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SMOKE MANAGEMENT ISSUES IN BUILDINGS WITH LARGE ENCLOSED SPACES

Roger Harrison*, BRE Certification, UK

and

Michael Spearpoint, Department of Civil Engineering, University of Canterbury, New Zealand

ABSTRACT

Buildings that provide sporting, entertainment, and leisure facilities (e.g. sports arenas, exhibition halls, etc) can often contain large enclosed spaces or voids. In the event of a fire, these buildings often require the use of a smoke management system to provide conditions for safe means of escape for the building occupants.

This paper raises a range of issues relating to smoke management in buildings with large enclosed spaces, including smoke management methods, design scenarios and some simple calculation methods.

Experience of actual installed systems in real buildings has led to concerns on the efficacy of some smoke management systems, especially over the lifetime of a building. This paper discusses some of these concerns, real examples of sources of failure, and the importance of proper documentation, commissioning, maintenance and testing of these systems. As a way of addressing these concerns, a process validation methodology is presented to evaluate the design, the designer, the implementation of the design, and the long-term management, operation and maintenance of such systems.

1 INTRODUCTION

The majority of deaths in fire are due to the inhalation of smoke. Smoke causes direct visual obscuration by absorbing and scattering light, reduces the visibility of escape signs and may cause pain to the eyes and respiratory tract. Smoke may also reduce or eliminate the capacity for building occupants to escape due to reduced visibility and thermal hazards. Another consideration is the toxic hazard of asphyxiant gases (such as carbon monoxide, carbon dioxide and hydrogen cyanide).

The controlling physical processes in the movement of smoke in a fire are:

- Buoyancy forces - due to the density difference between hot gases and ambient air.
- Air expansion forces - generated by heat from the fire.
- Internal building airflow - e.g. due to stack effect, lift motion.
- Forced ventilation - e.g. smoke exhaust, HVAC, wind effects.

* Author for correspondence, contact at: brec@wbl.co.nz

Buildings that provide sporting, entertainment, and leisure facilities can often contain large enclosed spaces or voids. These large enclosed spaces can occupy many storeys in height. In the event of a fire, the lack of physical separations (e.g. walls, floors) can allow smoke and hot gases to move unimpeded to locations far removed from the fire source. These types of buildings are also likely to contain significant numbers of people and can contain large quantities of combustible materials. Therefore, controlling the production and transport of smoke is of particular importance.

The use of a smoke management system in buildings with large enclosed spaces can provide conditions to allow safe means of escape, by ensuring adequate separation between the escaping occupants and the hot smoky gases from a fire. Property protection can primarily be achieved by providing improved conditions for effective fire-fighting operations in addition to limiting the spread and temperature of the smoke.

The design of these systems requires appropriate calculation methods to predict the volume of smoky gases produced in order to determine the required exhaust fan capacity or ventilator area for a required design layer height. There are considerable differences in the calculated smoke production rates depending upon the chosen design fire scenario and calculation method. Whilst over-sizing of the required smoke exhaust can be uneconomical, under-sizing can compromise life safety and property protection.

2 SMOKE MANAGEMENT METHODS

There are a number of different smoke management methods available for buildings which contain large enclosed spaces. Morgan et al [1] describe various alternative approaches such as:

- <u>Smoke and heat exhaust ventilation</u> - Smoke management in buildings with large enclosed spaces is generally provided by a Smoke and Heat Exhaust Ventilation System (SHEVS). Hot smoky gases are collected at high level and vented to the outside (see Figure 1). Supply of inlet replacement air below the smoke layer is crucial, and must be included in the design along with the sizing of the smoke venting system. Natural or mechanical exhaust ventilators can be used, with the latter required, for example, if external wind effects are likely to reduce the efficacy of smoke exhaust. Some form of physical smoke containment may also be required, for example, using smoke curtains or downstands to create smoke reservoirs. A critical design parameter for this type of system is the clear layer height between the occupants and the smoke layer interface. Guidance on acceptable clear layer heights varies worldwide [2-5], but is usually of the order of 2 to 3 m above the highest egress route open to the enclosed space.

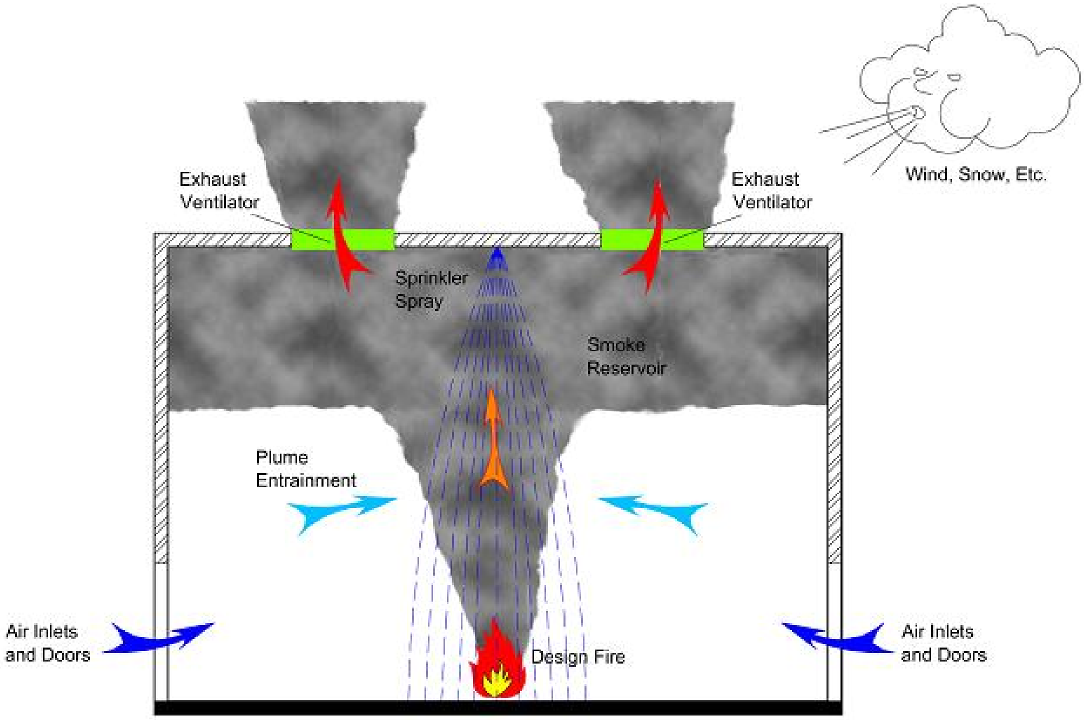

Figure 1: Smoke and Heat Exhaust Ventilation (courtesy of NV IFSET SA)

- Smoke and heat exhaust from each storey separately - In some cases it may be impractical to provide smoke exhaust ventilation from the space if the height of rise of the smoke layer from the floor is too large. It may be beneficial to prevent smoke from entering the space altogether. This can be achieved by the use of strategically placed smoke curtains around the enclosed space at each storey, and providing smoke exhaust ventilation from each storey separately.

- Depressurisation - Where the boundary between a large enclosed space and adjacent areas are linked by small openings (e.g. doors gaps, leaky façade), it is possible to prevent smoke from travelling through these openings to adjacent areas by reducing the pressure of the gases in the smoke layer. In this case, smoky gases are removed from the smoke-affected space in a way that maintains the desired pressure differences and/or air speeds across leakage openings between that space and adjacent spaces. This approach is known as depressurisation. This technique is similar to that employed for natural environmental ventilation in atrium buildings [6].

- Temperature control ventilation from the large enclosed space - This strategy is used when the height of the smoke layer above the floor is not a critical design parameter. In this case, smoke exhaust can be used to achieve a maximum value of the temperature of the layer of smoky gases. This approach allows the use of materials which would otherwise be damaged by hot gases (e.g. façade materials which are not fire-resisting).

- Smoke filling - This approach can be applied to buildings which have particularly large volumes, such that smoke ventilation may not be necessary. This strategy becomes viable when smoke can be contained in a roof void for the duration of the required safe egress time for the occupants of the building. In this case, the height of the smoke layer may not reach an unacceptable value before the fire consumes the available fuel. This approach assumes that the fire grows at a predictable rate. Klote and Milke [7] provide empirical relationships to determine the smoke layer height above the fire with respect to time for both steady and growing fires. This strategy should only be used if the designer can demonstrate by calculation that smoke ventilation is not necessary.

- Smoke clearance - This approach provides sufficient ventilation to remove smoke from the enclosed space after the fire has been suppressed.

3 DESIGN FIRE SCENARIOS

The volume of smoky gases generated from a fire within a large enclosed space is highly governed by the amount of air entrained into the rising smoke plume. The amount of air entrained into the plume will depend on the configuration of the plume produced. Milke [8] identified five configurations of smoke plume which may exist within buildings with large enclosed spaces, these are:

- Axisymmetric plume - An axisymmetric plume is generally expected from a fire located near the centre of a space or room. Entrainment of air will occur over the full height of the plume until it reaches the interface with a smoke layer which may have formed above (see Figure 1).

- Spill plume - If a fire were to occur in a room (e.g. a shop unit, concession area) fronting onto a large enclosed space, a horizontally moving buoyant layer of hot smoky gases will form within that room (see Figure 2). This layer will spread laterally and flow toward the opening connecting to the space. If there are no smoke control measures to confine the smoke layer to the room of origin, this horizontally moving layer will flow out of the opening. If a balcony exists beyond the compartment opening, smoke will flow beneath the balcony. The smoke flow will then rotate around the free edge of the balcony. The smoke will then rise vertically as a plume into the space and entrain large quantities of air. This type of plume is commonly known as a balcony spill plume.

  Spill plumes can be categorised into two groups: balcony and adhered spill plumes, depending on whether a balcony is present from the room opening adjacent to the enclosed space. Figure 3 shows a schematic drawing of an adhered spill plume. In this case, there is no balcony present at the room opening and the subsequent plume adheres to the vertical surface above the opening as it rises.

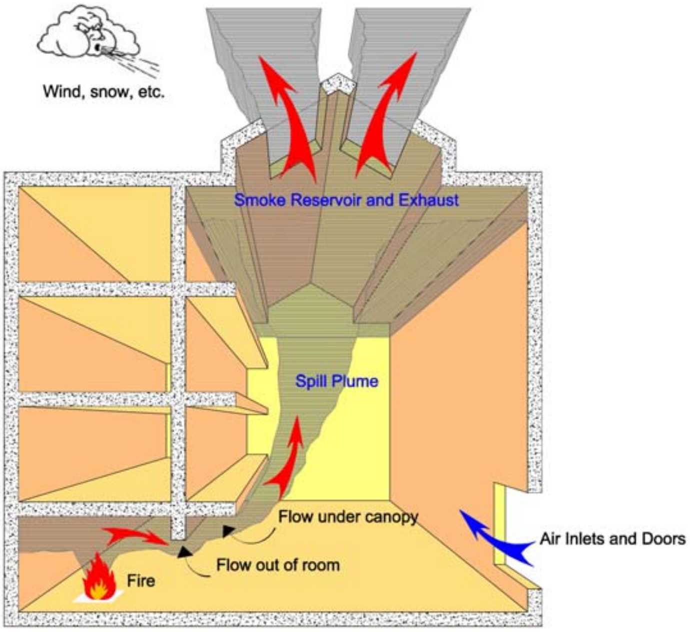

Figure 2: A balcony spill plume (courtesy of NV IFSET SA)

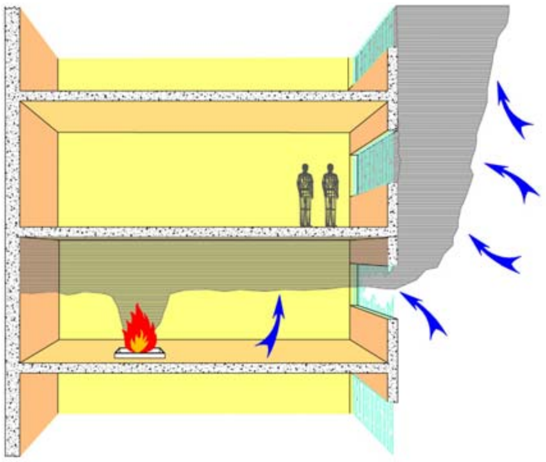

Figure 3: An adhered spill plume (courtesy of NV IFSET SA)

- Wall plume - A plume which is generated from a fire against a wall is known as a wall plume. Zukoski [9] developed a wall plume entrainment correlation based on "mirror symmetry". Work by Poreh and Garrad [10] as highlighted that further research on wall plume entrainment is desirable.

- Corner plume - A plume which is generated from a fire located in the corner of a room, where the walls form a 90^o angle, is known as a corner plume. Zukoski [9] treated corner plumes in a similar manner to a wall plume with the use of "mirror symmetry" for plume entrainment. Again, work by Poreh and Garrad [10] has demonstrated that further research is desirable for corner plume entrainment.

- Window plume - A window plume is a plume which flows from a window (or doorway) into an enclosed space [7]. Window plumes are generated from post-flashover fires [11] and therefore only have limited applicability. The window plume entrainment correlation is given by Klote and Milke [7].

4 SIMPLE CALCULATION METHODS

The designer has a number of options available for evaluating the performance of a smoke management system. When applying systems to 'standard' type geometries, various guidance publications [e.g. 1,2,12,13] provide simple 'hand calculation' methods which can be used. This section will focus on some of these simple 'hand calculation' methods available for the axisymmetric and spill plume design fire scenarios.

For complicated and novel designs, or when the smoke management system deviates from 'standard' configurations, it may be necessary for the designer to model the movement of smoke using either reduced scale physical modelling or computer modelling. However, these methods are beyond the scope of this paper and will not be further discussed.

4.1 Axisymmetric plume

Morgan and Mason [14] carried out a comparison of four commonly used design formulae to predict the mass flow rate of gases produced from an axisymmetric plume. These formulae are given by,

1. Zukoski et al [15]
2. The Chartered Institute of Building Service Engineers (CIBSE), UK [13]
3. Heskestad [16]
4. Thomas et al [17]

Zukoski et al [15] developed the following correlation from experimental data

$$M = 0.071 Q_c^{1/3} \left(z - z_0\right)^{5/3} \qquad (1)$$

where

M = the mass flow rate of air entrained into the plume (kg/s)

Q_c = the convective heat flow in the plume (kW)

z = height of smoke layer above the base of the fire (kW)

z_0 = height above the base of the fire of the virtual origin of the smoke plume (m)

Equation 1 applies to plumes with a value of z higher than the height of the luminous flame in the fire plume. Equation 1 treats the plume as if it rose from a virtual point source at a height of z_0. Where

$$z_0 = -1.02D + 0.083 Q_c^{2/5} \qquad (2)$$

where,

D = effective horizontal dimension of the fire (m)

CIBSE [13] also adopts Equation 1 for design purposes, however, the CIBSE [13] approach states that 'For most solid fuels found in buildings, the value of z_0 is likely to be small and for design purposes it may be taken as zero, that is, the source is at the base of the fire.’

By assuming that $z_0 = 0$, Morgan and Mason [14] treated the CIBSE [13] approach as a separate formula for comparison purposes.

Heskestad [16] developed an alternative design formula by re-analysing the data given by Zukoski et al [15], given by Equation 3.

$$M = 0.071 Q_c^{0.33} (z - z_0)^{1.67} \left[1 + 0.026 Q_c^{0.67} (z - z_0)^{-1.67}\right] \qquad (3)$$

In this case, both z and z_0 are measured from the top of the fuel stack, rather than at the base.

The final design formula used for comparison purposes was developed by Thomas et al [17]. This is more commonly known as the ‘large fire plume model’ and was simplified by Hinkley [18] to become

$$M = 0.188 P z^{1.5} \qquad (4)$$

where

P = the horizontal perimeter of the fire (m)

It was originally thought that Equation 4 was only applicable for low heights of rise of plume, however, Hinkley [18] and Poreh and Morgan [19] have shown that Equation 4 applies a much greater range of heights of rise of plume (e.g. up to 10 times the value of D).

Morgan and Mason [14] carried out a range comparisons by varying z and the convective heat output per unit area of the fire source. Comparisons gave rise to the following conclusions:

- The Heskestad method consistently predicted a higher mass flow rate compared to the Zukoski et al method. Since the Heskestad method defines z from the top of the stack of fuel, whereas, the comparisons assumed a liquid fuel fire at floor level, Morgan and Mason raised the possibility that this method was being used outside its range of application. However, the Heskestad model gave reasonably close agreement with the large fire plume model, particularly at higher heights of rise.

- The Zukoski et el method usually predicts a lower entrainment compared to the large fire plume model, however, the difference was within 20% for the range conditions studied.

- The effect of assuming that $z_0 = 0$ (i.e. using the CIBSE method) was relatively small for fires with large convective heat release rates per unit area (i.e. approx 750 kW/m^2), but becomes very significant for fires with smaller heat release rates (i.e. approx 250 kW/m^2). These discrepancies were worse for shorter heights of rise, with differences up to a factor of 2 for the range of conditions studied (i.e. for heights of rise up to 4 m).

- The effect of assuming that $z_0 = 0$ can lead to serious underestimates of mass entrainment when using the CIBSE method compared to the Zukoski et al method where z_0 is calculated explicitly.
- The advice given by CIBSE, to take $z_0 = 0$ for all practical engineering designs, should be disregarded for low heat release rates per unit area and for relatively short heights of rise.
- As a higher predicted mass flow rate will lead to a more conservative approach in smoke management calculations, the continued use of the large fire plume model can be justified for many designs.

4.2 Spill plume

There are various simple calculation methods for the balcony spill plume which are currently used by designers of smoke management systems. Some of the most commonly used methods are given by:

- Law [20]
- CIBSE [13]
- NFPA 92B [12]

Law [20] developed the following formula to determine the mass flow rate of gases produced by a balcony spill plume given by,

$$M = 0.31(Q_T W^2)^{1/3}\left(z + 0.25h_{comp}\right) \qquad (5)$$

where

Q_T = the total heat release rate (kW).

h_{comp} = the height of the balcony above the base of the room opening (m).

W = width of compartment opening (m)

z = height of rise of plume above the spill edge (m)

A modified version of Equation 5 is included within guidance given by CIBSE [13] and in NFPA 92B [12] given by Equation 6.

$$M = 0.36(Q_c W^2)^{1/3}\left(z + 0.25h_{comp}\right) \qquad (6)$$

Comparison of these methods with new experimental scale model data (i.e. from a 1/10th physical scale model) obtained by Harrison [21], for a range of fire sizes, is shown in Figure 4 by plotting $\frac{M'}{\left(Q_T'\right)^{1/3}}$ with respect to z for the method by Law, and $\frac{M'}{\left(Q_c'\right)^{1/3}}$ with respect to z for the CIBSE and NFPA 92B method.

where,

$$M' = \frac{M}{W} \quad \text{and} \quad Q_T' = \frac{Q_T}{W} \quad \text{and} \quad Q_c' = \frac{Q_c}{W}$$

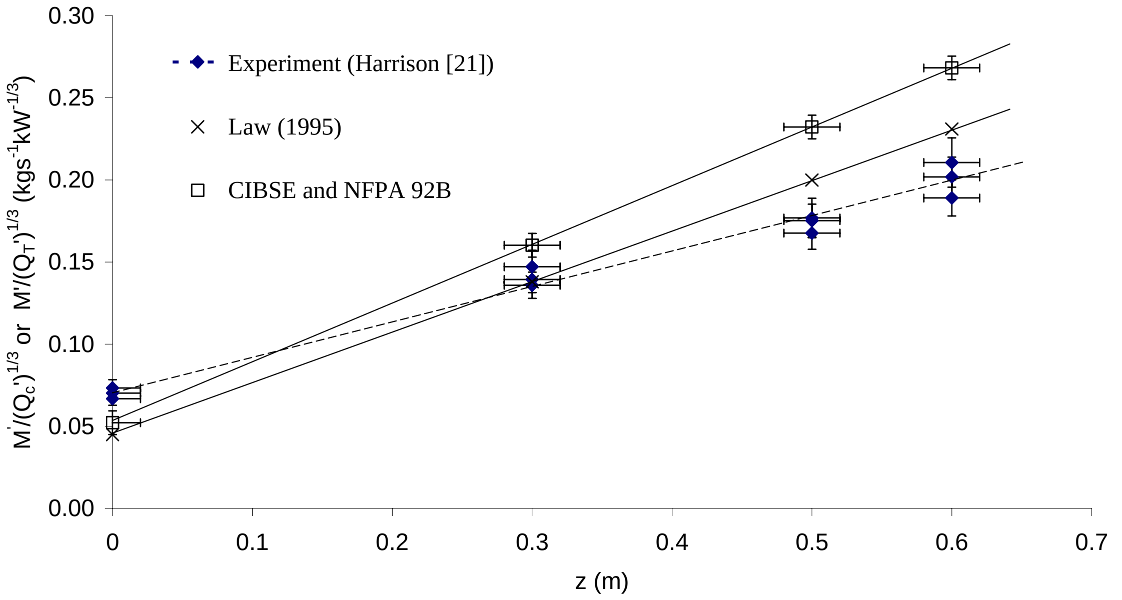

Figure 4: Comparison of calculation methods for the balcony spill plume with data from Harrison [21]

Figure 4 shows that all the simplified formulae under-predict the mass flow rate due to a balcony spill plume at a very low height of rise. However, above a height of rise of approximately 0.3 m (3 m full scale), all of the methods generally tend to over predict the mass flow rate of gases due to a balcony spill plume. The slope of the line relating the mass flow rate gases with respect to the height of rise of the plume, is generally greater for the various simplified formulae compared to the experiment.

The experimental data obtained by Harrison [21] has been used to develop a new simple calculation method in the form of Equation 8.

$$M = 0.20Q_c^{1/3}W^{2/3}z + 0.0017Q_c + 1.5M_b \qquad (8)$$

where,

M_b = the mass flow rate of gases at the spill edge (kg/s)

At present, there are no robust simple calculation methods for the adhered spill plume. Further research continues on the development of new and improved calculation methods for the spill plume at the University of Canterbury, New Zealand.

For the specific case of a plume flowing into single storey mall, whose ceiling is not too much taller than the shop unit opening onto the mall, the following simplified formula, which is an extension of Equation 4, is given by Morgan et al [1].

$$M = 0.38Pz^{1.5} \qquad (9)$$

However, it must be stressed that Equation 9 is particularly case specific, and only applies where the height of rise of plume is less than 2 m above the top of the shop opening. Equation 9 can now be considered to be superseded by new guidance [21] on the influence of balcony/downstand combinations on smoke flows from compartments.

4.2.1 The importance of the spill plume

Milke [22] carried out a comparison between the smoke production rate of an axisymmetric plume with that of a balcony spill plume. The smoke production rate for the spill plume was determined using the formula developed by Law [20]. Comparison between each type of plume was made for a fire with a convective flow in the plume of 5000 kW. The smoke production rate for the spill plume was determined for a variety of balcony heights and spill edge lengths.

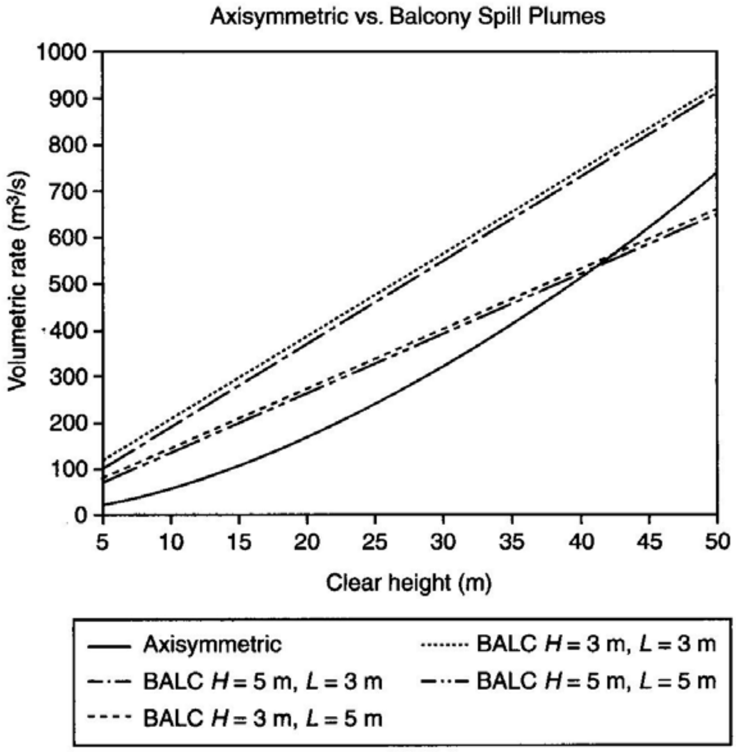

Figure 5: Comparison of smoke production between an axisymmetric and a balcony spill plume [22]

Milke [22] demonstrated that for the conditions studied, the spill plume entrains a greater amount of air than an axisymmetric plume for a height of rise up to 40 m (see Figure 5). This height of rise will cater for the majority of design layer heights in buildings with large enclosed spaces and confirms that the spill plume generally provides the worst case condition for smoke production rate. Beyond a height of 40 m, the spill and axisymmetric plumes are likely to behave similarly in terms of smoke production rate. This is likely to be due to entrainment into the ends of the spill plume as it rises, causing it to become three dimensional in nature, and similar to an axisymmetric plume.

5 SYSTEM RELIABILITY, COMMISSIONING, MAINTENANCE AND MANAGEMENT

Smoke management systems can be complex and involve the operation of many interacting components, including detection systems, exhaust fans, natural ventilators, automatic smoke curtains, dampers, fresh air intakes, etc. Experience of actual installed systems in real buildings has led to concerns on the efficacy of some smoke management systems, especially over the lifetime of a building.

5.1 Reliability

There is limited data on the reliability of smoke management systems. Klote and Milke [7] provide data based on five different system designs as shown in Table 1 . The level of complexity was increased for each design.

System	No of HVAC system fans	No of other components	Reliability of new system before commissioning	Mean life of commissioned system (months)
#1	3	0	0.97	116
#2	0	3	0.83	46
#3	3	9	0.56	14
#4	5	18	0.31	8
#5	5	54	0.03	3

Table 1: Reliability data given by Klote and Milke [7]

Table 1 shows that as the number of components used in the system increases, the reliability of the system decreases significantly, such that the mean life of the commissioned system with 5 fans and 54 other components is just 3 months. However, it must be stressed that the analysis assumed that failure of any one component would lead to failure of the complete system, which may not be the case in reality.

Moran [23] carried out a survey of smoke exhaust systems in shopping centres around the Brisbane region. 32 centres responded to the survey of which 15 had some form of smoke exhaust system. 5 out of the 15 centres reported problems, with various incidents of failure, such as: motor (1), contractor (1), fan bearing (3), fan motor blade (3), fire detection (2) and water ingress (1).

Moore and Timms [24] provided data on the efficacy of systems from less complex designs that are appropriate for low-rise shopping centres (see Table 2).

<table>
<tr><th></th><th colspan="3">Probability of attaining the efficacy range: Design 1, Design 2</th></tr>
<tr><th rowspan="2">Efficacy range</th><th colspan="3">Maintenance, Installation and Commissioning quality</th></tr>
<tr><th>Low</th><th>Medium</th><th>High</th></tr>
<tr><td><25%</td><td>0.128,0.143</td><td>0.008, 0.0089</td><td>0.0015, 0.0016</td></tr>
<tr><td>>25% and <50%</td><td>0.083,0.216</td><td>0.023, 0.042</td><td>0.0188, 0.0244</td></tr>
<tr><td>>50% and <75%</td><td>3.1×10^{-10}, 5.1×10^{-13}</td><td>3.8×10^{-14}, 7.5×10^{-17}</td><td>8.2×10^{-16}, 2.8×10^{-18}</td></tr>
<tr><td>>75%</td><td>0.789, 0.64</td><td>0.968, 0.949</td><td>0.979, 0.974</td></tr>
</table>

Table 2: Reliability data from Moore and Timms [24]

These data demonstrate the benefits of a robust maintenance, installation and commissioning regime in increasing the probability of the efficacy of a smoke management system over the lifetime of a building.

5.2 Sources of failure

The efficacy of a smoke management system can be dependent on a number of factors. Morgan [25] describes some common sources of error in the design, construction and implementation of a smoke management system. The following list of errors is not definitive [25]:

- Inadequate theories - All calculation methods have theories which have been developed for relatively idealised geometries. Real buildings can depart from those ideal conditions. Typical examples include: spill plumes rising past non-straight spill edges; where the smoke flow approaches the straight spill edge at other than a right angle; and plumes which are partially adhered and partially free.

- Unknown input data - The building geometry is usually known when designing, but there are several necessary input parameters which are more subjective in many cases (i.e. specifying the design fire).

- Poor communications - There can be poor communications between the system designer and the installer/s of the system; and between both and the architect; and between all of them and the regulators. Examples include:

    - a system which had smoke curtains installed 1.5 metres too short.
    - channelling screens fitted half-way across a shop's open front, completely negating the reason for fitting them.
    - a hole in fixed smoke curtains at the reservoir boundary in order to allow a smoke detector's light beam to pass through.

  Problems can arise when late detail design changes are made without telling either the designer or the regulator because the changes are (wrongly) thought to be trivial. Changes to the building structure over the lifetime of the building may also reduce the efficacy the smoke management system, if these changes are not brought to the attention of the designer.

- Poor construction/installation – Installation on site is often done by workers who do not know what the equipment is for, or why it is being fitted, and where the workers are under severe time pressure to finish the job. Some consequences have included:

    - a wheelbarrow and bricks left inside a smoke exhaust duct partially blocking it.
    - a fan installed backwards.
    - restraints intended to protect equipment during transit to the site not being removed before fitting.

- Forgetfulness - A common example is the omission of smoke dampers in HVAC ducting, allowing siphoning of smoke when the HVAC is shut down.

- Simple incompetence - Although this is rare, examples have included:
  - designing ducts not strong enough to withstand the internal drop in pressure when fans are activated.
  - failure to design expansion joints into ducts held rigidly at the ends while immersed in the hot buoyant smoke layer.

The examples given in the list above are real, however, they are not intended to be identifiable, for legal reasons.

5.3 Commissioning

A smoke management system should be commissioned after installation to ensure proper operation. As a minimum, 'cold' functional tests should be carried out of separate items of equipment, checking that the items match specification. The tests should confirm interconnections and controls between interacting components of the system.

In some cases it may be desirable to test the performance of a system using buoyant smoke generated from a 'real' fire in situ, which is more commonly known as Hot Smoke Testing. Possible reasons for carrying out a hot smoke test are:

- where the design formulae cannot be applied with confidence.
- where the approving authority demands a test.
- to test the proper operation of the components of the complete system as installed.

One of the two best known methods was developed by Atkinson and Marchant, which resulted in the publication of an Australian Standard [26]. This method uses alcohol fires directly beneath the final smoke reservoir, with pyrotechnic smoke generators being used to make the smoke visible. The second was developed by BRE, and has been used jointly by BRE and the IFSET [1]. This second method also uses alcohol fires, but uses cosmetic oil-mist generators to make the smoke visible. The difference between the two methods is that the second has been used to test the "worst-case" condition of a spill plume scenario. Both methods require that the results of the test fire be extrapolated to the design fire size. Both methods have demonstrated that Hot Smoke Tests can be performed with no damage to the building being tested.

Other methods for hot smoke testing include:

- Use of propane burners to generate the hot gases and pyrotechnic smoke to visualise the plume (see Figure 6).
- Ad-hoc burning of appropriate fuels (e.g. armchair, wood).
- Use of space heaters to generate the hot gases and pyrotechnic smoke to visualise the plume.

Figure 6 A hot smoke test in a sports arena [27]

A hot smoke test provides a means to assess the 'real' performance of a smoke management system. It provides a means of ensuring that the design of a scheme has been properly implemented. A hot smoke test can supplement any routine tests carried out in the building, especially if there is a complex logic system or complex geometry, and can provide an opportunity to observe the interactions between components that may normally have to be assessed in isolation. The information obtained from a hot smoke test can include an assessment of the appropriateness of the core design with regards to air extraction and supply, the effectiveness of the basic implementation with regards to wind, local turbulence, bulk air movements, the formation of stagnant zones, smoke movement through voids or smoke getting into the wrong place, the essential and effective interactions between the various operating components, and the effect of the fine detail of the building design on the system, such as balconies and other structural features (many of which are seldom included in the simplified calculations).

5.4 Approved products and services

The efficacy of smoke management systems can be further enhanced by ensuring the use of products and related services which are fit for purpose and properly installed and maintained in accordance with the manufacturer's instructions or a relevant standard. Third-party certification schemes (e.g. the LPCB certification mark, visit www.redbooklive.com) for fire protection products and related services are an effective means of providing the fullest possible assurances, offering a level of quality, reliability and safety that non-certificated products may lack.

5.5 A process validation methodology for the use of fire safety engineering

As a way of addressing the concerns regarding the quality of smoke management systems which are being designed, specified and installed, it is important to be able to evaluate the design, the designer, the implementation of the design, and the long-term management, operation and maintenance of the safety systems, by means of well-accepted, practical and transparent criteria i.e. Key Performance Indicators (KPIs).

BRE has been commissioned by the Building Regulations Division of the Department for Communities and Local Government in the UK (DCLG) to carry out a three-year study on the development of KPIs to be used generally for buildings designed using fire safety engineering principles [28]. The overall aim of this project was to conduct an investigation to determine the range, potential and ways forward in establishing acceptable and meaningful KPIs for fire safety engineering.

Once the project was underway, the concept of KPIs was found to be misleading and was dropped in favour of the term “critical success factors” as part of a process validation scheme.

This study examined the way fire engineered systems are designed, implemented on the construction site, commissioned, approved, maintained and managed, and has sought to identify ways by which the fire safety engineering might be evaluated (and, consequently, how the engineer might be evaluated). A particularly important aspect of this study is an assessment of the ability of system designers and fire safety engineers to utilise available computational fire engineering tools for design and hazard assessment.

This project was intended to be an investigation to determine the range, potential and ways forward in establishing acceptable and meaningful generic assessment criteria for fire safety engineering. It has identified the users of such a scheme, in various capacities, but in particular those charged with the duty of approving design schemes. Issues that have been addressed include:

- Fire safety engineering qualifications, scope and limitations.
- Competent application of fire modelling tools in establishing design choice.
- Design appropriateness, practicality, buildability, maintainability, reliability, testability.
- Management implications.
- Long term implications (reliability over the life of the building).

The project has had two distinct components. The first represents a scoping study to explore the development of assessment criteria for the whole range of the fire engineered package from design through to installation. There is a need for more exploratory work for the broader package.

The second component concerns the use of computer fire simulation within the overall design and hazard assessment process. The outline of a consensus already exists on the needs for criteria for this component, as a result of which computer modelling tools have already been identified as important for the assessment process and are being specifically addressed through a benchmarking process.

5.5.1 Case study: A smoke management system in a shopping and leisure complex

In order to evaluate the process validation scheme it was necessary to review/assess real buildings that have been designed using fire engineering principles. It is important to stress that the process validation scheme was being evaluated and not the actual buildings.

As part of this study, a review and assessment was made of a 4-storey shopping and leisure complex consisting of covered malls and an 8-screen cinema. The complex had approximately 90 shops distributed over three floors. The top floor comprised of toilets, offices etc. Original problems with the smoke management system as built resulted in legal action.

The key element in the fire engineered strategy was the use of a "zoned" smoke management system to protect the covered malls. This involved the operation of smoke exhaust ventilation and smoke curtains. The atrium space was divided into four zones which were defined by the structure of the building and smoke curtains which drop in the event of a fire. The smoke curtains are configured such that certain curtains do not drop (depending on the location of the fire) to combine two adjacent zones. This then provides two zones, such that the smoke is vented from the affected zone, and make-up air is provided from the unaffected zone. Due to faults with the implementation of the original smoke control proposals, and subsequent legal action, this strategy is different to that originally proposed.

The assessment/review highlighted the following issues:

- The fire safety manager had a lack of understanding of the required cause and effect of the smoke curtain system in the enclosed space and the purpose of the smoke management system itself. This confusion occurred after the fire alarm system had been upgraded (less smoke curtains operated after this upgrade). The Fire Safety Manager assumed (incorrectly), that these changes were part of a new a fire strategy.

- Poor communication had led to the fire safety manager to be unclear on the purpose of the smoke management system. The fire strategy document appears to have been ignored by the fire safety manager.

- The smoke management system was tested every month. However, since there was some confusion on the correct cause and effect regarding the smoke curtains, it is unclear what these tests actually achieved.

- Testing of the smoke management system was not entirely appropriate, as only one zone within the mall was regularly tested (only varying the storey of fire origin). This was due to the presence of a manual call point in this zone making it more convenient to trigger the system. Triggering of the system in other zones involved the activation of a smoke detector at high level. Activation of the system from 3 of the 4 zones had not been carried out since commissioning some 13 years earlier.

- A system test of the smoke management system was carried out by triggering the system on the second floor in the central mall (the zone that is routinely tested). Smoke curtains were observed to descend and the smoke extract and air inlet fans operated. The smoke curtains with the exhaust zone operated correctly, however the majority of curtains in the inlet zone did not operate. It was observed that there were some large gaps between smoke curtains and some curtains descended to a different depth than others. Measurements of the air velocities from the fans on the roof demonstrated that the extract fan capacities were as per the fire strategy. The inlet fans provided a volume flow rate which was approximately one third of the extract flow rate. However, it appears that sufficient inlet air was obtained from other leakage paths.

- As the majority of the smoke curtains in the 'inlet' zone did not operate in the first system test, there could have been significant implications on the efficacy of the smoke management system if a fire were to occur in this zone. However, as it not clear whether these curtains should have operated, the fire safety manager invited BRE to carry out a further test in another ‘zone’ with all contractors responsible for the smoke management system being present.

- Prior to the second system test, a discussion took place with all contractors and personnel responsible for the smoke management system. The contractor responsible for the signalling of the smoke curtains was not aware of the required cause and effect for the building. He was also not aware of the fire strategy report.

- Late changes were made to the fire strategy prior to the opening of the building. These changes resulted in the non-operation of specific smoke curtains to combine adjacent zones. The original contractor responsible for the signalling of the smoke curtains was not prepared to be responsible for those curtains which do not drop. Prior to the opening of the building, it was agreed that the contractor responsible for the fans and dampers would also take responsibility for the signalling of those specific smoke curtains. Therefore, two different contractors were responsible for different parts of the same system. These contractors had not been communicating with each other.

- For the second system test, a smoke detector was activated within a zone which was an 'inlet' zone during on the first system test. Some smoke curtains in this zone descended and the smoke extract/air supply fans operated. Only half of the curtains in the 'extract' zone operated and none of the curtains in the 'inlet' zone operated. The configuration of the curtains was such that the mall consisted of a single smoke control zone.

At the time of the tests, serious problems with the smoke management system were highlighted. However, as a result of the review, the relevant contractors are now communicating and the cause and effect requirements and purpose of the smoke control system are now clear. Problems with the signalling and operation of the smoke curtains have been resolved.

5.5.2 General findings

The general findings of the study have highlighted a number of issues which strongly suggest that the discipline of fire safety engineering has some way to go before we may have the same confidence in the fire safety systems in these sophisticated buildings as we do in traditionally designed buildings. Problems were identified at all stages of the design, construction and operation of buildings that, in the event of a fire, could have life safety implications.

The need for a process assessment scheme, that can provide a means of both design process validation and assist in the monitoring and management of fire safety over the lifetime of the building, has become very apparent. It has become evident that many fire safety managers, even in highly prestigious buildings, are newly qualified, poorly qualified or new to the particular building, do not understand the full extent of their responsibilities and have no robust and well-ordered documentation. Some specific issues identified include:

- The need for thorough and comprehensive documentation covering all aspects of the fire safety design, and not just the "engineered" parts.

- The need for a well established and transparent audit trail for documentation.

- The need for clear communications between the fire safety engineer and the fire safety manager on all aspects of the fire engineering, including the testing and maintenance implications.

- The need to clearly specify the management assumptions in the fire design.
- The need for the manager to own and maintain comprehensive documentation covering all aspects of the fire safety design.
- The need for continuity during management changes.
- "Mix and match" buildings which involve a fire engineered part attached to a "traditionally" designed part and the need to ensure proper integration.
- The complexity and interactions between the control systems in a large modern building.
- The importance of properly arranged and documented commissioning tests.
- The integration of fire safety with other safety issues.
- The need for full and appropriate co-ordination and consultation with Building Control bodies and the fire service (and other safety enforcers).

The proposed prototype assessment scheme offers a means to address these issues, although substantial development is still needed. The scheme is intended to increase the reliability of the fire safety system being effective in the event of a fire. It therefore needs to apply over the entire working life-time of the building, and therefore addresses: design (including Fire Safety Engineering); construction, approvals and certification; commissioning and hand-over; day-to-day operation of the structure; training, inspection and maintenance; refurbishment, extensions or change of use; the structure when empty/ not in use and demolition.

It is intended to be of value to the whole range of people involved in the life-cycle of the building. Many of the issues identified apply to all buildings, not just those using fire engineered principles. The scheme that has evolved is in essence a "check list". The study to date has shown strong support from most of those consulted for the use of qualitative assessment criteria since quantitative criteria are not practicable. It has also shown strong support for the adoption of “Binary” assessment criteria (Yes/No) where “No” may mean rejection of the entire design if the parameter involved is crucial to safety. Given the variety of design, some factors may not be applicable to all circumstances.

The proposed methodology provides a means of seeking to ensure that each and every key element within the design process has been considered (and shown in the documentation to have been considered) with the necessary level of detail. An example of part of the process validation methodology is given in the Appendix. A full version can be obtained from the lead author of this paper. BRE welcomes comments and feedback on the scheme, particularly where it has been tested on real projects.

6 CONCLUSIONS

This paper presents a range of issues relating to smoke management in buildings with large enclosed spaces, including various smoke management methods, design fire scenarios and simple calculation methods, in addition to issues relating to the overall design process, reliability, commissioning and maintenance of such systems. Following a review of actual installed systems and real examples of sources of failure, there are concerns over the efficacy of some smoke management systems, especially over the lifetime of a building. The importance of proper documentation, commissioning, maintenance and testing of these systems is crucial to ensure effective operation and performance. As a way of addressing these concerns, a process validation methodology is presented to evaluate the design, the designer, the implementation of the design, and the long-term management, operation and maintenance of such systems.

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APPENDIX – AN EXAMPLE OF PART OF THE GENERIC PROCESS VALIDATION METHODOLOGY

1. Approvers of Regulation	
1.1. Professional Credentials for key individuals	
1.1.1. Does the enforcer or AI, or the head of the enforcement team, have a FSE professional qualification appropriate to the design being checked?	
1.1.2. Is the regulatory check being done by someone at least as highly qualified as the designer in terms of professional qualifications?	
1.1.3. Where sufficient in-house expertise does not exist, has the enforcer or AI considered employing a suitably qualified "Third Party Checking Consultant"?	
1.1.4. Where design includes special features which require specialist knowledge, has consideration been given to employing suitable third-party specialists?	
1.1.5. Has it been ensured that the "Third Party Checking Consultant" is not paid directly by the Commercial side when working for an enforcer or AI?	Note: Cost and charges may be passed on, but it must be crystal clear that the "Third Party Checking Consultant" is INDEPENDENT of commercial interests.
1.2. Documentation	
1.2.1. Does the documentation include a detailed description of the fire safety design; with a full explanation of assumptions made, source documents for calculations, key values adopted for calculations, drawings showing appropriate details, etc.? (See above).	Note that good drawings can save many words of text. Note also the importance of all such drawings being fully updated. Crucially, the drawings need to be "as installed" rather than "as intended".
1.2.2. Has the enforcer or AI provided written reasons for any amendments or limitations applied to the fire safety design?	
1.3. Checking procedures for Compliance	
1.3.1. Has adequate documentation been provided?	
1.3.2. Have the critical success factors listed above for the design been complied with?	
1.3.3. Can the enforcer or AI establish what is "plausible" in terms of "reasonable" criteria?	
1.3.4. Is the enforcer or AI able to use available "Best Practice" Guidance?	
1.3.5. Does the enforcer or AI require specialist FSE help?	
1.3.6. Does the enforcer or AI require specialist computer modelling help?	
1.3.6.1. Has the computer modelling been used sensibly?	
1.3.6.2. Are the computer models used "Bench Marked" models?	

1.3.7. Have the relevant codes/ guidance been properly interpreted?	
1.3.7.1. Have the available "Best Practice" Guidance documents been used?	Note that a “NO” answer does not necessarily invalidate the design, especially where good alternatives have been adopted. This will be particularly the case for innovative designs.
1.3.8. Does the design satisfy the requirements? Is this clear?	
1.3.8.1. Have the source guidance documents been "pick and mixed"? Has this been done properly?	
1.3.9. Have the continuing enforcement issues relating to the life of the building been considered?	
1.3.10. Is appropriate in-situ commissioning proposed?	If not, should it be demanded?
1.3.11. Where a disagreement exists as to the compliance of a design, has the primary checker (either the senior qualified in-house team member, or the third-party consultant), tried to resolve the differences by direct discussion with the designers, before other enforcement routes are taken?	Note: This ensures that the checker’s arguments are themselves checked by the original designer.
1.3.12. Where disagreement continues, has the possibility of arbitration by a specialist expert been considered?	
1.3.13. Is the approval subject to proof of operation by in-situ commissioning and/or acceptance tests?	
1.3.14. Is there provision for continuing enforcement to ensure that there are no significant departures from the fire safety strategy and its implementation?	We need to be realistic regarding what can be expected from Building Control bodies or fire officers, and the resources they have available to employ third party checkers. However, we need to identify the expectations put upon them by the fire safety engineers. There appear to be differences in approach between London and the rest of England and Wales. The importance of commissioning tests is mentioned above.
1.3.15. Is there a robust maintenance etc regime proposed?	
1.3.16. Are adequate back-up systems provided?	
2. Fire Safety Management	
2.1. Professional Credentials for key individuals	
2.1.1. Has the Fire Safety Manager (who may be a team leader in a large building) evidence of appropriate training in fire safety?	
2.1.2. Is the fire safety manager a member of an appropriate learned institute with an interest in fire safety?	Preferable but not always essential.
2.1.3. Is the fire safety manager encouraged to take part in CPD courses recognised by appropriate learned institutes?	

2.1.4. Is the fire safety manager sufficiently senior in the managing organisation to have the authority and resources necessary for him/her to fulfil their duties and responsibilities? (Note: In particular, it should not be possible for them to be over-ruled by commercial considerations on fundamental safety issues.)	
2.2. Documentation	
2.2.1. Is there a "Building Log Book" available to the fire safety manager? (See above).	
2.2.2. Does this documentation include a copy of the final fire safety strategy report prepared by the FSE designers, as well as details of the installed fire safety systems provided by the suppliers and installers of those systems?	
2.2.3. Does the Log Book include details of changes which may affect the fire safety systems in the building?	
2.2.4. Has adequate documentation been provided regarding the managers duties and responsibilities? Does the documentation provided by the designer provide adequate information on the manager's duties?	
2.2.5. Is the documentation kept in a safe but identified location?	
2.2.6. Does the documentation enable the fire safety manager to understand how design helps the building management?	Have provisions been made by the building owners or management to enable the fire safety manager to understand how design helps the building management?
2.2.7. Does the documentation enable the manager to understand what needs to be provided in the fire safety system for reliability, availability, resilience, inspectability, maintainability, repairability, testability?	Have provisions been made to enable the manager to understand what has been provided in the fire safety system for reliability, availability, resilience, inspectability, maintainability, repairability, testability?
2.2.8. Does the documentation enable the manager to ensure that the safety systems are correctly installed?	
2.2.9. Are adequate "back-up" systems provided?	
2.2.10. Have provisions been made to enable the manager to recognise and allow for changes in building use?	Change of use can imply significant implications for the Fire Safety provisions even where there is no "change of use" in purely regulatory terms. E.g. changes of geometry within a single category such as retail can imply a redesign of active and passive fire protection designs.
2.2.11. Have provisions been made to enable the manager to recognise and allow for changes in occupancy levels?	For example, this can have major implications for Means of Escape, which can lead to redesign of stairwells and other features.
2.2.12. Is there continuity during management changes?	
2.2.13. Are there un-diffused responsibilities, with clear and comprehensive lines of responsibility?	In many complex buildings, different engineers have responsibility for different parts of the fire safety system, with little co-ordination.
2.2.14. Do the manager's duties include regular inspection and testing of the fire safety	Strengthen? On-going maintenance, testing; adequate maintenance, checks, repair?

equipment to ensure proper function as described in the fire safety strategy, according to a schedule set down in the Building Documentation/Log Book?	
2.2.15. Do the manager's duties include frequent inspection of Means of Escape and Means of Fire Service Access to ensure compliance with the fire safety strategy?	
2.2.16. Do the manager's duties include ensuring rapid repair and restitution of any fire safety equipment found to be faulty, and that temporary additional safety precautions are put into place pending successful completion of that action?	
2.2.17. Do the manager's duties include ensuring regular maintenance schedules of fire safety equipment as recommended by the suppliers/installers of that equipment?	
2.2.18. Do the manager's duties include ensuring that the documentation is kept up-to-date by including a full maintenance record, details of any tests, descriptions (with drawings where needed for clarity) of any alterations to the building, etc?	
2.2.19. Do the manager's duties include ensuring that any authority with continuing enforcement responsibilities, and the fire service in any case, receives updated copies of the "Building Log Book" when any alterations or amendments are included therein?	
2.2.20. Do the manager's duties include ensuring that the full documentation is made available to any successor, including when the building changes ownership or management regime? (Note; the Fire Safety Manager's overall duties should be as defined elsewhere (notable BS 9999 (draft) or BS 5588 Part 12 (in due course)) but the duties specified above are those that are specific to a fire engineered building).	It is evident that the proper communications between the fire safety engineer and the "fire safety" manager is a critical, if not the critical, component in the fire safety engineering process. Similarly, the manager must have available all other documentation relating to the safety systems, such as instruction books and results of commissioning tests. There is also a significant issue regarding the relationship of the fire safety manager and the other people in the building with parallel duties, e.g. for maintenance or other safety issues. Co-ordination of these responsibilities is essential if key elements of the safety system do not "fall through the cracks". Similarly there is a need for good co-ordination between managers of different parts of the building, for example between owner managers and tenants.