RECONCILING MENTAL HEALTH ANTI-LIGATURE & FIRE ENGINEERING REQUIREMENTS

(A NEW ZEALAND CASE STUDY)

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ABSTRACT

New Zealand's current focus on mental health has driven widespread improvements to existing facilities, in conjunction with the construction of new facilities. The presence of anti-ligature features has been significantly increased as part of these works to reflect society's developing expectations. Standard anti-ligature solutions are available for many features such as sprinkler heads, however, smoke detectors remain a challenge in high-risk zones. Adaptation of detectors to meet anti-ligature requirements has therefore resulted in a variety of innovations, including covers on smoke detectors. It's no secret these fixtures impact detector performance but this is often justified by a qualitative assessment in the Fire Engineering design. Given the vulnerability of users within these spaces, a more detailed assessment and quantified understanding is necessary. Using the limited data available and testing the sensitivity of assumptions, a series of scenarios were investigated using modelling. The findings are presented in this paper.

BACKGROUND

Noting the specific relevance of this paper to New Zealand fire engineering in mental health facilities, this section provides background for those who may be unfamiliar with these aspects.

New Zealand Mental Health & Fire Engineering

Significant changes in global accessibility to social media in recent years has driven a focus on mental health worldwide. Combining this with the psychological impact of the COVID-19 pandemic has resulted in an increased dependency on mental health services. In parallel, recent conversations led by the World Health Organization (WHO) have sought to emphasize the place mental health has as a basic human right [8]. Capital expenditure increases to prioritize mental health is therefore at the forefront of New Zealand healthcare budgets, allowing for a $2.6 billion (NZD) spend in 2024.

Allocation of this budget is varied but includes construction of new purpose-built mental health facilities and refurbishment of existing facilities. Refurbishment of existing facilities is necessary due to society's developing expectations on provision of suitable anti-ligature features. However, anti-ligature requirements (i.e. restricting the ability to tamper) are often in direct contrast to fire protection design which requires 'exposed' fittings to allow for identification / activation in the event of a fire. Balancing compliant fire engineering designs with satisfying anti-ligature requirements is becoming more challenging as a result, with fixtures previously dubbed as anti-ligature having to downgrade to "anti-tamper".

It is therefore common practice in New Zealand to apply a 'risk zone' approach. This designates highly staffed areas / open / circulation areas as low-risk zones and allows for standard fire protection fixtures. Comparatively, bedrooms and ensuites which have limited staff visibility are designated as high-risk zones, which require anti-ligature consideration.

However, high risk zones cannot simply be exempt from fire protection fixtures to satisfy anti-ligature requirements. Anti-ligature sprinkler heads have therefore been developed to combat this and serve as a practical solution to satisfying both fire engineering and anti-ligature requirements. Whereas smoke detectors continue to demand greater investigation.

At present there are two solutions. The first and most widely utilized, is the application of aspirating smoke detection systems. While this satisfies both anti-ligature and fire engineering requirements, this also causes operational difficulties due to service users tampering / blocking sampling points. They also involve a high capital expenditure which is not always suitable with limited budgets, especially when refurbishing existing buildings. The alternative solution, and the focus of this report, has been provision of smoke detector covers on standard point type smoke detectors. It's commonly expected that these covers impact the detector's performance, but this is often qualitatively justified in the fire engineering design – particularly for existing buildings.

Identifying the current shortfall in this approach, and the opportunity to develop a better outcome for mental health in New Zealand, the following investigation was initiated. This applied computational fluid dynamics (CFD) models, notably using Fire Dynamics Simulator (FDS), to quantify the impact different smoke detector covers may have on detector performance.

New Zealand Regulatory Framework

The following section provides a brief outline of New Zealand's regulatory framework, as the governing requirements for the case study. This follows a tiered system as illustrated in the figure below. The overarching tier, the Building Act (2004), provides the primary legislation governing all building construction. The Building Act imposed the secondary legislation, Building Regulations 1992, which included Schedule 1 (Building Code). The New Zealand Building Code (NZBC) then acts to defined performance criteria that buildings must demonstrate are met before being accepted by the Building Consent Authority.

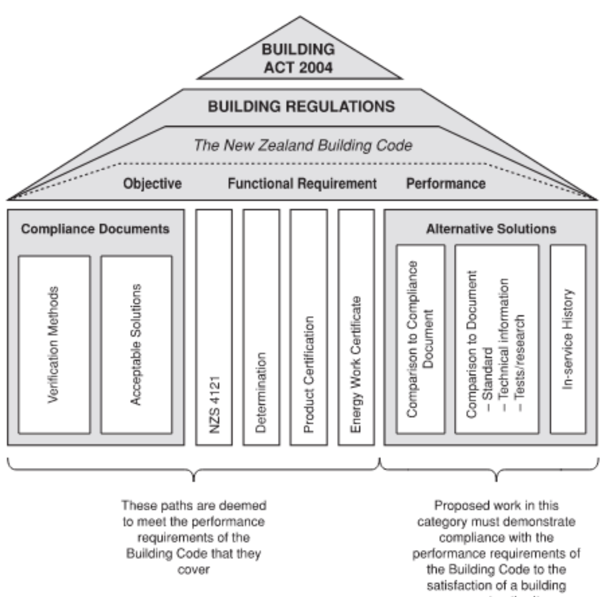

Figure 1: New Zealand Regulatory Framework Illustration [9]

The New Zealand environment therefore contains multiple compliance pathways by following either 'deemed to satisfy' compliance documents (Verification Methods or Acceptable Solutions), or by applying an Alternative Solution. The unique nature of mental health facilities and their service users typically requires an Alternative Solution approach. Although this often relies on aspects of the Acceptable Solutions / Verification Methods. There are also limited dispensations to apply an Acceptable Solution approach when altering an existing mental health facility. Focusing on Alternative Solutions, compliance with the NZBC performance criteria includes satisfying Clause C4 'Movement to place of safety'. This corresponds to the ability of the design to facilitate evacuation prior to failure of tenability criteria.

In the context of a sprinkler protected mental health facility, as was the case for this study, NZBC Clause C4 defines failure as when the fractional effective dose of carbon monoxide (FED_{CO}) exceeds 0.3 when typically measured at 2.0m above the relevant floor level. No consideration of visibility is required [1]. The following has focused on smoke detector response delay with reference to its impact on FED_{CO} as a result.

METHODOLOGY

This section describes the analysis approach, including assumptions made, when developing the CFD models for quantifying smoke detector cover impacts for different configurations. It is noted that all simulations were undertaken using FDS (Version 6.8.0) and created using Pyrosim (Version 23.2.0816).

Building Geometry & Model Domain

It was not intended for this investigation to be specific to a given mental health facility but rather broadly reflect the general design of these buildings in New Zealand. A typical bedroom geometry was therefore produced for the model, based on reviews of several new and existing facilities within New Zealand. This identified average sizes, and their configuration. The result, and its FDS representation, is shown in the figure below. For simplicity of the model, the ceiling space was also ignored given tenability conditions within this space were not relevant.

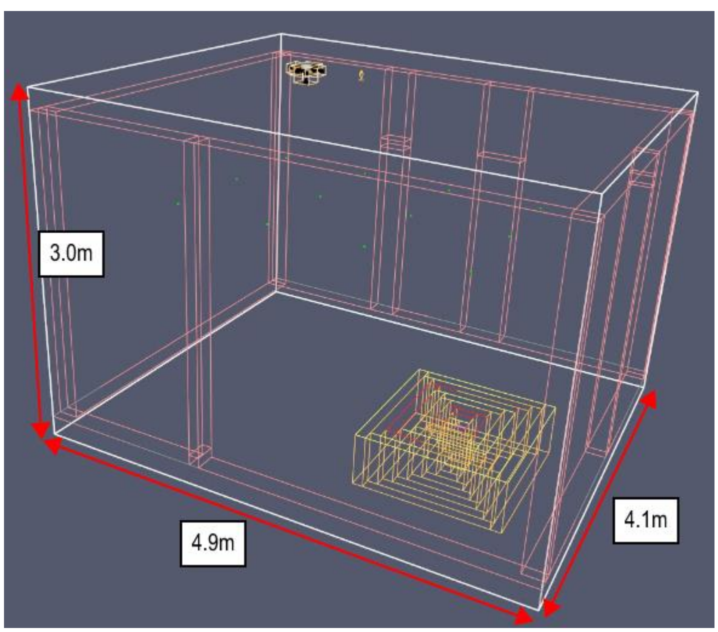

Figure 2: Indicative FDS Domain & Bedroom Geometry

General Assumptions / Parameters

To provide a standard baseline for the simulations, the following variables were assumed. Consideration of how these may impact the results has not been investigated at this time but is not expected to produce a significant impact due to the building geometry.

- Ambient Temperature: 20°C
- Ambient Pressure: 101,325 Pa
- Wind: Excluded
- Relative Humidity: 40%

In addition, several key parameters were kept consistent throughout all simulations as outlined in the table below. Values for these were calculated in accordance with the Verification Method C/VM2 as appropriate for New Zealand. Specific deviations from this include reducing the smoke detector spacing from the specified 7m due to room dimension limitations. The smoke detector was instead placed 200mm off the wall to provide the maximum spacing from the fire while being in accordance with the New Zealand Standard 4512:2021 for fire detection and alarm systems. Refer to these documents for further details on requirements. Again, it is expected that altering these parameters to be specific to other countries or refining the solution procedure (i.e. using direct numerical simulation / refined mesh) would affect the results. Despite this, the broader analysis presented is still relevant.

It is noted Version 6.8.0 of FDS is restricted to rectangular mesh distribution. Investigation into different shapes (i.e. rectangular vs. pyramidal vs. circular) could not be undertaken as a result and presents an opportunity for future analysis. However, this also defined the cover geometry to allow for alignment with the mesh configuration and produced a rectangular cover as illustrated in Figure 3. This was kept consistent across all models while the free area was varied.

Table 1: FDS Baseline Parameters Summary

Model Parameter	Value
Wall Leakage	0.1% Area
Door Leakage	10mm Gap Around Door
Cover Leakage	HVAC Model
Smoke Detector Characteristics	Optical Density at Alarm - 0.097m^{-1} (20% OBS) Radial Distance - 3.8m Distance Below Ceiling - 25mm Type – Heskestad Ionization (L=1.8m)
Materials	Walls & Ceiling – Plasterboard Floor – Concrete Detector Cover – Steel (1mm)
Mesh Dimension	0.1m
Fire	Heat of Combustion (ΔH_C) – 20 MJ/kg Medium Growth Rate (refer "Model Scenarios" below for details) HRRPUA – 1000kW/m^2 Discretized Rectangular Burner
Species Yield	CO – 0.04 kg/kg Soot – 0.07 kg/kg
Simulation Mode	Large Eddy Simulation (LES)

The most critical of these parameters, and the basis for this investigation, is use of the HVAC sub-model. As noted in the section below, anti-ligature smoke detector covers can require hole sizes as low as 2mm to meet Health Guideline standards. Even when accounting for the total free area of a given cover, this area is smaller than that which could be resolved by the mesh grid. The HVAC sub-model was therefore applied to capture the sub-grid 'leakage' of the covers. This followed the simplified leakage approach similar to that described in the FDS User Guide for door leakage [6]. Each face of the cover was assigned a free area equating to that particular cover (see 'Model Scenarios' below) and modeled as a single duct with the terminal nodes defined at either face of the cover. The cover faces themselves were 0.1 x 0.1m block obstructions. Refer to the figure below which illustrates this configuration.

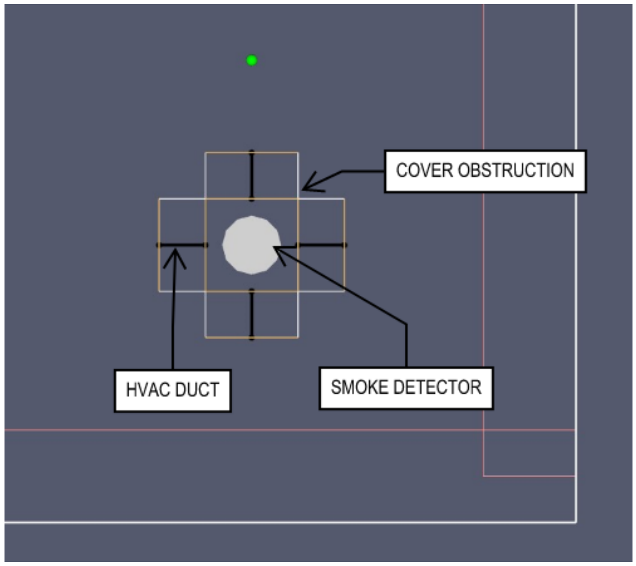

Figure 3: Indicative Smoke Detector Cover Layout

The use of the Heskestad Ionization type smoke detector is also important. This relies on a single lag time based on the external free stream velocity and a characteristic length of the detector that is dependent on detector geometry. Currently, manufacturer's do not provide details on characteristic length and as such this investigation has used the default FDS characteristic length of 1.8m. Lag time can play an important part in smoke detector activation, hence the implications of using the FDS default is discussed in later sections. Similarly, it has been proposed that a single lag time is not sufficient, with Cleary identifying shortfalls with this approach at velocities less than 0.5 m/s [2,5]. Further discussion on this is also provided in later sections.

Model Scenarios

Smoke detector covers currently available vary significantly between companies and countries - not only in bulk shape and size, but also in their perforations. Given activation of smoke detectors is reliant on smoke reaching the detector, perforation size directly correlates to the potential impact a cover may have. This alone is not sufficient to dictate the influence on smoke detector performance however, with the number of perforations also critical. Accounting for both factors can be achieved by consideration of free area. Hence, smoke detector cover free area was chosen as the primary variable for this analysis, with different simulation scenarios created to quantify the relationship between smoke detector performance and cover free area.

Reviewing smoke detector covers freely available online produced limited data on their perforation size and number of holes, with only one having the dimensions necessary to calculate these values. Based on this data though, the cover qualified as anti-ligature by current Health Guideline standards. This cover (Cover 1) formed the first scenario for investigation, with the sensitivity of the results on cover free area varied around this baseline.

While free area was the primary focus of analysis, fires are not prescriptive and differ based on numerous environmental factors. Fire growth rate is a crucial component of this, with different growth rates producing smoke with different temperatures and velocities. Again, it is expected this would influence the impact of a smoke detector cover since lower temperature / velocity smoke would have less energy available to penetrate the cover. It was therefore also desired to quantify the relationship between cover free area and fire growth to the smoke detector performance.

Commonly in fire engineering, the t-squared (t^2) fire growth model is applied, with the rate itself assigned based on the use / type of space within the building. For a mental health facility bedroom fire, the New Zealand C/VM2 approach assigns a fast t^2 growth rate [7]. Comparatively, physical test data has illustrated a bed / mattress fire is more comparable to a medium t^2 growth rate [3,4]. Scenarios considered for this assessment therefore included slow, medium, and fast growth rates to suitably capture the range of credible fire developments. Specific assessment of a realistic fire (i.e. growth and decay and smoldering) was discounted at this stage since the results are focused on the short-term impact of detector covers as opposed to long-term tenability.

Combining analysis of the effect of both smoke detector cover free area and fire growth rate, ten (10) scenarios / simulation configurations were produced. Table 2 below summarizes these.

Table 2: Model Scenarios Summary

Model Scenario	Cover Configuration (total free area)	t^2 Fire Growth Rate
Scenario 1	No Cover	Medium (0.0117kW/s^2)
Scenario 2	Cover 1 (0.009m^2)	
Scenario 3	Cover 2 (0.05m^2)	
Scenario 4	Cover 3 (0.0125m^2)	
Scenario 5	Cover 4 (0.018m^2)	
Scenario 6	Cover 5 (0.0045m^2)	
Scenario 7	No Cover	Fast (0.0469 kW/s^2)
Scenario 8	Cover 1 (0.009m^2)	
Scenario 9	No Cover	Slow (0.00293 kW/s^2)
Scenario 10	Cover 1 (0.009m^2)	

RESULTS

The sections below detail the results of each of the scenarios outlined above and how they compare based on either cover configuration or fire growth rate. Brief commentary is also provided on a high-level mesh sensitivity analysis and review of how the HVAC model approach compared to a block obstruction cover with passive holes.

Cover Configurations

Figure 4 illustrates the results from each of Scenarios 1 – 6 with their corresponding smoke detector cover configuration. This clearly demonstrates any form of anti-ligature cover has a considerable impact on the detection performance of a smoke detector. Only Cover 2, with a free area of 0.05m^2, showed essentially equivalent performance. However, to achieve this free area would require perforations that could only be classed as anti-tamper and would be unsuitable for mental health facilities due to current anti-ligature expectations as a result.

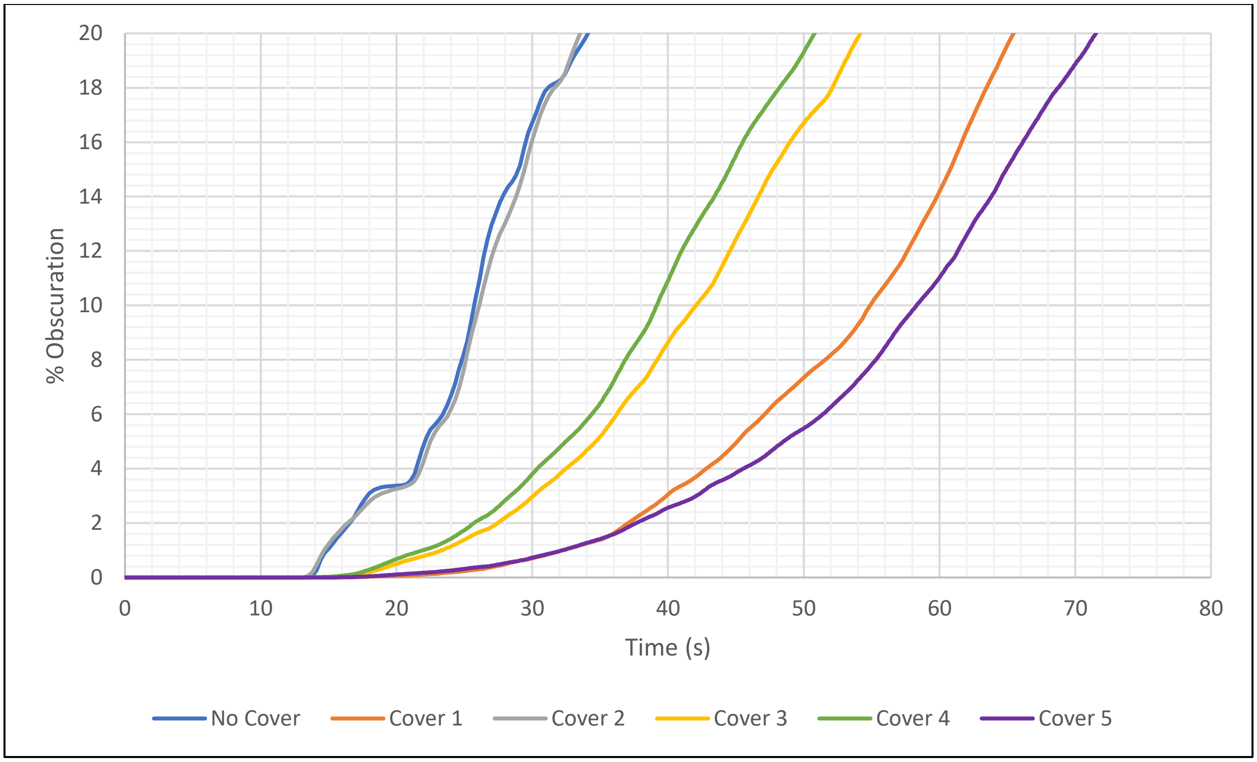

Figure 4: Plot of Smoke Detector % Obscuration Against Time for Cover Scenarios

Considering a 20% obscuration (OBS) alarm threshold, the delay associated with each cover is described in the table below. The free area of Cover 3 is double Cover 1, and the free area of Cover 5 is half that of Cover 1, however the results do not maintain this factor of difference. This illustrates the correlation between cover free area and detector performance is not linear.

Table 3: Summary of Cover Configuration Detector Activation

Model Scenario	Cover Configuration (total free area)	Detector Activation Time (20% OBS)	Delay (s)	Multiplier
Scenario 1	No Cover	33.96	-	-
Scenario 2	Cover 1 ($0.009m^2$)	65.3	31.34	1.92
Scenario 3	Cover 2 ($0.05m^2$)	33.4	-	-
Scenario 4	Cover 3 ($0.0125m^2$)	54.14	20.18	1.59
Scenario 5	Cover 4 ($0.018m^2$)	50.76	16.8	1.49
Scenario 6	Cover 5 ($0.0045m^2$)	71.48	37.52	2.1

Focusing on Scenario 2, as the anti-ligature cover with 2mm perforations for which there was data available online, provision of this cover could be expected to delay smoke detector activation by 1.9 times of the detection time without a cover. Further, to achieve equivalent performance to no cover at 20% OBS ($0.097m^{-1}$) would require a sensitivity of 1.5% OBS ($\sim 0.007m^{-1}$). This is not currently achievable with detectors available in the market, but more importantly, is not a practical solution given the likelihood of spurious alarms at this low threshold. Such an approach would also remove the inherent safety factor provided by modelling smoke detectors per C/VM2. This is because C/VM2 specifies an alarm threshold of 20% OBS despite standard detectors typically having a threshold of 7% OBS. Based on this modelling, there is no practical way of achieving an equivalent smoke detector performance when fitted with a cover, regardless of its free area. The obvious exclusion to this is any cover which is essentially 100% free area, such as for Cover 2.

Reviewing this in terms of tenability, Table 4 demonstrates the smoke detector covers continue to have a considerable impact. While FED_{CO} is well within the tenability limit assigned by the NZBC (< 0.3), these results are at the time of smoke detector activation and therefore represent the early stages of fire growth. This difference in FED_{CO} would be maintained throughout the required safe egress time as a result given occupant evacuation would be delayed due to the corresponding smoke detector activation delay. It can be inferred from this that tenability conditions would be considerably worse at each key evacuation point in situations involving smoke detector covers. Should staff be required to assist, visibility is also expected to be more challenging.

Table 4: Summary of Cover Configuration Tenability at Detector Activation

Model Scenario	Cover Configuration (total free area)	Average FED_{CO} at Detector Activation (20% OBS)	Multiplier
Scenario 1	No Cover	0.000052	-
Scenario 2	Cover 1 (0.009m^2)	0.000760	14.6
Scenario 3	Cover 2 (0.05m^2)	0.000049	-
Scenario 4	Cover 3 (0.0125m^2)	0.000420	8.1
Scenario 5	Cover 4 (0.018m^2)	0.000360	6.9
Scenario 6	Cover 5 (0.0045m^2)	0.001200	23.1

Fire Growth Sensitivity

The results from the simulations with varying fire growth rates (Scenarios 1,2 and 7 – 10) can be found in Figure 5. Similarly, comparison between the growth rates at the alarm threshold (20% OBS) is described in Table 5. These results maintain the relationship evidenced in the cover configurations scenarios, with each fire growth rate resulting in a smoke detector activation multiplier of at least 1.5 times that of an uncovered detector.

The multiplier applied to detector activation delay is relative only to that fire growth rate (i.e. within the covered and uncovered medium fire scenarios). This appears to indicate there is no strong correlation between the fire growth rate and the delay multiplier. The cover free area is therefore the governing variable rather than growth rate.

Table 5: Summary of Fire Growth Rate Detector Activation

Model Scenario	Cover Configuration (total free area)	t^2 Fire Growth Rate	Detector Activation Time (20% OBS)	Delay (s)	Multiplier
Scenario 1	No Cover	Medium (0.0117 kW/s^2)	33.96	-	-
Scenario 2	Cover 1 (0.009m^2)		65.30	31.34	1.92
Scenario 7	No Cover	Fast (0.0469 kW/s^2)	22.94	-	-
Scenario 8	Cover 1 (0.009m^2)		40.46	17.52	1.76
Scenario 9	No Cover	Slow (0.00293 kW/s^2)	52.92	-	-
Scenario 10	Cover 1 (0.009m^2)		92.00	39.08	1.74

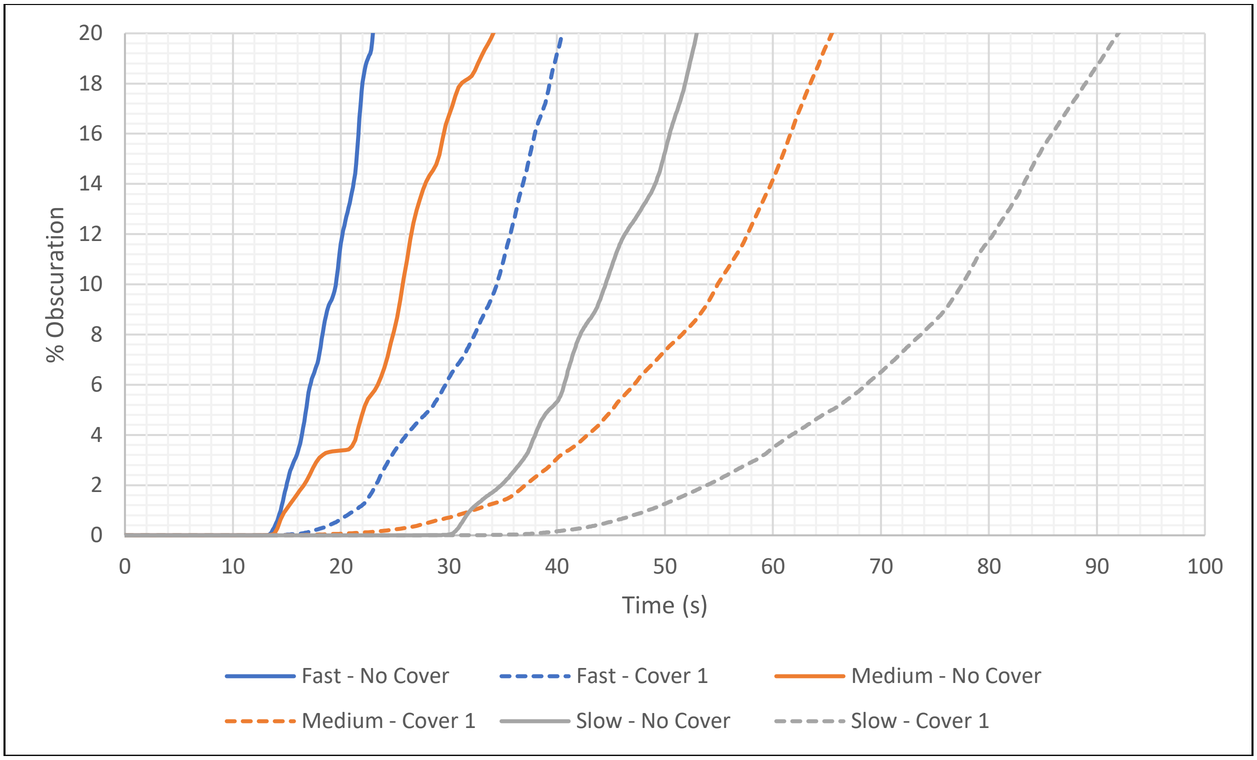

Figure 5: Plot of Smoke Detector % Obscuration Against Time for Fire Growth Rate Scenarios

HVAC Model Sensitivity

The quantified impact of a smoke detector cover, as highlighted above, is significant. It was necessary to test the sensitivity of the HVAC model approach as a result. Scenario 4 (Cover 3) was chosen for this purpose. The free area of this cover was based on that which could be achieved using block obstructions and holes within a 0.05m mesh. This 'passive' cover therefore did not use the HVAC model but rather created holes within the cover obstruction that were a single mesh grid on each face, equating to the same free area as the HVAC model cover. The plot below illustrates the difference in results between these two approaches. These show generally good agreement, with the maximum difference in % OBS not exceeding 6.7%, and an average difference of 2% OBS. Considering this in terms of the delay in time between the two results - for a given % OBS, the passive approach didn't reach the same % OBS until a maximum of approximately 8 seconds later. This corresponds to an 'error' of 20%.

Applying this broadly to the previous results discussed for cover configurations, an anti-ligature smoke detector cover (i.e. Cover 1) could reasonably be expected to delay smoke detector activation up to 2.3 times (i.e. multiplier of 1.92 plus an 'error' of 20%).

It may be that this difference between the two results can be attributed to the smoke detector model utilized. As mentioned in Section "General Assumptions / Parameters", the Heskestad ionization detector was applied, however as shown in the figure below, velocity results were typically below 0.5m/s. Hence, as identified by Cleary et al., a two-parameter smoke detector model may be more appropriate to capture the increased lag time at these low flow speeds [2]. On this basis, it is expected that applying a Cleary model smoke detector would reduce the difference between these two results and is an avenue for further research. Until such time, consideration should be given to allowing for at least a 20% error within the time delay multiplier.

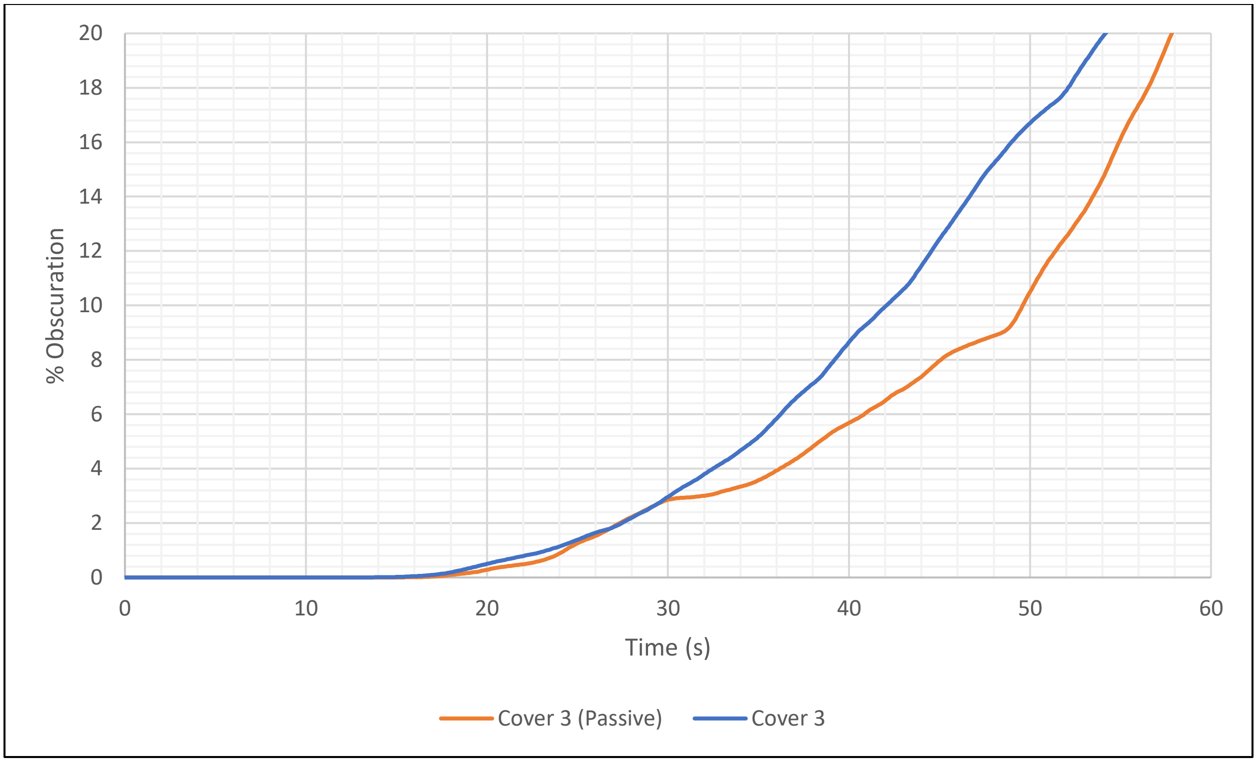

Figure 6: Plot of Smoke Detector % Obscuration Against Time for a Passive Cover Relative to the HVAC Model

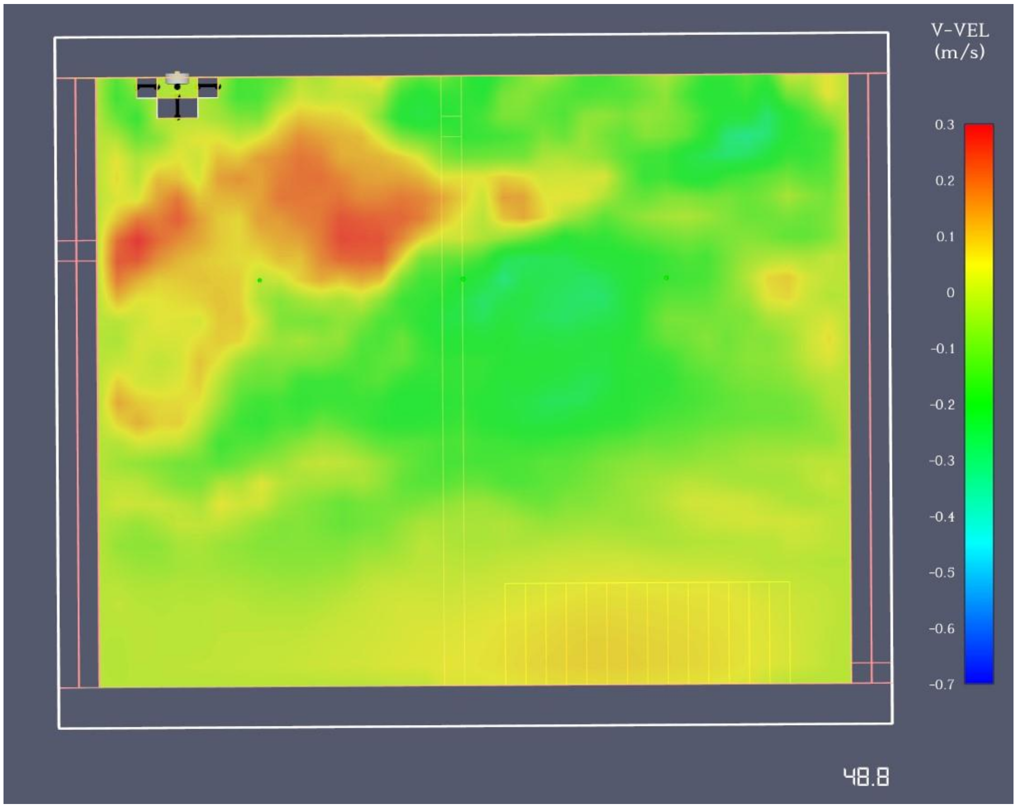

Figure 7: 2D Slice File of Cover 1 Velocity Contour

Mesh Sensitivity

The sensitivity of the results to mesh resolution was also briefly investigated through the % OBS measured by the smoke detector. This was reviewed for Scenario 1 (no cover) to avoid introducing errors that may have otherwise been produced by the HVAC model resolving sub-grid movement that would not physically be sub-grid with the more resolved meshes.

Three mesh resolutions were simulated being 0.2m, 0.1m, and 0.05m. The results of these simulations can be seen in Figure 8. Evidently, there was substantial variation between the 0.2m mesh grid compared to the others. Comparatively, minimal variation can be seen between the 0.1m and 0.05m mesh. For the purposes of this study, this was considered to demonstrate suitable mesh convergence to be able to capture the bulk smoke movement and justified a 0.1m mesh resolution for all scenarios.

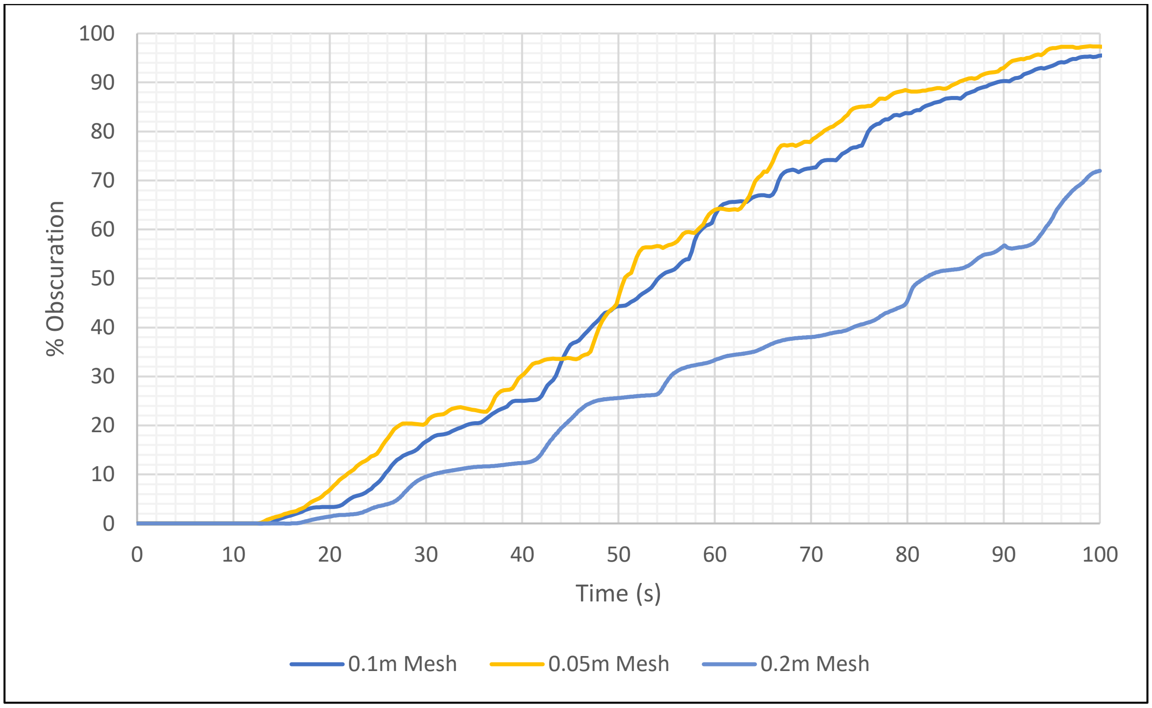

Figure 8: Plot of Smoke Detector % Obscuration Against Time for Mesh Configurations

CONCLUSIONS

Balancing anti-ligature requirements with fire engineering requirements in mental health facilities in New Zealand is becoming increasingly challenging. Focus at present is on reconciling smoke detector requirements given current solutions are either expensive (aspirating systems) or not suitably justified in the design (qualitative support of smoke detector covers). Physical testing of smoke detector covers is also cost / time prohibitive for many projects. This paper has investigated the viability of using FDS' HVAC model to quantify the impact of smoke detector covers as a means of satisfying both anti-ligature and fire engineering requirements.

Considering the results presented above, it is proposed they support the use of the HVAC model to capture the broad impact of a smoke detector cover. It should be noted there are several factors that are likely to impact smoke detector performance (such as cover orientation, detector chamber lag time) which have not been quantified in this study. These aspects, as well as consideration of how combining the perforations as a total free area compared to discrete perforations, present opportunities for further study.

Despite this, these initial results identified the time delay multiplier of an anti-ligature cover could be up to 2.3 times that of an uncovered smoke detector, dependent on the rate of fire growth and cover free area. The results also identified that simply lowering the sensitivity of a covered smoke detector to try match the equivalent performance of an uncovered detector is not physically achievable. Such an approach should account for the operational impact of increased spurious alarms and the removal of an inherent safety factor provided by the modelled alarm threshold relative to realistic detector performance.

While this study and time delay multiplier provides a strong framework, this is specific to the bedroom modelled in this case study and should not be applied directly to fire engineering designs. This should instead serve as a demonstration that modelling / quantification of the impact of smoke detector covers is necessary in fire engineering designs, but more importantly, achievable.

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