DEFINING THE TIME TO UNTENABLE CONDITIONS FROM CFD MODELLING RESULTS

Ryan J. Quickenden

Department of Civil & Natural Resources Engineering, University of Canterbury, New Zealand
e-mail: rjq12@uclive.ac.nz

Keywords: Tenability, Visibility, Fire Modelling, C/VM2, CFD Modelling.

Abstract. *The New Zealand Building Code states that when visibility at a height of 2 m falls below 10 m due to smoke, tenability within a room is lost. This point is not clearly defined for CFD modelling due to the realistic level of detail provided including the non-uniform and dynamic smoke layer not descending at a uniform rate throughout the compartment. This makes it difficult to assess when the visibility 2 m above the floor has fallen below 10 m sufficiently to cause the compartment to be considered untenable. This research paper examines the conditions within a number of compartments when designed to the New Zealand Verification Method 2 (C/VM2) and is intended to provide guidance for fire engineers on when it is appropriate to assume that tenability has been lost due to visibility. The results suggest that a non-sprinklered compartment can be assumed to fail when 80% of the compartment has lost visibility at a height of 2 m. For sprinklered compartments a value of 30% may be appropriate however is less reliable.*

1 INTRODUCTION

Designing a structure using New Zealand's Protection from Fire Verification Method (C/VM2) requires the designer to calculate the available safe egress time (ASET) of the occupants from each fire cell. The ASET is calculated based on the tenability limits as set out in the C/VM2 document and the conditions within the structure during a fire determined by numerical modelling software. One of the limits requires that the visibility within an occupied compartment must not fall below 10 m at a height of 2 m from the floor, except for rooms under 100 m^2 where the visibility must not fall below 5 m. When the conditions within the space exceed the tenability limits, any remaining occupants within the space are considered to be incapacitated and therefore casualties of the fire.

Loss of visibility is not directly hazardous however it has a negative psychological effect likely to reduce walking speeds and hence extend exposure time to the toxins within the smoke. The susceptibility for tripping or falling may also be increased due to loss of visibility.

1.1 CFD and Zone fire models

The conditions within a fire cell are generally determined by using either a two-zone model or a Computational Fluid Dynamics (CFD) model. A two-zone model divides the compartment into an upper smoke/hot gas zone and a lower cool zone. Each zone is assumed to be uniform throughout the compartment. Because of this simplification, these models are unable to consider local effects such as hot and cold spots. Figure 1 illustrates a typical fire environment inside a compartment using the two zone concept.

Zone models do not incorporate conservation of momentum equations and as a result the upper smoke layer is assumed to form instantaneously and descend from the ceiling at a uniform rate throughout the room. The tenability limits are reached simultaneously at every point in the room. A detailed description of the zone modelling concept including the physical and mathematical assumptions is available in Chapter 10 of Enclosure Fire Dynamics [1].

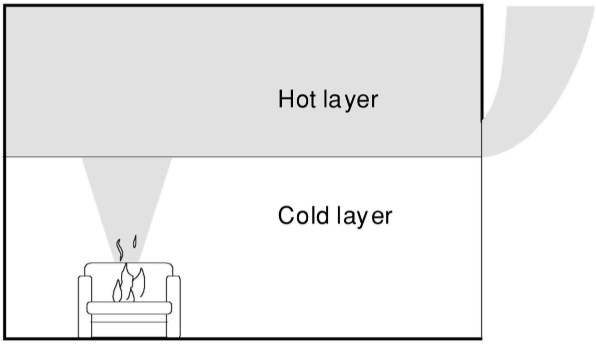


Figure 1: Two-zone modelling of a fire in an enclosure [1].

In CFD models, the compartment is divided into many three-dimensional grid cells where calculations of the conservation of mass, energy and momentum equations are performed at each grid cell for every simulation time step. Figure 2 illustrates a small compartment divided into a grid as would be used in a CFD model.

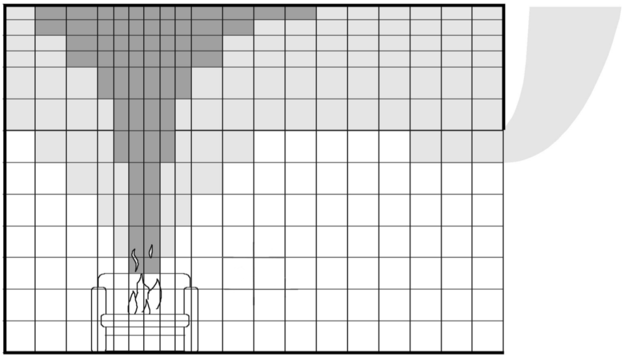


Figure 2: CFD model divided into a large number of subvolumes [1].

The increased complexity of CFD models generally results in representations of the conditions within the room far closer to reality compared with zone models. The hot gaseous upper layer is no longer homogeneous nor does it descend at a constant rate throughout the room. A detailed description of the CFD modelling is also available in Chapter 10 of Enclosure Fire Dynamics [1].

Because of this increased level of detail, the tenability limits are reached at different times at different parts of the room and, in some cases, the point in the room can even become tenable again. In these cases, occupants within the room may be considered incapacitated when the tenability limits have been exceeded in only a small portion of the room and perhaps only for a short period of time.

C/VM2 Commentary Appendix C [2] contains advice on how to deal with the similar issue of defining the layer height. As the layer height is generally synonymous with loss of visibility, this method was used as a guideline and for comparison. By using several monitoring points throughout the room spaced as shown in Figure 3, one of two criteria can be met:

(a) Simple criteria – Compartment fails when any one of the monitoring points fails,

(b) Complex criteria – Determine the average time for visibility to drop below 10 m at 2 m above the floor at all monitoring points, ${t_{\text{layer}}}^{avg}$, as well as the standard deviation for those times, σ_{layer}. The layer is assumed to have reached 2 m when:

$$t_{layer} = min\left(0.95{t_{layer}}^{avg},\ {t_{layer}}^{avg} - \sigma_{layer}\right) \tag{1}$$

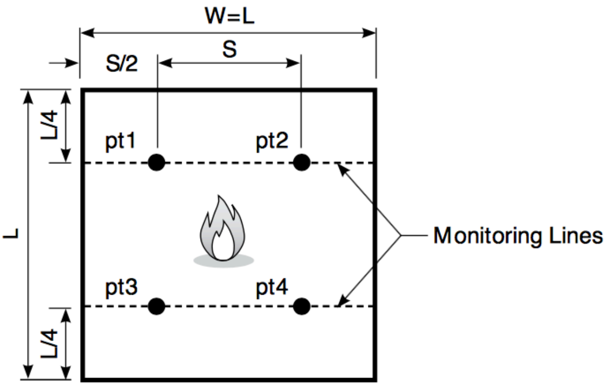


Figure 3: Monitoring point spacing [2].

This method is only defined for ceiling heights 6 m and above, and for ultra fast and rack-growth fires. This was based on a series of simulations, many of which that were outside of the recommended software limits, and generally gives a scattered result.

1.2 Research objectives

The aim of this research was to define the point when it is appropriate to assume the conditions within a compartment have become untenable due to loss of visibility when undertaking CFD modelling. The answer was to be as simple as possible and preferably be in terms of the percentage of the compartment that has lost visibility. This is intended to assist Fire Engineers in the design process and will not necessarily satisfy the requirements, but rather satisfy the intent of C/VM2. This work does not suggest different values for the tenability limits, but at what time it is appropriate to say that the limits have been reached.

To date the only apparent existing research for defining an appropriate time to the loss of tenable conditions due to visibility is that in Appendix C of the C/VM2 Commentary.

1.3 Modelling software background

Within New Zealand the modelling softwares ‘Fire Dynamics Simulator’ and ‘B-RISK’ are commonly used by Fire Engineers to show a building design complies with the requirements of the New Zealand Building Code with respect to fire.

Fire Dynamics Simulator (FDS) is a CFD modelling software that uses the Large Eddy Simulation technique to determine the characteristics of a fire environment. For the purposes of design FDS assumes, among other things, that only a single gas species is available for combustion and that physical processes that occur at small length and time scales such as diffusion can be approximated. A detailed description of the FDS software is given in the FDS Technical Reference Guide [3].

B-RISK is a two-zone modelling software based on the previously developed BRANZFIRE software. B-RISK does not include conservation of momentum in the model requiring it to incorporate a number of sub-models such as plume entrainment, vent flows, and ceiling jet correlations. Other assumptions are also required to be included such as the instantaneous formation of the hot upper gas layer. A detailed description of the software is given in the B-RISK User Guide and Technical Manual [4].

Both FDS and B-RISK calculate visibility, S, with the following equation:

$$S = C/K_m \rho Y_s \tag{2}$$

Where C is the non-dimensional characteristic constant of an object being viewed through smoke, K_m is the mass extinction coefficient (m^2/kg), and ρY_s is the density of smoke particulate (kg/m^3).

B-RISK is only capable of giving a single value for the entire compartment however FDS tracks the smoke movement around the compartment and can give a value of visibility at any point.

It is known that both CFD and two-zone models such as FDS and B-RISK have a tendency to over estimate the soot concentration and hence visibility in the hot upper gas layer of a compartment fire with a prescribed soot yield [5]-[6]. The FDS Validation Guide notes that the FDS software has a bias factor of $\delta = 2.54$ [7] when predicting smoke concentrations. Research by Jassens et al. found a similar result with FDS exhibiting bias factors of $\delta = 2.40$. It is believed that these results are due to a number of soot specific behaviours such as particle settling and deposition not being fully represented within the model. Floyd [6] incorporated all of these behaviours into FDS to investigate the effects on soot concentration in a compartment fire, however he found that this made a very small improvement on the poor predictions of FDS.

1.4 Modelling software limits

1.4.1 FDS

The grid resolution of CFD models is extremely important in order to ensure the results are accurate and the software has not been used outside the domain it was intended for. The FDS user guide suggests the level of resolution be determined by the non-dimensional expression $D^*/\delta x$ where D^* is given by:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \tag{3}$$

In this equation, $\dot{Q}$ is the heat release rate (kW), ρ_∞ is the ambient air density $(\mathrm{kg/m^3})$, c_p is the specific heat of air $(\mathrm{kJ/kg.K})$, T_∞ is the ambient air temperature (K) and g is the acceleration due to gravity $(\mathrm{m/s^2})$.

The FDS validation guide contains a table of $D^*/\delta x$ values used to validate the model and range between 2 and 32. The U.S. Nuclear Regulatory Commission also undertook research to validate FDS and suggested that values of 5 and above give favourable results [8]. For this research, any $D^*/\delta x$ greater than 5 was considered acceptable.

FDS is only capable of modelling items the same size or larger than the grid resolution and whose dimensions are equal to some multiple of the grid resolution. Because of this, modelling a radially spreading fire with a constant heat release rate per unit area is difficult and causes the heat release rate curve to be staggered rather than a smooth t^2 curve as required by C/VM2. This effect is more pronounced for coarser grid resolutions.

1.4.2 B-RISK

Fires that are small compared to the compartment create smaller rises in gas temperatures near the ceiling and a distinct hot upper gas layer may not occur due to the excessive cooling, smoke transport delays and the influence of air currents and ambient thermal gradients. Fires that are large compared to the compartment have higher ceiling jet velocities creating more pronounced wall jets, greater mixing between upper and lower gas layers and an increase of thermal radiation effects. These effects are avoided by controlling the size of the fire. The Technical Recommendation for C/VM2 calculations by Wade [9] suggests the following limit on the non-dimensional fire size, $\dot{Q}^*$:

$$\dot{Q}^* = \frac{\dot{Q}}{1110 H^{5/2}} \leq 0.15 \tag{4}$$

Where $\dot{Q}$ is the heat release rate (kW) and H is the ceiling height (m).

For long corridors, tall atriums or shafts and large rooms with low ceiling heights, the hot upper gas layer would not be expected to reach the extremities of the compartment instantaneously due to transport lag. This is an issue for zone models such as B-RISK due to the assumption that the hot upper gas layer forms instantaneously throughout the entire compartment. This can be corrected by creating several smaller compartments and connecting them with large vents so that they are essentially a single compartment. Wade suggests the following limits on the geometry of the compartment [9]:

The Aspect ratio, AR,

$$W/L \leq 5 \tag{5}$$

The shape factor, SF,

$$0.4 \leq \frac{A_F}{H^2} \leq 70 \tag{6}$$

Where W and L is the room width and length (m), H is the ceiling height (m), and A_F is the floor area (m^2).

2 METHODOLOGY

The research objective was undertaken by modelling a number of different compartments using FDS and B-RISK and observing and comparing the results from both softwares. Given that both softwares are available to be used by engineers, the comparison between the two was done to ensure that one software is not largely favourable over the other.

The compartments were limited to floor areas between 500 m^2 and 5000 m^2 due to ASET not being required for compartments with a total floor area less than 500 m^2, and extra design requirements above 5000 m^2. The extra design requirements are in Section 4.8 of the C/VM2 document.

The design fires used within the models were given the characteristics specified in Table 2.1 of C/VM2 and are shown in Table 1 below. Along with these fire characteristics, C/VM2 provides a generic chemical formula for the fuel as $CH_2O_{0.5}$. In all cases the fire was situated in the centre of the compartment and as close to but not exceeding 0.5 m in height. The walls and ceiling were modeled as having 10 mm plasterboard with an insulated backing and a 100 mm thick concrete floor. In accordance with C/VM2 the walls were considered to have a leakage area of 0.1%. No other openings were added.

The non-dimensional constant, C, for calculating visibility was taken as 3 for this study which is equivalent to a light reflecting sign. The mass extinction coefficient used within FDS is 8700 m^2/kg as suggested for flaming combustion of wood and plastics [10] while B-RISK uses 8790 m^2/kg similar to flaming combustion of ethane gas [4].

Table 1: Design Fire Characteristics.

Building Use	Fire Growth Rate (kW)	Species Production	Radiative Fraction	Peak HRR
All buildings including storage with a stack height less than 3 m	$0.0469t^2$	$Y_{soot} = 0.07$ $Y_{co} = 0.04$ $Y_{CO_2} = 1.5$ $Y_{H_2O} = 0.82$ $\Delta H_c = 20\ MJ/kg$	0.35	20 MW at 500 – 1000 kW/m^2
Capable of storage to a stack height of between 3 m and 5 m	$0.188t^2$		0.35	50 MW at 1000-2500 kW/m^2
Capable of storage to a stack height of more than 5 m above the floor	$0.00068t^3H_{st}$		0.35	

The fraction of the room that has reached the tenability limit combined with the relative and absolute difference between FDS and B-RISK was used to decide on an outcome.

2.1 FDS and B-RISK set-up

Table 2 summarises the model geometries tested along with the respective value of $D^*/\delta x$ for FDS. Each compartment was modeled with and without sprinklers. Preliminary results revealed standard response sprinklers either did not activate before visibility was lost or activated too late to have a noticeable impact on the results. For this reason quick response sprinklers were used with an RTI of 50 $m^{0.5}s^{0.5}$, C factor of 0.65, a radial distance of 3.25 m and a distance of 25 mm from the ceiling in accordance with C/VM2 Table 3.2.

B-RISK was used in NZBC - VM2 mode with the same input parameters as FDS. Due to the model limits discussed previously, many of the compartments modelled in B-RISK were divided into several compartments connected by large vents to make a room of equivalent size.

Table 2: FDS Model Characteristics.

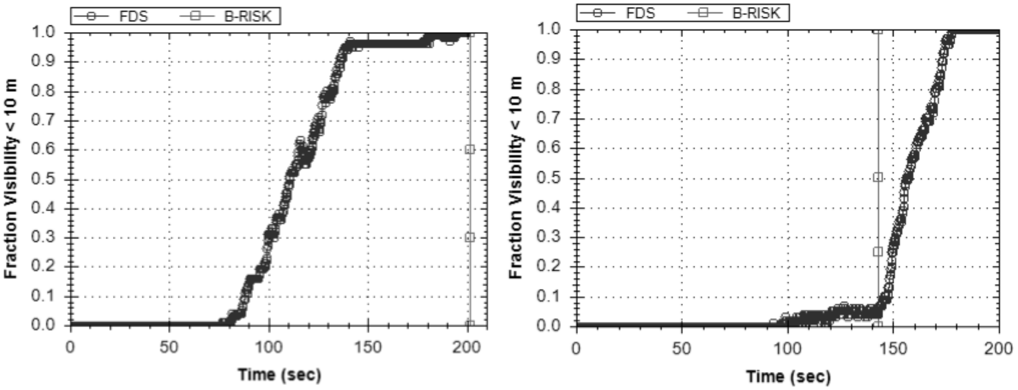
Compartment geometry	Floor area (m^2)	FDS Non-Sprinklered $\delta/_{D^*}$	FDS Sprinklered $\delta/_{D^*}$
Square Compartments			
25 m x 25 m x 3 m	625	5.6	7.6
25 m x 25 m x 6 m		9.1	5.9
25 m x 25 m x 9 m		10.7	6.4
50 m x 50 m x 3 m	2500	9.7	6.6
50 m x 50 m x 6 m		11.6	5.0
50 m x 50 m x 9 m		7.7	6.5
70 m x 70 m x 3 m	4900	8.5	8.2
70 m x 70 m x 6 m		13.4	10.3
70 m x 70 m x 9 m		9.1	6.4
Rectangular Compartments			
15 m x 45 m x 3 m	625	5.7	7.7
15 m x 45 m x 6 m		8.3	5.9
15 m x 45 m x 9 m		11.6	6.3
30 m x 90 m x 3 m	2500	8.7	6.5
30 m x 90 m x 6 m		9.6	6.1
30 m x 90 m x 9 m		7.2	6.5
39 m x 117 m x 3 m	4900	7.8	6.5
39 m x 117 m x 6 m		9.6	5.1
39 m x 117 m x 9 m		9.1	6.5

Visibility was recorded at 100 uniformly distributed points throughout the square compartment, and 108 points throughout the rectangle compartment. A Slice File recording the visibility in plan view at a height of 2 m was also recorded in each FDS simulation.

3 SIMULATION RESULTS

Before the results are given, it should be noted that all of the non-dimensional fire sizes, Q*, from the B-RISK modelling in the non-sprinklered compartments with a floor area of 2500 m^2 and above were outside the limits recommended by Wade.

The difference in results between FDS and B-RISK appears to be highly dependent on either the fire size or the ceiling height. With reference to the failure time of B-RISK, FDS tends to lose visibility earlier when the ceiling height is low and loses visibility later when the ceiling height is high. An example of this is shown in the visibility loss curves in Figure 4. The same characteristics in results were observed for both of the aspect ratios that were investigated. These characteristics were observed regardless of whether the compartment was sprinklered or not.



(a) (b)

Figure 4: 25 m x 25 m compartment. (a) 3 m ceiling; (b) 9 m ceiling.

As expected, sprinklers also flatten the visibility loss curve resulting in an extended time to loss of visibility. Due to the flattening of the visibility loss curve for the sprinklered compartments, they can take well over 1000 seconds to go from 1% visibility loss to 100%.

The flattening of the visibility loss curve for sprinklered compartments means that there is a much larger relative difference between softwares when specifying a generic failure point compared with a non-sprinklered compartment. This essentially makes the sprinklered compartments a large source of error for the final answer. In order to get a more sensible answer the data was split into non-sprinklered and sprinklered.

Table 3 shows the difference (%) between FDS and B-RISK at certain times of the FDS model (given as a percentage of visibility lost) when averaged over all of the non-sprinklered compartments and sprinklered compartments separately. A negative value indicates B-RISK giving a longer failure time. For non-sprinklered compartments, the average difference between FDS and B- RISK becomes very low if FDS is assumed to fail at approximately 90%. For sprinklered compartments, the average difference between FDS and B-RISK becomes very low if FDS is assumed to fail at approximately 30%.

Table 3: FDS and B-RISK Comparison.

	Difference Between FDS and B-RISK when FDS has reached the given percentage of visibility loss (%)									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Non-Sprinklered Compartments										
Average Difference	-33.0	-23.6	-20.1	-16.1	-13.5	-10.9	-7.3	-3.9	-2.1	8.1
Standard Deviation	19.9	17.9	19.0	19.3	19.4	19.9	20.5	20.8	24.4	24.4
Sprinklered Compartments										
Average Difference	-23.8	-7.3	0.71	13.3	17.7	25.4	34.0	20.7	31.3	40.5
Standard Deviation	36.8	43.7	48.3	54.7	56.1	60.1	65.5	70.7	78.1	61.3

4 DISCUSSION

The results show that B-RISK fails over a wide range of the FDS visibility loss curve. The percentage the B-RISK fails at when compared with FDS seems to be highly dependent on either the ceiling height or fire size. This is an issue when attempting to specify a generic failure point, particularly for larger and sprinklered compartments which can take over 1000 seconds to go from 1% to 100% loss of visibility.

Observing all of the results together, the average percentage of FDS visibility loss at B-RISK failure is 40%. Using this as a guide for the tenability limit, the largest difference between B-RISK and FDS is 497 seconds. As the percentage used is lowered from 40%, the standard deviation and maximum difference between software results decreases however B-RISK tends to fail after FDS. As the percentage used is increased from 40%, the standard deviation and maximum difference between software results increases, and B-RISK begins to fail before FDS. Considerably better results are achieved by splitting up the compartments into sprinklered and non-sprinklered.

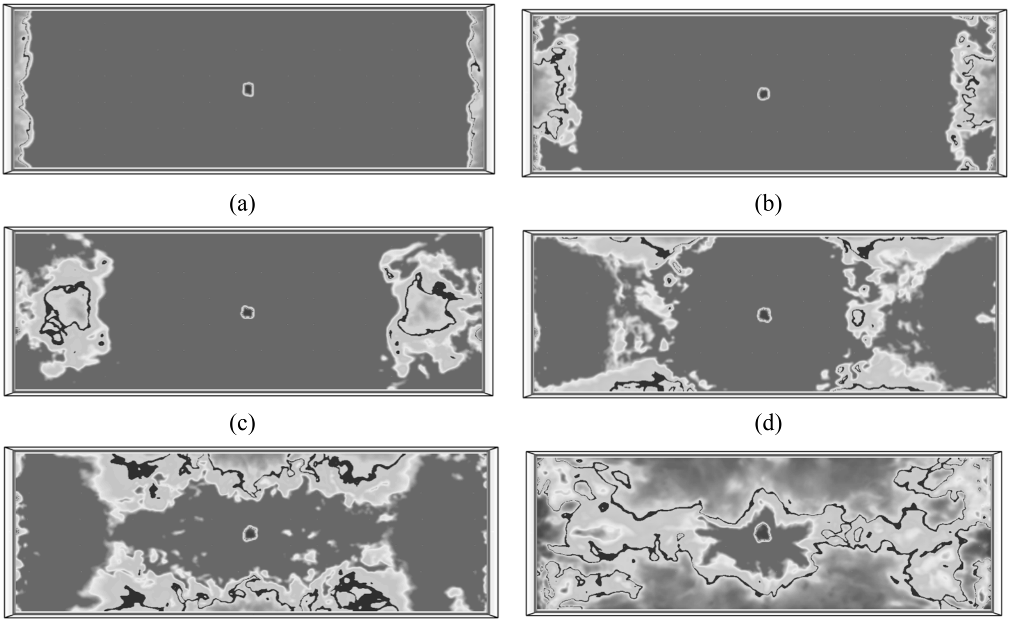
For non-sprinklered compartments, if FDS is considered to fail at 80% it results on average in a 4% difference between FDS and B-RISK with a standard deviation in relative differences of approximately 20%. Although on average FDS and B-RISK give more similar results at 90%, the spread of results is greater than at 80%. Using 80% results in FDS underestimating B-RISK by 4% (rather than 2%) however it also reduces the standard deviation from 25% to 21%. Using 80% also improves on the method suggested in the C/VM2 Commentary by giving values between FDS and B-RISK almost 12% closer on average. Although 80% may seem high, it must be remembered that, as discussed previously, both FDS and zone models such as B-RISK are known for over estimating the smoke concentration by as much as 150%.

The sprinklered compartments still have a wide spread of results, however, assuming FDS fails at 30% the relative differences are reasonable in most cases. Due to the high standard deviation of 48% and the effect the sprinklers have on the visibility loss curve, when using 30% as a guide the differences between FDS and B-RISK can be quite significant – as much as 814 seconds in this study. However this method gives values almost 7% closer to B-RISK on average than the method suggested in the C/VM2 Commentary. Although there can be large differences between FDS and B-RISK when using 30%, it is suggested that this be used in the absence of a better guideline.

Ideally, a sliding scale would be used which gives the failure percentage depending on the ceiling height of the compartment. Based on the results observed in this study, this would be a lower percentage for high ceiling heights and a higher percentage for low ceiling heights. Unfortunately insufficient data has been collected from this research to form such a scale.

As fire modelling software develops and is able to more accurately predict the visibility within compartments, the following should be considered. In the early stages of all the cases investigated so far there exists a transient phase where the bottom of smoke layer exhibits a wave-like behaviour. Because of this behaviour, small sections of the compartment lose tenability for a small period of time as the smoke wave passes by. From the cases described within this report, this period of tenability loss can last from a few seconds up to approximately 30 seconds and is dependent on the compartment geometry and fire size. During this transient phase up to approximately 10% of the compartment can lose visibility at 2 m. The Slice Files shown in Figure 5a to Figure 5f give an example of this. The sections enclosed by the black lines in the Slice Files represent the areas where the visibility has fallen below 10 m. The transient stage is shown in Figure 5a to Figure 5d. Figure 5e and Figure 5f shows the uniform filling stage.

As these waves move through the compartment and do not affect a single area for a significant period of time, this period could be ignored when assessing tenability due to loss of visibility. At some point this behaviour disappears and the fraction of visibility lost at 2 m continues to increase at a steady rate until visibility is completely lost at every point in the compartment. This steady rate of visibility loss occurs mostly when the fraction of the room that has lost visibility at 2 m consistently exceeds 10%. It would therefore recommended that, when modeling becomes more accurate for estimating soot concentrations in the upper layer, the room be considered to fail when the visibility is lost for over 10% of the compartment consistently.



(a) (b) (c) (d) (e) (f)

Figure 5: 30 m x 90 m x 6 m compartment smoke filling. (a) 128 sec; (b) 143 sec; (c) 166 sec; (d) 195 sec; (e) 225 sec; (f) 277 sec.

5 CONCLUSION

For non-sprinklered compartments, assuming that visibility has been lost when 80% of the compartment has visibility fall below 10 m at a height of 2 m when using FDS gives similar results to B-RISK. It also generally gives a value closer to B-RISK than the method suggested in the C/VM2 Commentary. For sprinklered compartments, assuming FDS fails at 30% gives similar differences in results to the method suggested in the C/VM2 Commentary and is by no means a superior method.

For design purposes the following is suggested:

(a) For non-sprinklered compartments assume FDS fails when the visibility falls below 10 m at a height of 2 m over 80% of the compartment.
(b) For sprinklered compartments, assume FDS fails when the visibility falls below 10 m at a height of 2 m over 30% of the compartment.

When modelling softwares are able to estimate soot concentrations in the upper layer more accurately, assuming any compartment fails when the visibility is lost for over 10% of the compartment consistently may be appropriate.

5.1 Recommendations for future research

Many other factors must be reviewed to determine a complete and sensible answer to the question “When is it appropriate to say visibility is lost?” Other factors include, but are not limited to:

(a) Irregularly shaped compartments (L or T shapes for example),
(b) Compartment ventilation such as windows or doors,
(c) Smoke filling due to a fire in an adjacent compartment (smoke flow through a door for example),
(d) Visibility in stairways,
(e) Tiered seating

The possibility of using a sliding scale to determine the percentage at which FDS fails depending on the ceiling height could also be investigated.

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