MINIMUM RESERVOIR DEPTHS FOR CONTAINING SMOKE WITHIN RESERVOIRS PROTECTED BY MECHANICAL EXHAUST

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ABSTRACT

The Building Code of Australia (BCA) generally requires large spaces to be protected by a mechanical smoke exhaust system. This requires the spaces to be divided at the ceiling level into smoke reservoirs to contain the smoke layer; and exhaust fan(s) installed to remove the smoke from each reservoir. Even though this is a Deemed-to-Satisfy solution, the BCA sets out both prescriptive and performance requirements the system must be designed to satisfy. One of the key performance requirements is that the smoke layer must be contained within the smoke reservoir.

Series of parametric studies were carried out using Computational Fluid Dynamics (CFD) analyses to examine the smoke filling of smoke reservoirs. The studies reveal that, with the BCA prescribed smoke extraction rates, smoke reservoirs with a minimum depth of 0.5 m specified by the BCA are insufficient to contain the smoke layer within the reservoirs. For smoke layer containment, the necessary reservoir depths are significantly larger than the BCA prescribed minimum of 0.5 m. These were investigated in the parametric studies and the necessary depths for smoke containment in the ideal, best case situations are given in the paper.

Further studies were also carried out to investigate the smoke extraction for a smoke reservoir with a minimum depth of 0.5 m. The results show that the smoke extraction rate required for containment of smoke within the reservoir is significantly higher than that prescribed by the BCA. The high exhaust rate is unlikely to be practical and may also introduce significant issues with make-up air. The viability of adopting the minimum reservoir depth and increasing the smoke exhaust rate for containing the smoke layer is questionable. Hence, in order to achieve the BCA requirements, reservoir depth greater than the BCA prescribed minimum is necessary.

NOTATIONS:

A	=	Horizontal area of smoke reservoir (m)
A_{max}	=	BCA maximum allowable area for smoke reservoir = 2000 m^2
d	=	Depth of smoke reservoir (m)
d_{min}	=	BCA minimum smoke reservoir depth = 0.5 m
h	=	Height to underside of smoke layer (m)
h_{min}	=	BCA minimum allowed smoke layer height = 2 m
H	=	Height of enclosure containing the smoke reservoir (m)
V	=	Smoke exhaust rate for the smoke reservoir (m^3/s)
HRR	=	Heat release rate of fire (MW)
t	=	Elapse time from start of fire (s)

INTRODUCTION

Mechanical Smoke Exhaust

The Building Code of Australia (BCA) generally requires large spaces to be protected by a mechanical smoke exhaust system designed in accordance with the requirements set out in Specification E2.2b of the BCA. Essentially, it requires the spaces to be divided at the ceiling level into smoke reservoirs to contain the smoke layer; and exhaust fan(s) installed to remove the smoke from each reservoir (see Figure 1 below).

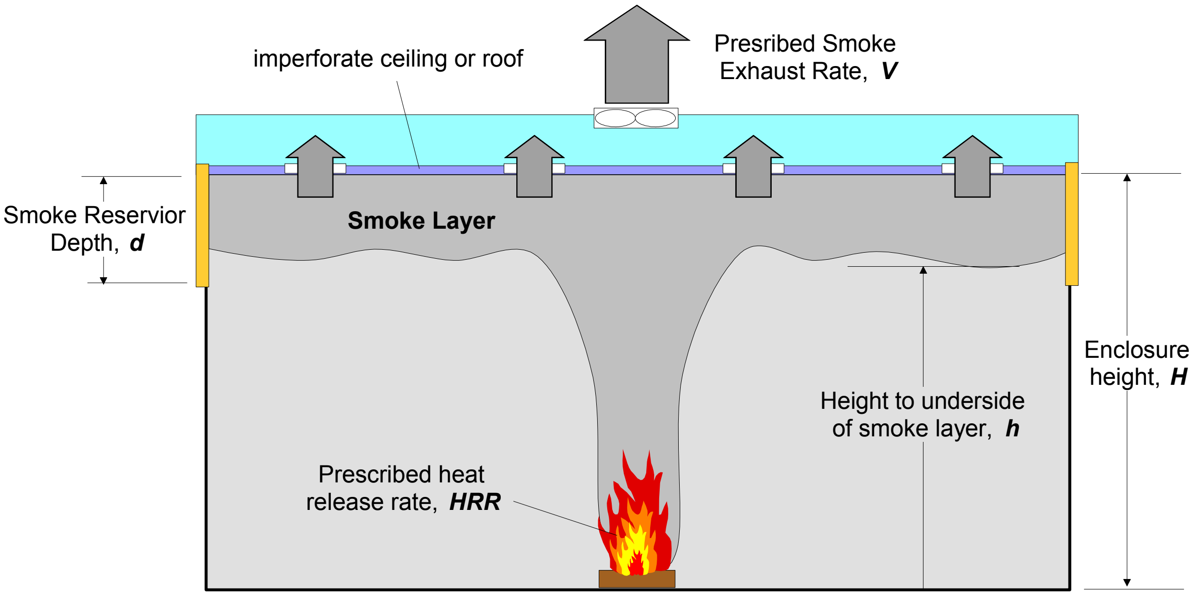

Figure 1 *Typical system design incorporating mechanical smoke exhaust system*

Even though this is a Deemed-to-Satisfy solution, the BCA sets out both prescriptive and performance requirements the system must be designed to satisfy.

Prescriptive Requirements

For the reservoir size, the BCA prescribes the following limits:

- maximum horizontal area, A_{max} = 2000 m^2
- minimum reservoir depth, d_{min} = 0.5 m

For the design of the mechanical smoke exhaust, it prescribes:

- heat release rate, *HRR* (for a given building classification and sprinkler protection)
- minimum smoke layer height, h_{min} = 2 m
- smoke exhaust rate, *V* for a given *h* and *HRR* (see Figure 3)

Performance Requirements

In addition to these prescriptive requirements, the BCA also sets out requirements for the performance of the smoke exhaust systems. The key one is that the smoke layer must be contained within the smoke reservoir. Other requirements are also set out with respect to plug-holing, make-up air and other aspects of the systems.

Design Process

No guidance is given in the BCA with respect to the analysis or design method to achieve the required performance for the smoke exhaust system. Given the interdependency of V, h and d, an iterative design process is required to achieve the performance requirements for the smoke exhaust system.

In a typical case where the ceiling height H is known or fixed, the designer must ensure sufficient d or V for containment of the smoke layer within the reservoir (i.e. $h \geq (H - d)$). This may involve an iterative process as shown in Appendix A of this paper.

It is unclear how many of the existing systems have been designed. Computational Fluid Dynamics (CFD) analyses of various existing buildings revealed that many of the smoke exhaust systems do not achieve the BCA required performance. In these instances, it was found that the reservoirs fall significantly short of the containment requirement and the smoke spreads significantly outside the reservoirs. It appears that only the prescribed limits on reservoir area and depth (i.e. A_{max} and d_{min}) are incorporated in their designs. The required performance for smoke layer containment have either been ignored or not understood by the designers.

This raises two fundamental questions with respect to the limits set by the BCA with respect to the smoke reservoirs in the above situations:

1. Given a BCA prescribed smoke exhaust rate V, can the smoke layer be contained within the smoke reservoir of the limiting size of A_{max} and d_{min}?
2. If not, what is the least d required for containing the smoke layer within the reservoir?
3. Or alternatively, what is the least smoke exhaust rate value required for containing the smoke layer within the smoke reservoir of the limiting size of A_{max} and d_{min}?

In order to provide some answers to the above questions, three series of parametric studies were carried out using CFD analyses to examine the smoke filling of smoke reservoirs with the operation of smoke exhaust systems. These are described in subsequent sections of this paper.

PARAMETRIC STUDIES

For the purpose of the parametric studies, an ideal situation of a single smoke reservoir with an area of A_{max} is examined using the CFD program, Fire Dynamic Simulator (FDS) [1]. The smoke reservoir is assumed to be located within an infinitely large space without any bounding walls. One of the BCA prescribed *HRR* of 5 MW, was arbitrarily chosen as the fire source for the purpose of the studies. The fire is assumed to be located centrally on the floor within the smoke reservoir.

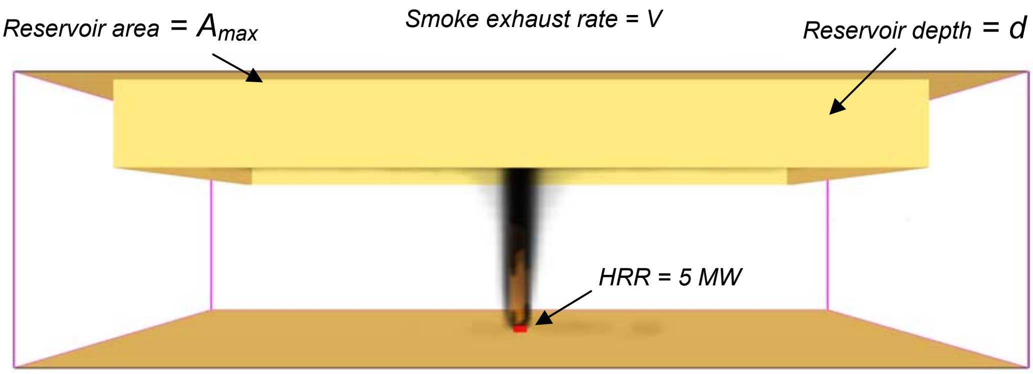

Figure 2 *A typical FDS model*

For the sake of simplicity, the effects of plug holing were eliminated by modelling the ideal case where the smoke is extracted uniformly over the entire surface of the smoke reservoir. The adverse effects of make-up air were also eliminated by placing the smoke reservoir within an infinite space without any bounding walls.

It is important to note that the situation examined represents the best case scenario where all aspects are assumed to be the most advantageous for extraction of smoke from the reservoir.

Other model parameters and assumptions made in analysis are summarised below:

- A = 40 x 50m (i.e. = A_{max} of 2000 m^2)
- h range examined = 2 to 15 m
- Total simulation time t = 1800 s
- *HRR* remains constant over the entire analysis period
- Effect of sprinklers (if present) on the smoke behaviour is ignored
- Smoke exhaust fan starts up instantaneously and operates at its full capacity V over the entire analysis period

For the purpose of determining the level of containment of the smoke layer, devices for measuring the smoke layer height were incorporated in the model. The smoke layer is considered to be contained within the smoke reservoir if $h \geq (H - d)$ over the simulation time of 1800 s. This is further confirmed by examining the visual output of the model.

SERIES 1: *d* = 0.5 m

The first series of analyses were carried out by assuming the minimum BCA prescribed reservoir depth d_{min} of 0.5 m for various assumed *h* values ranging from 2 m to 15 m. This is aimed at examining whether a smoke reservoir with the minimum d_{min} = 0.5 m could fulfil the requirement of smoke layer containment.

For the purpose of this study, the smoke exhaust rates prescribed by the BCA were used based on the assumed *h* values (see Figure 3 below).

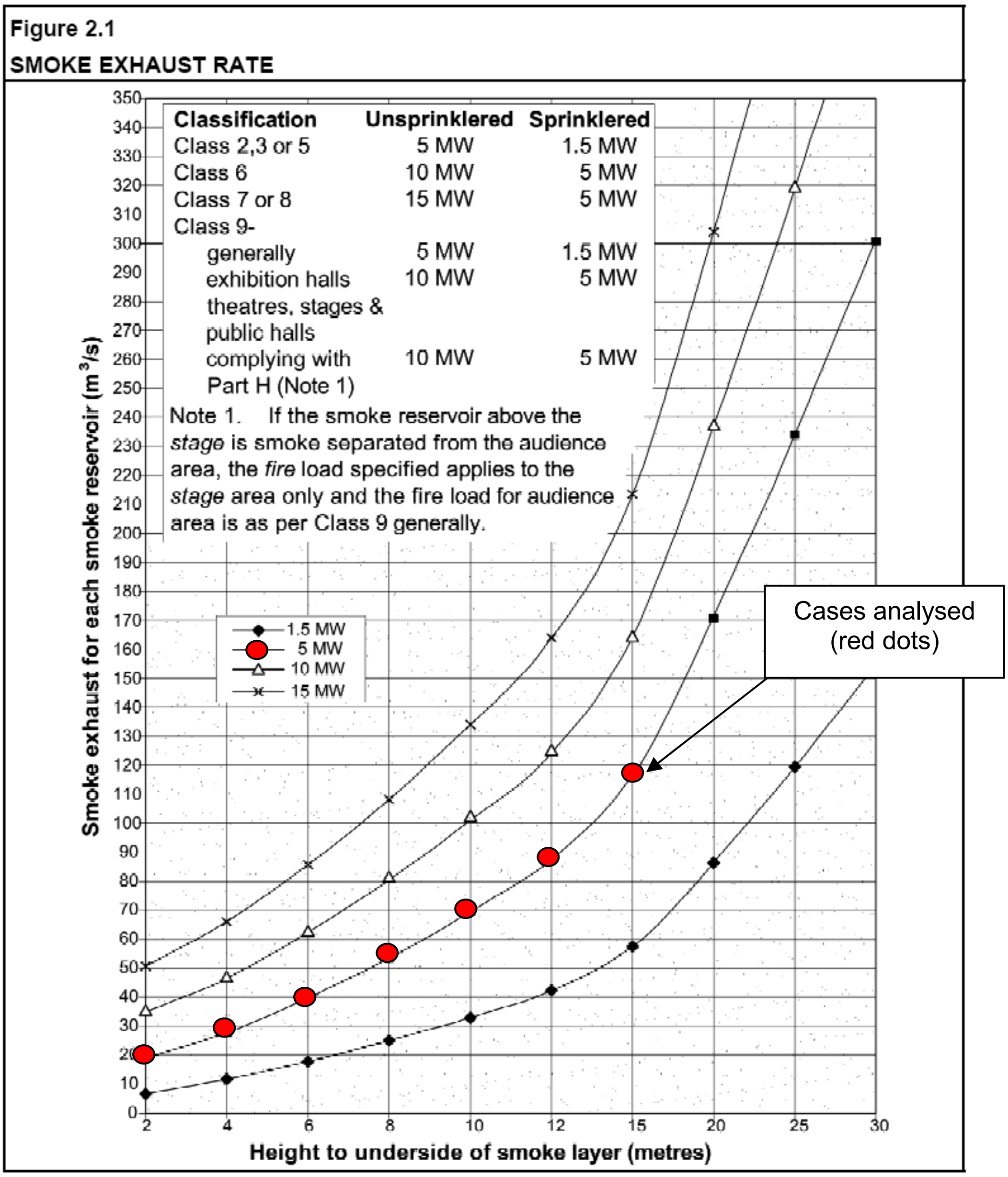

Figure 3 *BCA Spec E2.2b, Figure 2.1 Smoke Exhaust Rate [2]*

The results of the analyses in this series show that in all cases examined, the smoke spreads out of the reservoir. In each case, the *h* values measured in the analysis are smaller than the *h* values assumed at the start of the analysis, and *h* < (*H* – d_{min}).

The following figures show two examples with a relatively small and a relatively large assumed *h* values.

Figure 4 *Assumed h = 2 m, d = 0.5 m, t = 1800 s*

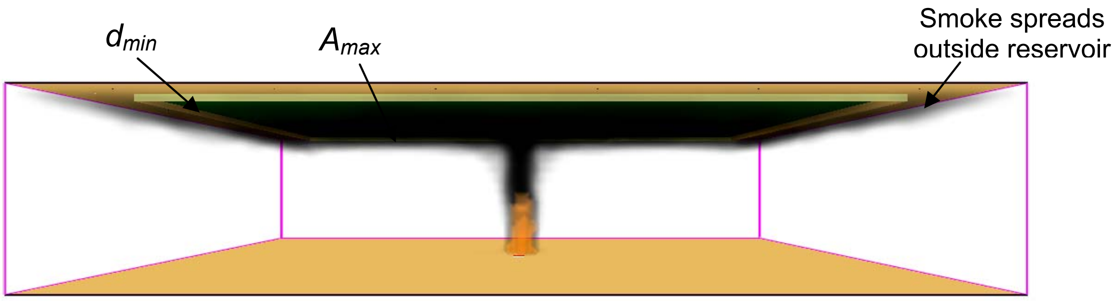

Figure 5 *Assumed h = 12 m, d = 0.5 m, t = 1800 s*

In all the cases examined, the smoke flows out of the reservoirs. This is despite the fact that the smoke reservoirs and smoke extraction are arranged in the most advantageous situation as discussed earlier. It can be expected that the performance is likely to be worse in less ideal situations. This leads to a firm conclusion that, with the BCA prescribed smoke extraction rate, the minimum reservoir depth of 0.5 m is insufficient to contain the smoke layer within the reservoir for a constant 5 MW fire and for the assumed *h* ranges considered.

SERIES 2: Incrementing *d*

Having completed Series 1, a second series of analyses were carried out to determine the minimum smoke reservoir depth required to contain the smoke layer for various *h* and the corresponding BCA smoke exhaust rate *V*.

This was achieved by incrementing *d* in steps of 0.5 m for each *h* value until the smoke layer is contained within the smoke reservoir (i.e. $h \geq (H - d)$).

The results of this analysis series shows that the *d* values required to contain the smoke layer within the reservoirs are significantly larger then the BCA prescribed minimum of 0.5 m. The findings are summarised in Figure 6.

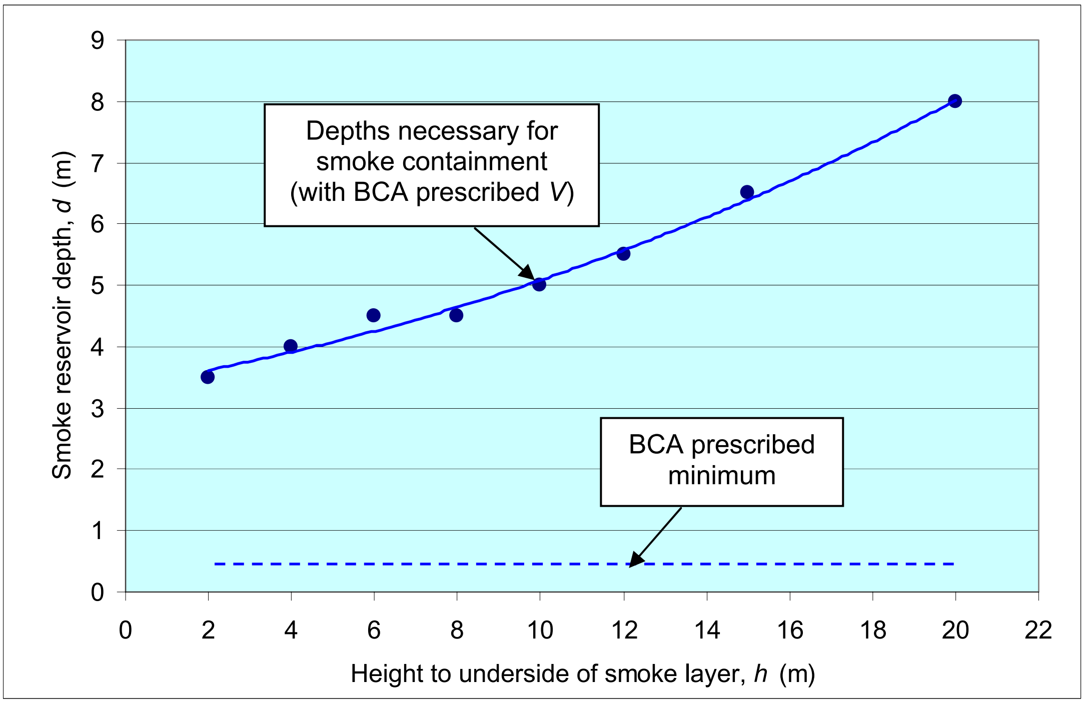

Figure 6 *Least Smoke Reservoir Depth Necessary for Containment of Smoke Layer*

The following figures shows two examples with a relatively small and a relatively large h values when the smoke layers are contained within the reservoirs.

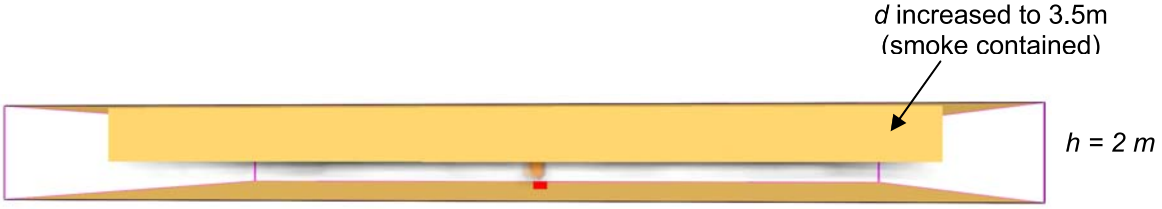

Figure 7 *Assumed h = 2 m, d = 3.5 m, t = 1800 s*

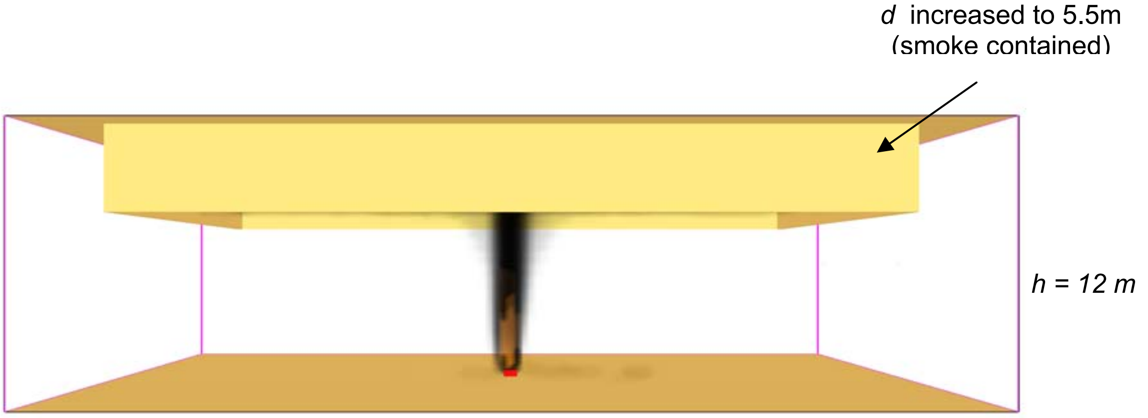

Figure 8 *Assumed h = 12 m, d = 5.5 m, t = 1800 s*

It is noted that in this analysis series, by keeping h constant, H increases with increasing d. This differs from the design process discussed earlier where H is fixed.

It is also important to remember that the situation analysed is an ideal case where the reservoir, fire and smoke exhaust are arranged in their most advantageous conditions. The *d* values in Figure 6 apply only to these best case scenarios. It is to be expected that the depth would be larger in less ideal situations.

SERIES 3: Incrementing *V*

A third series of analysis were carried out as a limited study to determine the smoke exhaust rate *V* necessary to contain the smoke layer for the BCA prescribed d_{min} of 0.5 m. For the purpose of this study, the case where *h* = 4 m was arbitrarily chosen.

The study was carried by incrementing *V* in steps of 30 m^3/s until the smoke layer is contained within the reservoir. Further analyses were then carried out to refine the limiting value to an accuracy of 5 m^3/s.

The results of the analyses are summarised in the table below.

Table 1 *Determining minimum V for d_{min} and h = 4 m*

V (m^3/s)	*Smoke Layer Contained within Reservoir (YES/NO)*
60	NO
90	NO
120	NO
150	NO
155	YES
180	YES

The following figures show two examples with different *V* values in the series.

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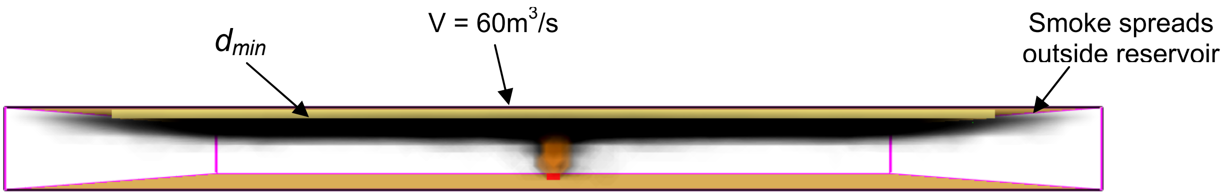

Figure 9 *Assumed h = 4 m, d = 0.5 m, V = 60 m^3/s, t = 1800 s*

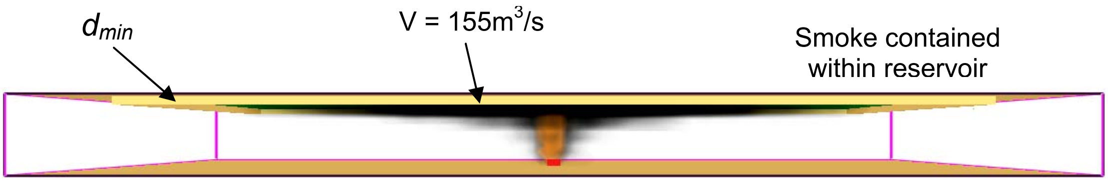

Figure 10 *Assumed h = 4 m, d = 0.5 m, V = 155 m^3/s, t = 1800 s*

It can be seen from this case study that, with the minimum *d* of 0.5 m, the smoke exhaust rate to contain the smoke within the reservoir is significantly higher than the corresponding value prescribed by the BCA.

It is noted that the resulting high exhaust rate is unlikely to be practical and may also introduce significant issues with make-up air. The practicality of increasing the smoke exhaust rate alone in containing the smoke layer is therefore questionable.

CONCLUSIONS

Parametric studies using CFD analyses have been carried out to examine the smoke filling of smoke reservoirs. The studies reveal that the, with the BCA prescribes smoke extraction rates, smoke reservoirs with a minimum depth of 0.5 m prescribed by the BCA are insufficient to contain the smoke layer within the reservoirs. For smoke layer containment, the necessary reservoir depths are significantly larger than the BCA prescribed minimum of 0.5 m. These were investigated in the parametric studies and the necessary depths for smoke containment in the ideal, best case situations are given in the paper.

Further studies were also carried out to investigate the smoke extraction for a smoke reservoir with a minimum depth of 0.5 m. The results show that the smoke extraction rate required for containment of smoke within the reservoir is significantly higher than that prescribed by the BCA. The high exhaust rate is unlikely to be practical and may also introduce significant issues with make-up air. The viability of adopting the minimum reservoir depth and increasing the smoke exhaust rate for containing the smoke layer is questionable.

In order to achieve the BCA requirements for smoke containment, reservoir depth greater than the BCA prescribed minimum is necessary. An iterative procedure will likely be required for determining the necessary reservoir depth d and/or smoke exhaust rate V to satisfy the BCA requirements. The results presented in this paper will provide useful guidance for the choice of initial trial values in the design process. They may also be useful for use in gauging the performance of smoke reservoirs in general.

REFERENCES

[1] McGrattan, K, B., Forney, G. P., Floyd, J.F, Hostikka, D., Prasad, K. “Fire Dynamic Simulator (Version 5) – User’s Guide”, National Institute of Standards and Technology, NIST 6784, 2008

[2] “Building Code of Australia. Volume 1 - Class 2 to Class 9 Buildings”, Australian Building Codes Board, 2008.

APPENDIX A – Determining *d* and *V* for known *H*