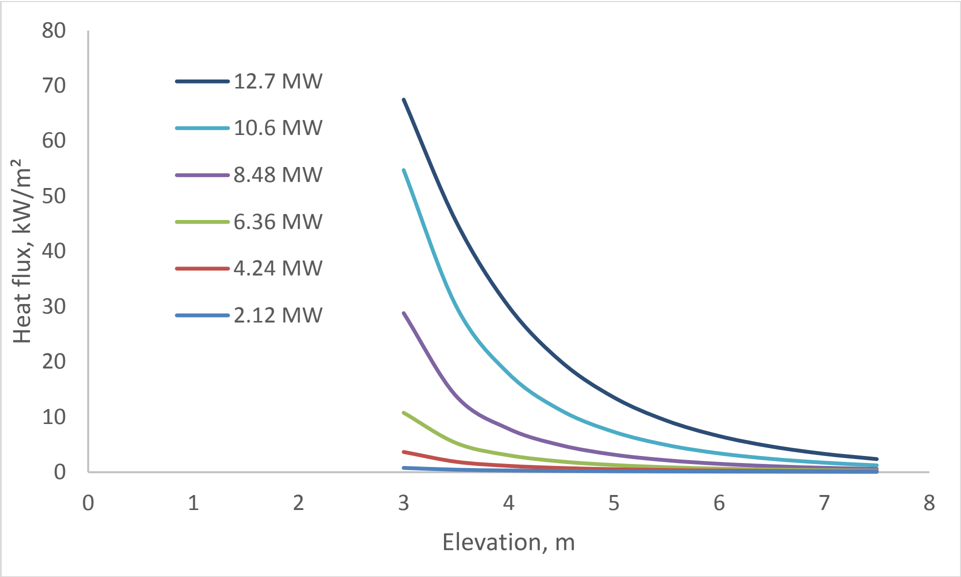


**Figure 18: Heat flux above a vent size 2(H) x 2 m, vent fire transition 8.48 MW**

In all seven trials, evaluation of the SmokeView output as shown in Figure 19, illustrated no sustained flaming from the vent was visible from the opening until the 100% HRR rate was exceeded. This was characterised by the flame pulsating considerably, just as was observed in the trials reported in Section 2.7. Similarly, analysis of the HRR data generated by FDS showed considerable fluctuation in magnitude.

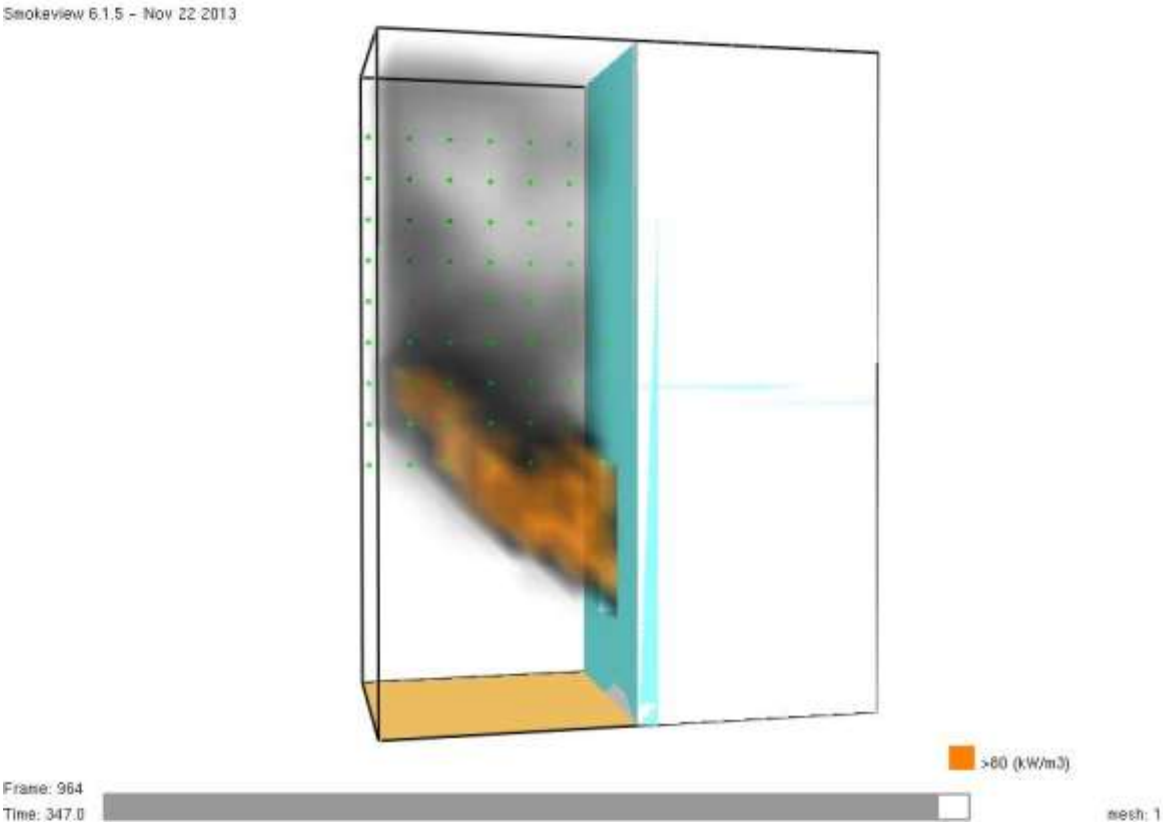


**Figure 19: SmokeView representation of external flaming**

Figure 19 shows the external flaming condition at 150% or 6.36 MW (347 seconds) from a 2(H) x 1 m vent. The green dots on the façade surface above the vent represent the data collection for the heat flux. The green dots in the airspace outwards and above the vent, although not reported here, are intended to monitor the extent of the flaming for comparison with the models reviewed.

Figure 20 shows the FDS simulation of the HRR for the compartment with a 2(H) x 1 m vent and where the HRR steps up in 25% increments at 60-second intervals. The interval 180 to 240 seconds is representative of 100% HRR corresponding with the ventilation-controlled condition ($HRR = 1500\ A_w H^{1/2}, \mathrm{kW}$), where theoretically a fire switches from being fuel-controlled to ventilation-controlled. What is apparent at 100% and beyond is the increasing fluctuation in the HRR, indicating pulsating flaming as was observed in the (actual) tests reported in Section 2.7.

Pulsating flaming is simulated in FDS as observed in the video clip of which Figure 19 is a snapshot and Figure 20. This shows the increasing magnitude of the pulsations and this instability is increasingly prevalent above the 100% HRR level.

If the 150% HRR (6.36 MW) in the range 300 to 360 seconds is considered, the peak pulsation HRR is 8.73 MW. This is over the theoretical limit of 4.24 MW for the 2(H) x 1 m opening size, a ratio of 2.06, or 1.06 over the ventilation limit. This value of 1.06 compares conservatively with the 1.32 suggested in the literature (Hu et al, 2012) for intermittent flaming. This shows that the extreme upper end of excess fuel supply may need to be higher than the 150% (excess) used in these simulations to capture the full extent of flame intermittency. As is shown in Figure 20, the degree of fluctuations in the HRR (noise) increase as it rises. Also it would be anticipated that the HRR would not need to increase very much more before a HRR spike of 9.84 MW (1.32 x 4.24 + 4.24) was reached.

This is also supported by the observation in the FDS modelling that further increases in fuel supplied in the compartment actually result in a temperature drop within. That would in practical terms reduce the pyrolysis rate of the solid fuel, suggesting an upper limit for the external flaming.

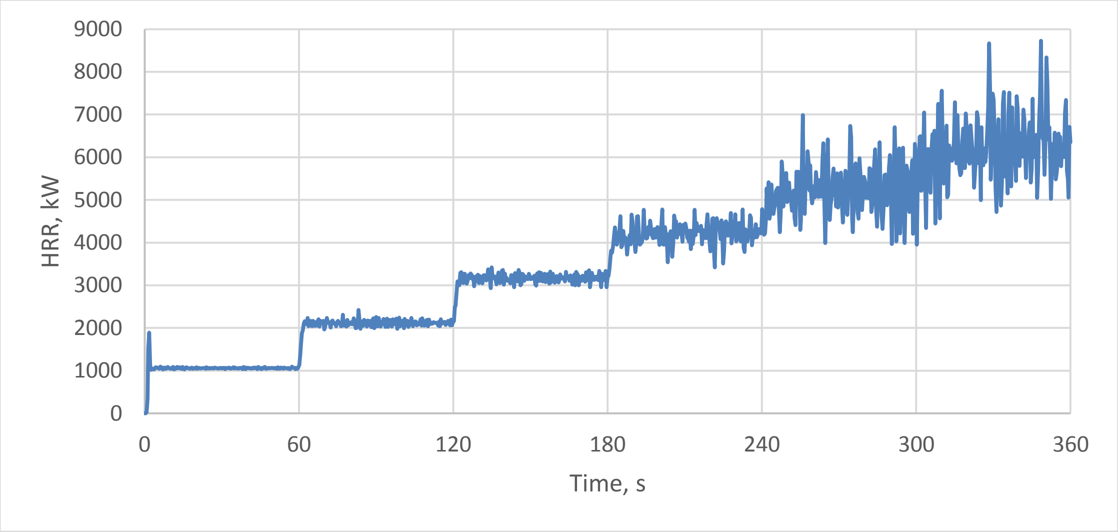


**Figure 20: Total HRR of fire both within and external to compartment with 2(H) x 1 m vent**

Further analysis of the heat flux data at nominally 100% (4.24 MW) and 150% (6.36 MW) is presented in Figure 21 and Figure 22. The mean heat flux is graphed along with the bounds of ± 2 standard deviations (SD) from the mean. Thus capturing approximately 95% of the range of the heat flux in the form of a superimposed normal distribution curve.

While demonstrating that the exposure is not steady, this also raises a question about the magnitude of heat flux that is required to break glass in the window immediately above. Is it a steady value such as a mean or a proportion of a pulsating max that is responsible? Or in energy terms, how much heat is absorbed by the glass over a period that causes fracture?

At some stage an upper-bound heat flux exposure for developing a set of guidelines would be required.

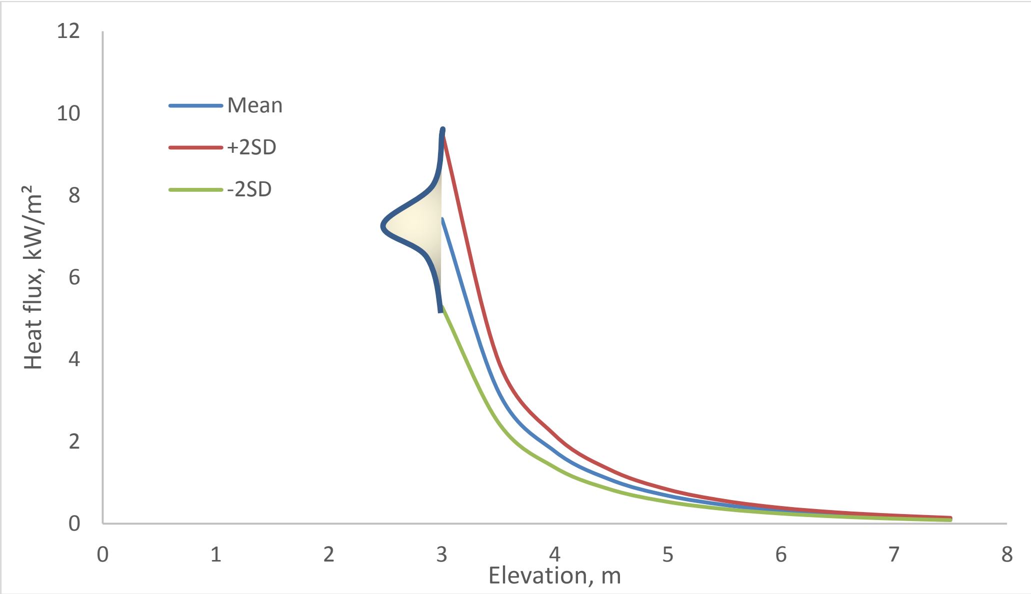


**Figure 21: Heat flux above 2(H) x 1 m vent at 100% (4.24 MW) HRR**

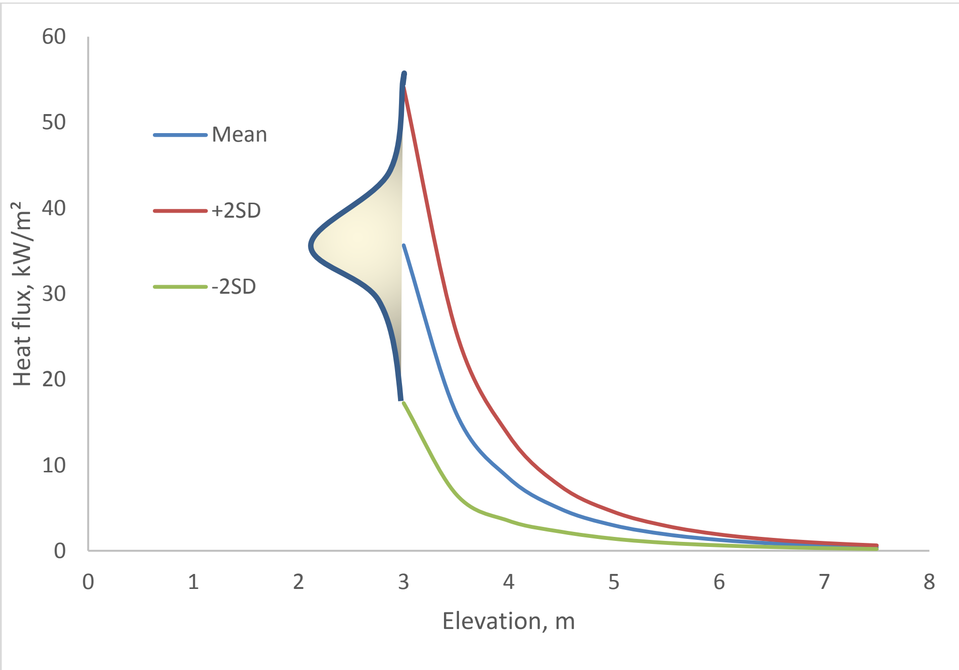


**Figure 22: Heat flux above 2(H) x 1 m vent at 150% (6.36 MW) HRR**

# APPENDIX C FDS CODE FOR VENT FIRE

Code for Vent 2H x 1W.

BRANZ Highrise office fire

All material properties are completely fabricated.

```
&HEAD CHID='SExternal facade 1 H=2, W=1', TITLE='SExternal facade, SVN $Revision:
3127 $'  /

/&MESH IJK=24,48,64, XB=0,3,-3,3,0,8 / Enclosure modelled multi storey
&MESH IJK=12,24,32, XB=0,3,-3,3,0,8 / Enclosure modelled multi storey

/&MESH ID='mesh1', IJK=24,24,64, XB=0,3,-3,0,0,8, MPI_PROCESS=0 / Outside of
Enclosure modelled multi storey
/&MESH ID='mesh2', IJK=12,12,32, XB=0,3,0,3,0,8, MPI_PROCESS=0 / Enclosure modelled
multi storey

SYNCHRONIZE=.FALSE


&VENT MB='XMIN', SURF_ID='OPEN' / ' Encl vent
&VENT MB='XMAX', SURF_ID='OPEN' / ' Encl vent
&VENT MB='YMIN', SURF_ID='OPEN' / ' Encl vent
&VENT MB='YMAX', SURF_ID='OPEN' / ' Encl vent
&VENT MB='ZMAX', SURF_ID='OPEN' / ' Encl vent

'Boundary files for SV

&BNDF QUANTITY='GAUGE HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='BURNING RATE' /

&TIME T_END=360.0 / '


'The Structure


'Material

&MATL ID           = 'Concrete'
    FYI          = 'Quintiere, Fire Behavior'
    CONDUCTIVITY  = 1.0
    SPECIFIC_HEAT = 0.88
    DENSITY      = 2200. /

&SURF ID            = 'WALL'
    RGB          = 200,200,200
    MATL_ID       = 'Concrete'
    THICKNESS      = 0.25 /

&SURF ID            = 'FLOOR'
```

```
     RGB           = 200,200,200
     MATL_ID       = 'Concrete'
     THICKNESS     = 0.25 /

&SURF ID           = 'CEILING'
     RGB           = 200,200,200
     MATL_ID       = 'Concrete'
     THICKNESS     = 0.25 /

'Walls
&OBST XB= 0,0.25,0,3,0,20, SURF_ID='WALL' /left wall
&OBST XB= 3,2.75,0,3,0,20, SURF_ID='WALL' /right wall
&OBST XB= 0,3,2.75,3,0,20, TRANSPARENCY = 1, SURF_ID='WALL' /rear wall
&OBST XB= 0,3,0,0.25,0,20, TRANSPARENCY = 1, RGB = 100,200,200, SURF_ID='WALL'
/front wall

'walls separate compartments


&HOLE XB= 3.5,4, 12.5, 12.75, 3.5, 4, COLOR='SILVER', DEVC_ID='timer 1 ' / ' hole in wall
&DEVC XYZ= 3.75, 12.625, 3.75, ID='timer 1', SETPOINT= 1.,QUANTITY= 'TIME',
INITIAL_STATE=.FALSE./


'Ceiling 1
&OBST XB= 0,3,0,3,3.75,4,TRANSPARENCY = 0.5, RGB = 100,200,200
SURF_ID='CEILING' /ceiling
'ceiling 2
&OBST XB= 0,3,0,3,7.75,8,TRANSPARENCY = 0.5, RGB = 100,200,200
SURF_ID='CEILING' /ceiling
'ceiling 3
&OBST XB= 0,3,0,3,11.75,12,TRANSPARENCY = 0.5, RGB = 100,200,200
SURF_ID='CEILING' /ceiling
'ceiling 4
&OBST XB= 0,3,0,3,15.75,16,TRANSPARENCY = 0.5, RGB = 100,200,200
SURF_ID='CEILING' /ceiling
'ceiling 5
&OBST XB= 0,3,0,3,19.75,20,TRANSPARENCY = 0.5, RGB = 100,200,200
SURF_ID='CEILING' /ceiling


&OBST XB= 0,3,0,3,0,0.25, SURF_ID='FLOOR' /floor


'vents

' front

&HOLE XB= 1, 2, 0, 0.25, 1, 3, COLOR='SILVER' / ' 1 x 2h window front


/&HOLE XB= 3, 3.5, 0, 0.25, 1, 3, COLOR='SILVER' / ' 1 x 2h window front

/&HOLE XB= 5, 6, 0, 0.25, 1, 2, COLOR='SILVER' / ' 1 x 2h window front
```

/&HOLE XB= 7, 7.5, 0, 0.25, 1, 2, COLOR='SILVER' / ' 1 x 2h window front

/&HOLE XB= 9, 9.25, 0, 0.25, 1, 3, COLOR='SILVER'  / ' 1 x 2h window front

/&HOLE XB= 11, 12, 0, 0.25, 2, 3 , COLOR='SILVER' / ' 1 x 2h window front

/&HOLE XB= 13, 13.5, 0, 0.25, 2, 3 , COLOR='SILVER' / ' 1 x 2h window front

/&HOLE XB= 15, 15.25, 0, 0.25, 2, 3 , COLOR='SILVER'/ ' 1 x 2h window front
/&HOLE XB= 17, 18, 0, 0.25, 1, 3 , COLOR='SILVER'/ ' 1 x 2h window front
/&HOLE XB= 19, 20, 0, 0.25, 1, 3 , COLOR='SILVER'/ ' 1 x 2h window front

'Fire

&SURF ID='BURNER1', HRRPUA=970,RAMP_Q='BURNER1 RAMP', COLOR='RASPBERRY' /  100% = 4.242 MW
&RAMP ID='BURNER1 RAMP', T=0, F=0 / '0
&RAMP ID='BURNER1 RAMP', T=1, F=0.25 /
&RAMP ID='BURNER1 RAMP', T=60, F=0.25/
&RAMP ID='BURNER1 RAMP', T=61, F=0.5/
&RAMP ID='BURNER1 RAMP', T=120, F=0.5/
&RAMP ID='BURNER1 RAMP', T=121, F=0.75/
&RAMP ID='BURNER1 RAMP', T=180, F=0.75/
&RAMP ID='BURNER1 RAMP', T=181, F=1/
&RAMP ID='BURNER1 RAMP', T=240, F=1/
&RAMP ID='BURNER1 RAMP', T=241, F=1.25/
&RAMP ID='BURNER1 RAMP', T=300, F=1.25/
&RAMP ID='BURNER1 RAMP', T=301, F=1.5/
&RAMP ID='BURNER1 RAMP', T=3600, F=1.5/

'&RAMP ID='BURNER1 RAMP', T=7200, F=1 / 8MW max

&OBST XB= 0.25, 2.75, 1, 2.75, 0, .3, SURF_ID='INERT' / Burner in middle, location of burning vehicle
&VENT XB= 0.25, 2.75, 1, 2.75, .3, .3, SURF_ID='BURNER1' / Burner

'Recorded parameters

&DEVC XYZ=1.5,0,3, QUANTITY='RADIATIVE HEAT FLUX' ID= '1.5, 0, 3', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,3.5 QUANTITY='RADIATIVE HEAT FLUX'  ID= '1.5, 0, 3.5', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,4, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 4', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,4.5, QUANTITY='RADIATIVE HEAT FLUX'  ID= '1.5, 0, 4.5', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,5, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 5', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,5.5, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 5.5', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,6, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 6', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,6.5, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 6.5', IOR=-2 / 'flux on wall

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&DEVC XYZ=1.5,0,7, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 7', IOR=-2 / 'flux on wall
&DEVC XYZ=1.5,0,7.5, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 7.5', IOR=-2 / 'flux on wall
/&DEVC XYZ=1.5,0,8, QUANTITY='RADIATIVE HEAT FLUX'ID= '1.5, 0, 8', IOR=-2 / 'flux on wall


&DEVC XYZ=1.5,1.5,3, QUANTITY='TEMPERATURE'ID= '1.5, 1.5, 3.65' / ' air temp 100 mm below ceiling to compare with upper layer temp
fire compartment temp


&DEVC XYZ=1.5, 0.0,3, QUANTITY='TEMPERATURE'ID= '1.5, 0, 3' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,3, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 3' /
&DEVC XYZ=1.5,-1.0,3, QUANTITY='TEMPERATURE'ID= '1.5, -1, 3'/
&DEVC XYZ=1.5,-1.5,3, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 3' /
&DEVC XYZ=1.5,-2.0,3, QUANTITY='TEMPERATURE'ID= '1.5, -2, 3'/
&DEVC XYZ=1.5,-2.5,3, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 3'/
&DEVC XYZ=1.5,-3.0,3, QUANTITY='TEMPERATURE'ID= '1.5, -3, 3' /

&DEVC XYZ=1.5, 0  ,3.5, QUANTITY='TEMPERATURE'ID= '1.5, 0, 3.5' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,3.5, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 3.5' /
&DEVC XYZ=1.5,-1  ,3.5, QUANTITY='TEMPERATURE'ID= '1.5, -1, 3.5' /
&DEVC XYZ=1.5,-1.5,3.5, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 3.5' /
&DEVC XYZ=1.5,-2  ,3.5, QUANTITY='TEMPERATURE'ID= '1.5, -2, 3.5'/
&DEVC XYZ=1.5,-2.5,3.5, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 3.5'/
&DEVC XYZ=1.5,-3  ,3.5, QUANTITY='TEMPERATURE'ID= '1.5, -3, 3.5' /

&DEVC XYZ=1.5,0,4, QUANTITY='TEMPERATURE'ID= '1.5, 0, 4' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,4, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 4' /
&DEVC XYZ=1.5,-1,4, QUANTITY='TEMPERATURE'ID= '1.5, -1, 4' /
&DEVC XYZ=1.5,-1.5,4, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 4' /
&DEVC XYZ=1.5,-2,4, QUANTITY='TEMPERATURE'ID= '1.5, -2, 4'/
&DEVC XYZ=1.5,-2.5,4, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 4'/
&DEVC XYZ=1.5,-3,4, QUANTITY='TEMPERATURE'ID= '1.5, -3, 4' /

&DEVC XYZ=1.5,0,4.5, QUANTITY='TEMPERATURE'ID= '1.5, 0, 4.5' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,4.5, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 4.5' /
&DEVC XYZ=1.5,-1,4.5, QUANTITY='TEMPERATURE'ID= '1.5, -1, 4.5' /
&DEVC XYZ=1.5,-1.5,4.5, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 4.5' /
&DEVC XYZ=1.5,-2,4.5, QUANTITY='TEMPERATURE'ID= '1.5, -2, 4.5'/
&DEVC XYZ=1.5,-2.5,4.5, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 4.5'/
&DEVC XYZ=1.5,-3,4.5, QUANTITY='TEMPERATURE'ID= '1.5, -3, 4.5' /

&DEVC XYZ=1.5,0,5, QUANTITY='TEMPERATURE'ID= '1.5, 0, 5' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,5, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 5' /
&DEVC XYZ=1.5,-1,5, QUANTITY='TEMPERATURE'ID= '1.5, -1, 5' /
&DEVC XYZ=1.5,-1.5,5, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 5' /
&DEVC XYZ=1.5,-2,5, QUANTITY='TEMPERATURE'ID= '1.5, -2, 5'/
&DEVC XYZ=1.5,-2.5,5, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 5'/
&DEVC XYZ=1.5,-3,5, QUANTITY='TEMPERATURE'ID= '1.5, -3, 5' /

&DEVC XYZ=1.5,0,5.5, QUANTITY='TEMPERATURE'ID= '1.5, 0, 5.5' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,5.5, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 5.5' /
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&DEVC XYZ=1.5,-1,5.5, QUANTITY='TEMPERATURE'ID= '1.5, -1, 5.5' /
&DEVC XYZ=1.5,-1.5,5.5, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 5.5'/
&DEVC XYZ=1.5,-2,5.5, QUANTITY='TEMPERATURE'ID= '1.5, -2, 5.5'/
&DEVC XYZ=1.5,-2.5,5.5, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 5.5'/
&DEVC XYZ=1.5,-3,5.5, QUANTITY='TEMPERATURE'ID= '1.5, -3, 5.5' /

&DEVC XYZ=1.5,0,6, QUANTITY='TEMPERATURE'ID= '1.5, 0, 6' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,6, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 6' /
&DEVC XYZ=1.5,-1,6, QUANTITY='TEMPERATURE'ID= '1.5, -1, 6' /
&DEVC XYZ=1.5,-1.5,6, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 6' /
&DEVC XYZ=1.5,-2,6, QUANTITY='TEMPERATURE'ID= '1.5, -2, 6'/
&DEVC XYZ=1.5,-2.5,6, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 6'/
&DEVC XYZ=1.5,-3,6, QUANTITY='TEMPERATURE'ID= '1.5, -3, 6' /

&DEVC XYZ=1.5,0,6.5, QUANTITY='TEMPERATURE'ID= '1.5, 0, 6.5' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,6.5, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 6.5' /
&DEVC XYZ=1.5,-1,6.5, QUANTITY='TEMPERATURE'ID= '1.5, -1, 6.5' /
&DEVC XYZ=1.5,-1.5,6.5, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 6.5' /
&DEVC XYZ=1.5,-2,6.5, QUANTITY='TEMPERATURE'ID= '1.5, -2, 6.5'/
&DEVC XYZ=1.5,-2.5,6.5, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 6.5'/
&DEVC XYZ=1.5,-3,6.5, QUANTITY='TEMPERATURE'ID= '1.5, -3, 6.5' /

&DEVC XYZ=1.5,0,7, QUANTITY='TEMPERATURE'ID= '1.5, 0, 7' / ' air temp im plume
&DEVC XYZ=1.5,-0.5,7, QUANTITY='TEMPERATURE'ID= '1.5, -0.5, 7' /
&DEVC XYZ=1.5,-1,7, QUANTITY='TEMPERATURE'ID= '1.5, -1, 7' /
&DEVC XYZ=1.5,-1.5,7, QUANTITY='TEMPERATURE'ID= '1.5, -1.5, 7' /
&DEVC XYZ=1.5,-2,7, QUANTITY='TEMPERATURE'ID= '1.5, -2, 7'/
&DEVC XYZ=1.5,-2.5,7, QUANTITY='TEMPERATURE'ID= '1.5, -2.5, 7'/
&DEVC XYZ=1.5,-3,7, QUANTITY='TEMPERATURE'ID= '1.5, -3, 7' /


&TAIL /'end of programme
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