Probabilistic Modelling of Open Plan Dwellinghouses

Plumis Automist
Research Report

IMPORTANT!

An independent fire engineer was commissioned by Plumis to undertake research on the performance of their Plumis Automist suppression systems for use in dwellinghouse and loft conversion design in order to facilitate a dialogue with authorities having jurisdiction (AHJ) when considering its products. It may not be assigned to or relied upon by a third party without agreement in writing. All copyright and other intellectual property in the document is retained and its contents unless transferred by written agreement.

The document focuses on the recommendations of guidance for three-storey dwellinghouses and loft conversions with only one habitable floor 4.5 m above access level. Sections 2 through to 5 outline the general recommendations of guidance documents for these types of dwellings, the implicit fire safety performance objectives of the guidance recommendations, and the documentation available to demonstrate whether the Plumis Automist system is able to meet these implicit performance objectives.

From Section 6 onwards, a probabilistic modeling assessment has been undertaken to demonstrate. whether the Plumis Automist system can be adopted in open plan arrangements which deviate from the recommendations of guidance. This document is not applicable to any type of accommodation other than those specified in the paragraph above, e.g., it cannot be considered applicable to dwellinghouses with more than one floor above ground level or multi-dwelling residential buildings.

This document is provided as general guidance to support the development of specific system design. The independent fire engineer is therefore not professionally liable for the adequacy of any specific systems. Liability will reside with the relevant members of the design team working on each scheme where the specific system is being adopted. The relevant members of the design team will need to verify that the information presented in the document is appropriate and applicable for the building works being carried out.

CONTENTS

1. INTRODUCTION

1.2 Plumis Automist system description

1.2.1 The Plumis Automist system is designed for domestic / residential applications. The system does not operate in the same way as traditional water mist systems but instead is initiated by a monitored wireless, or wired, combined smoke and heat detector, or a 5839-6:2019+A1:2020 [1] LD1 detection and alarm system via relay. Once initiated, the system uses an infrared (IR) thermopile sensor embedded within the nozzle head(s) to scan the room for a fire. The IR sensor measures temperature as a function of IR radiation, assessing for high temperature readings or differential increases in temperature between scans. Once the rate of change in temperature exceeds a given threshold, the head is considered to have successfully located a fire and discharges water droplets in its direction.

1.2.2 The water is discharged by the activation of a high-pressure pump (Figure 1a), which drives mains-linked water through the nozzle unit (Figure 1b). The spray nozzles for the system are wall-mounted and positioned around light switch height, e.g., 1.45 m from floor level. The nozzle achieves a water rate discharge of around 5.6 L/min with water droplets less than 100 µm in size.

1.2.3 Typically, only a single nozzle activates within the enclosure and directs its spray towards the fire, rather than spray being distributed throughout the enclosure. As a result, the system does not necessarily achieve a fixed design discharge density.

1.2.4 Previous studies carried out on the system using pans to collect the water spray have shown that the discharge density varies across the affected area depending on the nozzle location within the enclosure and its discharge direction. The local discharge density can reach up to 0.015 mm/s, with a modal value in the region of 0.01 mm/s. For a given fire incident, the local discharge density will also be influenced by the location of the fire relative to the nozzle head and the interaction of the spray with the fire plume.

1.2.5 A more detailed description of the system and its design motivations can be found in Spearpoint et al. [2], with further component information available from the system supplier [3], [4] as well as in the design, installation, operation, and maintenance manual (DIOM) [5].

(a) Controller and pump

(b) Nozzle discharging water

Figure 1 – Visualisations of the Plumis Automist system

2. GUIDANCE RECOMMENDATIONS FOR DWELLINGHOUSES

2.1 Approved Document B vol. 1

2.1.1 For new-build dwellinghouses with one storey more than 4.5 m above ground level, Approved Document B (ADB) vol. 1 [6] recommends either:

- A protected stairway be provided, separated by fire resisting construction at all storeys, either extending to a final access or providing access to a minimum of two fire-separated ground level final exits.
- An alternative escape route be provided for the top storey (leading to its own final exit), with the top storey separated from the lower storeys by fire resisting construction.

2.1.2 ADB affords no relaxations to these recommendations with the provision of an automatic water fire suppression system (AWFSS), but does provide separate guidance for loft conversions and work on existing dwellinghouses. Where a new storey is added to an existing dwelling through loft conversions to create a storey above 4.5 m, ADB suggests the following should apply:

- The full extent of the escape route should be addressed and fire resisting doors and partitions should be provided.
- Alternatively, sprinkler protection should be provided to open plan areas and a fire resisting partition and door should separate the ground floor from the upper storeys. This door should be arranged so that building occupants located in the loft are able to access an escape window at first floor level. ADB also indicates that cooking facilities should be separated from the open plan area with fire resisting construction.

2.1.3 At no stage does ADB make reference to the use of water mist systems, and instead only makes reference to sprinkler systems designed in accordance with BS 9251:2021 [7] for residential applications.

2.2 BS 9991:2015

2.2.1 For loft conversions in buildings less than 4.5 m tall, BS 9991:2015 [8] suggests fire resisting partitions and doors should be provided to protect the stair, and this stair should be protected at all levels and extend to a final exit, or facilitate escape via at least two separated escape routes at ground level. If an open plan arrangement exists at ground level, then it is recommended that an AWFSS be provided to the open plan area, and a fire resisting partition and door should separate the ground floor from the upper storeys. This door should be arranged so that building occupants located in the loft are able to access an escape window at first floor level. Loft conversions in dwellings taller than 4.5 m applies the same guidance as for new build dwellinghouses, described below.

2.2.2 For three-storey dwellinghouses with a single floor 4.5 m above access level, BS 9991:2015 suggests the design should meet one of the following:

- The topmost storey (i.e., above 4.5 m) should be separated from the lower storeys by fire resisting construction and be provided with an alternative means of escape.
- An internal stairway should be constructed as a protected stairway discharging directly to outside or via two independent escape routes.
- The dwellinghouse should be fitted throughout with an AWFSS, and designed in line with the above description for loft conversions.

2.2.3 In relation to AWFSSs, both BS 9991:2015 and its draft revision [9] suggests a water mist system conforming to DD 8458-1:2010 [10] or BS 8458:2015 [11] can be adopted as an alternative to sprinkler protection for loft conversions and houses with one or more floors above ground level.

2.2.4 Unlike ADB, BS 9991:2015 places no restriction on the enclosure of the kitchen in fire resisting construction. However, the guidance does not specify whether a suppression system can be used to support open plan designs which deviate from arrangements described above, such as dwellinghouses and loft conversions incorporating a single open plan stair on multiple storeys (e.g., ground and first floor).

2.3 Technical Handbook – Domestic

2.3.1 In Scotland, the Technical Handbook – Domestic, sometimes referred to as the Scottish Technical Handbook (STH), is adopted for the design of dwellings and residential buildings.

2.3.2 Compared to ADB vol. 1 and BS 9991:2015 which are adopted primarily in England, the STH is much more accommodating of open plan arrangements when a design incorporates suppression and enhanced early warning fire detection and alarm. For escape within open plan dwellings, it states the following:

- *"Open plan layouts are becoming more popular with modern living styles. For this option, the following guidance should be followed for open plan layouts provided the kitchen is remote from the exit door."*
- *"Where the topmost storey height is more than 4.5m above the adjoining ground an automatic life safety fire suppression system and an enhanced early warning system should be installed to protect the occupants. In a slower developing fire, the early warning system should provide the occupants with sufficient time to escape and in those cases where the fire develops quickly, the suppression system should control the fire giving the occupants the opportunity to escape."*

2.3.3 For the above, it recommends the AWFSS is designed and installed in accordance with BS 9251:2014 [12], and the automatic fire detection and alarm system should follow the guidance of BS 5839-6:2019 [13], for a Grade D LD1 system.

2.3.4 STH does make reference to alternative suppression systems, suggesting that *"the applicant and verifier should satisfy themselves that the alternative system has been designed, tested and approved for use in domestic and residential buildings and are fit for their intended purposes"*.

2.3.5 With specific reference to water mist systems, it is recommended in STH that these should be designed and installed in accordance with BS 8458:2015 [11] and nozzles should comply with BS 8663-1:2019 [14].

3. BACKGROUND TO OPEN PLAN DWELLINGS AND PERFORMANCE-BASED DESIGN

3.1 NF19

3.1.1 For flat design, the recommendations of ADB pose a significant limitation on the conditions for adopting bedrooms as inner rooms. In recognition of this, the National House Building Council (NHBC) commissioned the Building Research Establishment (BRE) to undertake a study (NF19) [15] into the risk from fires associated with open plan flat arrangements. NF19 included computational modelling of several flat arrangements and fire and evacuation scenarios where the relative level of safety achieved in traditional (i.e., ADB protected entrance hall) and open plan layouts were assessed via comparative analyses. These analyses considered the fractional effective dose (FED) for occupants escaping from the dwelling of fire origin, where the FED represents a measure of airborne pollutants (irritants and asphyxiants) inhaled by occupants, where toxins, such as carbon monoxide (CO), accumulate over time during occupant evacuation in a building impacted by fire.

3.1.2 From NF19 it was determined that open plan flat arrangements could achieve an equivalent or improved level of safety relative to guidance recommendations. This was reliant on the additional measures of residential sprinkler protection and the inclusion of an enhanced automatic detection and alarm system.

3.1.3 With respect to detection and alarm, NF19 recommended that smoke detectors and alarms be included in all habitable rooms (excluding bathrooms) and heat detectors and alarms provided in kitchens. This aligns with a Grade D LD1 system designed to BS 5839-6:2019+A1:2020 [1].

3.1.4 As a result of the performance-based assessments carried out and detailed in the NF19 study, open plan flat design was subsequently incorporated into the prescriptive guidance of BS 9991:2011 [16], its 2015 revision [8] (the current version), and the upcoming draft revision [9].

3.1.5 In 2020, Hopkin et al. [17] undertook a review of the fire safety design of open plan flats, including a comprehensive review of the NF19 study. In this review, it was identified that NF19 made a number of favourable assumptions around the performance of sprinkler systems, assuming that:

- Sprinklers achieve a quick response for the response time index (RTI) of 50 $m^{½}s^{½}$ and have no conductivity factor (C factor). Refer to Section 5.2 for more discussion around these parameters and their impact on response time.
- Sprinklers immediately extinguish the fire upon operation. Refer to discussion in Section 5.3 for common suppression assumptions.
- Sprinklers are 100% reliable (see Section 5.4 later).

3.1.6 Despite these favourable assumptions in the original performance-based assessment, sprinkler systems are frequently used to support open plan flat design and are not subject to the same level of scrutiny as novel solutions, in part due to their historical use and their inclusion in prescriptive guidance and its revisions over time.

3.1.7 Although not strictly applicable to multi-storey dwellinghouses, NF19 highlights the historical practice of applying performance-based analysis to support deviations from residential fire safety guidance, especially for open plan arrangements.

3.2 Alternative solutions and performance-based design

3.2.1 The prescriptive guidance in ADB and BS 9991:2015 provides one means of demonstrating compliance with the functional requirements of the Building Regulations for common buildings.

3.2.2 However, practitioners are allowed to adopt alternative solutions as long as they are adequately supported by a suitably qualified and competent professional, typically through the application of fire safety engineering principles and qualitative or quantitative analysis. This approach to fire safety design is acknowledged in ADB, where it is stated:

- *"Fire safety engineering might provide an alternative approach to fire safety. Fire safety engineering may be the only practical way to achieve a satisfactory standard of fire safety in some complex buildings and in buildings that contain different uses."*
- *"Fire safety engineering may also be suitable for solving a specific problem with a design that otherwise follows the provisions in this document."*
- *"BS 7974 and supporting published documents (PDs) provide a framework for and guidance on the application of fire safety engineering principles to the design of buildings."*

3.2.3 Similarly, BS 9991:2015 makes reference to the option of undertaking a qualitative design review (QDR) using BS 7974:2019 [18], the code of practice for the application of fire safety engineering principles to the design of buildings. BS 9999:2017 [19] explains three levels of guidance on fire safety as follows:

- *"**General approach.** This level is applicable to the majority of building work undertaken within the UK. In this case the fire precautions designed into the building usually follow the guidance contained in the documents published by the relevant government departments to support legislative requirements."*
- *"**Advanced approach.** This is the level for which BS 9999 is provided. The provisions of this document allow a more transparent and flexible approach to fire safety design through use of a structured approach to risk-based design where designers can take account of varying physical and human factors. Many of the measures recommended in BS 9999 are based on fire safety engineering principles, although it is not intended as a guide to fire safety engineering."*
- *"**Fire safety engineering.** This is the level for which BS 7974 is provided. This level provides an alternative approach to fire safety and can be the only practical way to achieve a satisfactory standard of fire safety in some large and complex buildings, and in buildings containing different uses."*

3.2.4 The BS 7974:2019 [18] code of practice provides a framework for a range of fire engineering approaches to be adopted in the fire safety design of buildings. The framework summarises a design process which considers: undertaking QDR and setting fire safety objectives; performing analyses of the design problem in the context of the defined objectives; and comparing the results of the analyses against acceptance criteria, to determine whether the design can achieve an adequate level of safety.

3.2.5 BS 7974:2019 notes that this approach to design can be used in conjunction with other standards (such as ADB, BS 9991:2015 and BS 9999:2017) and may also be used to support alternative approaches. BS 7974:2019 states that for any given functional requirement, the method of quantitative analysis can be either deterministic or probabilistic, and the acceptance criteria can be either absolute or comparative.

3.2.6 Hence, it is clear that the functional requirements of the Building Regulations, and the framework of guidance that exists within England, provides the flexibility for competent practitioners to deviate from the guidance documents. This is inclusive of alternative solutions which consider the application of new fire safety systems, such as the Plumis Automist suppression system, in lieu of conventional solutions.

4. PERFORMANCE OBJECTIVES OF SUPPRESSION SYSTEMS IN DWELLINGHOUSES

4.1 General observations

4.1.1 The previous sections highlight that within fire safety guidance, the inclusion of AWFSSs (often in combination with automatic fire detection and alarm) in both dwellinghouses and flats is used to accommodate more open plan designs, such as an open plan ground floor within a dwellinghouse or an open plan access room within a flat. The following sections therefore qualitatively details the performance objectives that an AWFSS might be expected to provide in the context of facilitating these open plan arrangements.

4.2 Means of escape

4.2.1 As demonstrated in the NF19 study, the primary intention and performance objectives for including AWFSS within dwellings (i.e., to support open plan arrangements) is to aid the escape of the dwelling's inhabitants. It can be qualitatively summarised that the engineering principles behind this approach are as follows:

- The AWFSS will activate at a given time after a fire incident, where the time of this activation will be a function of the growth and heat release rate (HRR) of the fire, its location within the dwelling, whether it is shielded in some fashion, and the response time of the system.
- Upon activation, the AWFSS will introduce water spray into the fire-affected enclosure and will suppress the fire by a combination of wetting and cooling the combustion surface (and any surrounding surfaces), cooling the air by vaporisation (energy absorption) and diluting the air with water vapour [20]. In the case of water mist, greater reliance is placed on the cooling and dilution mechanisms with less support from surface wetting [21].
- The suppression of the fire will reduce its HRR, reduce the enclosure temperatures, and minimise the likelihood of further fire spread within the fire-affected enclosure.
- In some instances, the AWFSS will extinguish the fire entirely, although it is important to note that this is not an expectation of the system and is not an explicit test criterion in standards like BS EN 12259-14:2020 [22] and BS 8458:2015 [11].
- By reducing the HRR and the likelihood of subsequent fire spread, the suppression system is also likely to reduce the production of soot and toxic gases, as these are typically proportional to the size of the fire (expressed proportionally to the mass flow rate as 'yields').
- The suppression system will operate for a sufficient length of time that it appropriately mitigates the hazard for any escaping occupants. For example, for application in dwellinghouses, the minimum requirement for a sprinkler system is Category 1 in accordance with BS 9251:2021 [7], operating for a minimum duration of supply of 10 min.
- Automatic fire detection and alarm can be provided within the dwelling to warn occupants of a potential hazard, such that they are able to make their escape earlier within the fire's development, when the hazard is comparatively less severe.

4.2.2 The combination of the above factors means that the conditions within the fire-affected enclosure would be expected to be less hazardous to escaping occupants (in terms of heat, visibility, and toxicity) than an enclosure not afforded an AWFSS. Similarly, the extent of smoke and heat spread both within and beyond the enclosure would be expected to be comparatively less.

4.2.3 Thus, the implication is that an AWFSS is able to adequately support escape in open plan arrangements where certain fire resisting elements have been omitted, as long as:

- The system demonstrated to 'respond' (i.e., activate) within a reasonable timeframe following fire ignition.
- Following activation, the system is shown to suppress the HRR of the fire for a sufficient period, enabling occupants to make their escape or await fire service rescue.
- The system is suitably reliable to perform the above objectives.
- The system operates for an adequate length of time to perform the above objectives.
- The system has undergone adequate fire testing and experimentation, e.g., to relevant fire safety standards, such that it can be reasonably assumed that it is able to meet the above performance objectives.

4.2.4 Where required, occupants should also be afforded a means of early warning in the event of a fire. However, this is typically achieved through the provision of a separate automatic fire detection and alarm system, and not directly through the AWFSS.

4.3 Firefighting

4.3.1 In the design of dwellinghouses, a dedicated rising mains is not typically provided, as the dwellinghouses are under 11 m tall in almost all cases and hose laying coverage is demonstrated as adequate and / or there is sufficient perimeter access for the fire service to fight the fire externally.

4.3.2 However, there will be secondary benefits for firefighting operations within the provision of AWFSS, even if these do not form the performance objectives of the system. These are consistent with those specified for means of escape including controlling the HRR and reducing the extent of the fire hazard, reducing enclosure temperatures, reducing the production of soot and toxic gases, etc. As a result, the severity of the hazard faced by the fire service would typically be less than in a dwellinghouse not provided with an AWFSS.

5. REVIEW OF PLUMIS AUTOMIST DOCUMENTATION AND RESEARCH TO DATE

5.1 Compliance with fire testing standards

Performance objective: the system has undergone adequate fire testing and experimentation.

5.1.1 Section 2.2 notes that BS 9991:2015 and its draft revision both allow for the inclusion of a water mist system to support dwellinghouse design and loft conversions, as long as it is tested to the appropriate standards, i.e., BS 8458:2015 (which supersedes DD 8458-1:2010 referenced in BS 9991:2015).

5.1.2 The Plumis Automist system has been independently tested by a third-party to verify that it is able to meet the performance requirements outlined in BS 8458:2015, and the system has an BSI verification certificate (VC 712581) which is effective until June 2025.

5.1.3 The Plumis Automist system incorporates deviations and alternative solutions to the standard in some instances, and these are openly detailed elsewhere [23]. These typically relate to how the water mist nozzles differ in their location and how they discharge water into the tested enclosure. The system is provided with a design, installation, operation and maintenance (DIOM) manual [5].

5.1.4 The independent fire testing covered a series of 11 fire tests where it was demonstrated that, in all instances, the system performed adequately to pass the standard acceptance criteria. A description of the tests and the results can be found in a publicly available test report [24], and two peer-reviewed research publications by Spearpoint et al. [2] and Hopkin et al. [20].

5.1.5 The system has also been subject to experiments for a series of shielded, slow growing fires, where it was typically shown to perform equivalent to or better than a sprinkler system provided with concealed sprinkler heads. Descriptions and results for these tests can be found in Spearpoint et al. [2].

5.2 System response time

Performance objective: the system is demonstrated to respond within a reasonable timeframe.

5.2.1 The time for a suppression system to activate is typically represented by its RTI and C factor. In the case of traditional sprinkler heads or water mist nozzles, these are reliant on heat transfer to a bulb / sensing element. Hence the RTI provides a thermal time constant for the heat responsive element of a head in relation to gas (smoke) velocity and convective heat transfer, and the C factor characterises the heat loss to surrounding construction (e.g., the sprinkler housing) due to conduction [25]. The higher either of these values, the longer it will take for the head or nozzle to respond to a fire and introduce water spray into the enclosure.

5.2.2 For domestic sprinklers, BS 9251:2021 suggests sprinkler heads conforming to BS EN 12259-14:2020. This typically results in the specification of quick response heads in line with BS EN 12259-1:1999 [26]. BS 8458:2015 for residential water mist also suggests thermally activated nozzles with quick response elements in accordance with BS EN 12259-1:1999. BS EN 12259-1:1999 indicates a quick response head typically achieves an RTI of 50 $m^{\frac{1}{2}}s^{\frac{1}{2}}$ or less, and a C factor of 0.8 $m^{\frac{1}{2}}s^{-\frac{1}{2}}$ or less.

5.2.3 The above parameters are applicable for pendent heads which are exposed beneath the ceiling. In contrast, concealed heads are more commonplace in residential design, with the head typically hidden above the ceiling by a cover plate for aesthetic purposes and to minimise the possibility of tampering [25].

5.2.4 For concealed heads, BS 9252:2011 and BS EN 12259-14:2020 provide an alternative test method referred to as the thermal response room test. In carrying out this test, neither the RTI nor C factor are explicitly defined and instead a time criterion is applied in the tests for the sprinkler head(s) to activate. In simulating these tests, Hopkin and Spearpoint [25] identified a design parameters of 290 $m^{\frac{1}{2}}s^{\frac{1}{2}}$ for the RTI and 0.5 $m^{\frac{1}{2}}s^{-\frac{1}{2}}$ required to pass the test, which also broadly aligned with previous experiments by Annable [27] and Yu [28].

5.2.5 Spearpoint et al. [2] subsequently assessed 13 different experiments involving the Plumis Automist suppression system, as well considering equivalent experiments considering the performance of a sprinkler system provided with concealed heads. In the experiments, it was identified that the concealed sprinkler heads produced activation times which ranged from 2 to 13.7 times greater than the Plumis Automist system. The experiments also verified that the previously identified RTI and C factor parameters for concealed heads appeared reasonable.

5.2.6 As the Plumis Automist system initiates and begins to scan the room with a thermopile sensor following the activation of a combined smoke and heat detector, it is generally not feasible to represent this type of complex interaction in simple modelling tools. Therefore, Spearpoint et al. instead used modelling tools and calibration to experiments to identify representative 'effective' values for the thermal response of the Plumis Automist system, estimating an RTI 20 $m^{\frac{1}{2}}s^{\frac{1}{2}}$ and a C factor of 0.25 $m^{\frac{1}{2}}s^{-\frac{1}{2}}$.

5.2.7 It can be seen that the RTI and C factor values of the Plumis Automist system are lower than those achieved by quick response pendent heads and nozzles, and substantially lower than the concealed sprinkler heads commonly adopted in residential design.

5.2.8 Figure 2 presents the implications of this activation with respect to ultra-fast, fast, medium, and slow αt^2 [29] growing fires within a representative residential enclosure. It highlights the importance early activation can have in reducing the extent of a potential fire hazard.

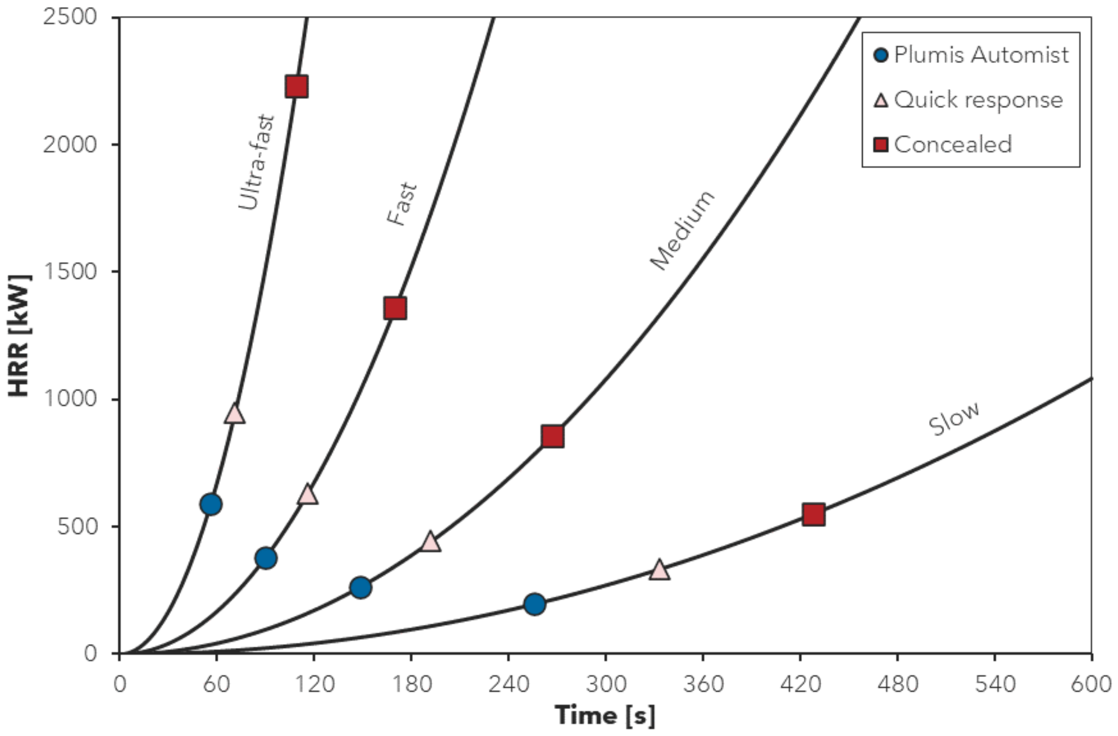


Figure 2 – System response times for different fire growth rates

5.3 Suppression performance

Performance objective: the system is shown to suppress the fire for a sufficient period.

5.3.1 In 2022, Hopkin et al. [20] undertook a review and fire modelling assessment of the different tests carried out to the BS 8458:2015, as described previously in Section 5.1. As part of this exercise, the thermocouple test data of the fire tests was compared against a series of B-RISK [30] zone model simulations, where the activation performance of the water mist system was represented in the models as an 'equivalent' sprinkler system (discussed in Section 5.2).

5.3.2 Three different, common practices for representing the suppression of the HRR following system activation were employed, to observe whether their application could be reasonably extended to the Plumis Automist system. These suppression assumptions were the sprinkler-controlled ('capped') HRR [31], the Nystedt model [32], and the Evans exponential decay model [33], where each has been derived from fire incident or experimental data. The implications of these models on the HRR are presented in Figure 3.

5.3.3 When comparing the thermocouple test data to the estimated layer temperatures of the zone modelling output, it was found that suppression assumptions traditionally applied for sprinklers remain appropriate for the Plumis Automist system. In most cases, an Evans exponential decay model was found to provide closest agreement between the models and test data, with the assumption of a controlled (or 'capped') fire shown to be largely conservative.

5.4 System reliability

Performance objective: the system is suitably reliable.

5.4.1 In the development of fire safety strategies for buildings, it is generally assumed that fire safety provisions are functional and operate as intended, although this is not always the case.

5.4.2 PD 7974-7:2019+A1:2021 [34] refers to US sprinkler reliability data where, for residential occupancies, 89% of relevant incidents resulted in sprinklers 'operating effectively'. In comparison, Koffel's [35] literature review on sprinkler reliability concludes that "when combining the operational effectiveness and performance effectiveness data as published in the August 2005 NFPA report, the overall reliability of automatic sprinkler systems is 91%".

5.4.3 A common criticism levied against 'novel' fire safety systems is the lack of knowledge or availability of data for their reliability and performance. However, it can be difficult to identify a system's reliability in a practical sense without their frequent inclusion in buildings, since reasonable quantification of reliability usually requires that a system is subject to a number of 'real' (i.e., non-experimental) incidents to build an adequate dataset of events.

5.4.4 In an attempt to address this issue, work has been carried out which considers fault tree analysis (FTA) and reliability targets for adequate performance of the Plumis Automist systems for specific application in dwellings. These studies are documented elsewhere [36], [37], but in summary it has been found that the target reliability for open plan dwellings is in the region of 60% for the Plumis Automist system to perform better than a residential sprinkler system incorporating concealed sprinkler heads, noting that this is described as a conservative value and 40 to 50% is referred to as achieving 'similar performance' in most cases.

5.4.5 The primary reason that the Plumis Automist system can be afforded a lesser reliability target than concealed sprinklers is due to how quickly it is able to activate and begin suppressing the fire, reducing the severity of conditions which the dwelling inhabitants may be required to escape through. The importance of this response time is demonstrated previously in Figure 2.

5.4.6 In contrast, the FTA approximates a 'conservative' worst-case reliability of 34% for the Plumis Automist system, acknowledging that it is difficult to calculate a more representative reliability owing to the inherent complexity associated with the sequence of initiation and software-related controls. In a separate sensitivity analysis on software related errors, it is suggested that a reliability of up to 87% could be achieved if the expected failure frequency class is assumed to be equivalent to a fire detection system. Hence, a wide reliability band of 34% to 87% has been identified.

5.4.7 With respect to installation, commissioning, and maintenance, the Plumis Automist system is installed by a certified and approved installer. An annual recommissioning procedure is provided by the installer to verify that the system is serviced and maintained to an adequate level of performance.

5.5 Minimum length of operation

Performance objective: the system operates for an adequate length of time.

5.5.1 BS 8458:2015 suggests that, for systems in domestic occupancies (applicable to dwellinghouses), the discharge duration should be at least 10 min from the operation of the first water mist nozzle. As noted in Section 4.2, the same expectation is applied for Category 1 sprinkler systems designed in accordance with BS 9251:2021.

5.5.2 In contrast, the Plumis Automist system is able to operate for a period of 30 min by default, which is 20 min greater than the discharge duration recommended in the standards. Therefore it can be reasonably assumed that the system will achieve an adequate length of operation to meet its performance objectives.

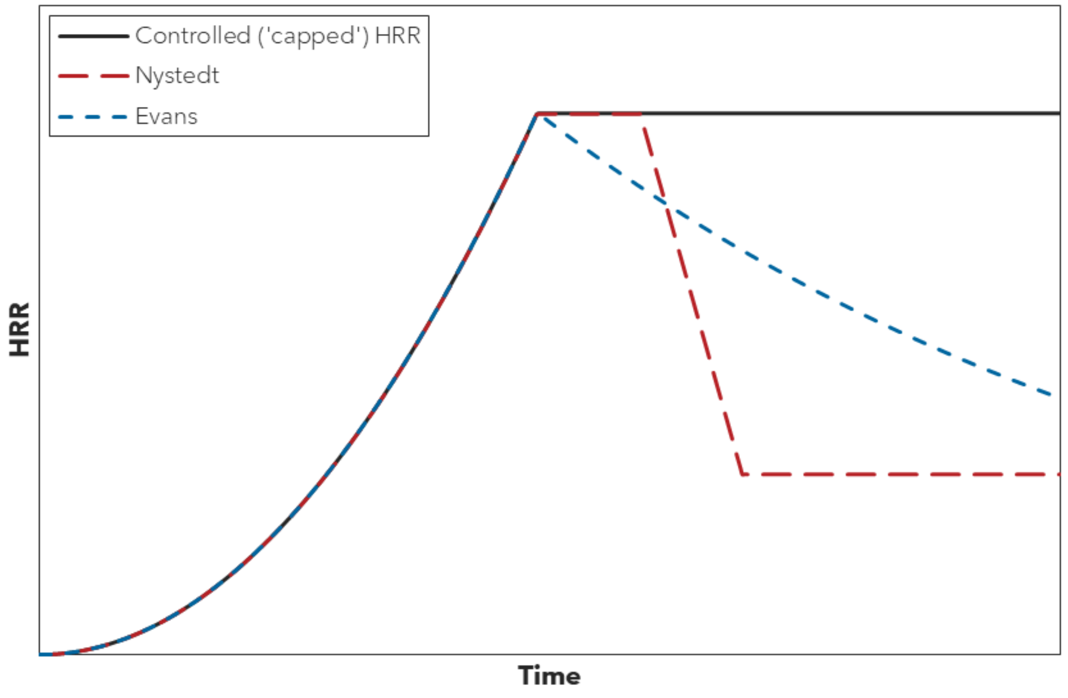


Figure 3 – Common suppression assumptions adopted for sprinkler systems

5.6 Summary

5.6.1 Table 1 provides a summary of the Plumis Automist system performance compared to the intended performance objectives of the system for domestic enclosures, focussing on compliance with standards, the system response time, suppression performance, system reliability, and its length of operation.

5.6.2 In all instances, evidence to date demonstrates that the system can typically perform equivalent to or better than the minimum expectations of a domestic sprinkler system, with the main remaining uncertainty relating to reliability of the system.

5.6.3 Therefore, in reviewing guidance recommendations for the provision of AWFSSs in both dwellinghouses (with one floor above 4.5 m from ground level) and loft conversions, it appears reasonable to assume that the Plumis Automist system can adequately support these applications in line with the guidance expectations.

5.6.4 The subsequent sections consider the use of the Plumis Automist system in dwellinghouse designs which deviate from guidance, specifically with a focus on arrangements with open plan stairs. For this, a probabilistic computational fire modelling assessment will be undertaken, similar to those detailed in NF19.

Table 1 – A summary of Plumis Automist system performance for the intended objectives

Objective	Sprinklers	Water mist	Plumis Automist	Adequate
Compliance with fire testing standards	Designed to BS 9251:2021 and tested to BS 9252:2011 or BS EN 12259-14:2020.	Tested to BS 8458:2015. Deviations from standard can be common.	Tested to BS 8458:2015 with an active BSI verification certificate. Both the test report and any deviations from the test standard are publicly documented.	✓
System response time	Concealed heads: RTI $\approx 290\ \mathrm{m}^{1/2}\mathrm{s}^{1/2}$ C-factor $\approx 0.5\ \mathrm{m}^{1/2}\mathrm{s}^{-1/2}$ Pendent heads: RTI $= 50\ \mathrm{m}^{1/2}\mathrm{s}^{1/2}$ C-factor $= 0.8\ \mathrm{m}^{1/2}\mathrm{s}^{-1/2}$	Typically equivalent to a sprinkler system but not always quantified (e.g., concealed nozzles).	Quicker than sprinklers and standard water mist nozzles. Quantified through assessment of experimental data: RTI $\approx 20\ \mathrm{m}^{1/2}\mathrm{s}^{1/2}$ C-factor $\approx 0.25\ \mathrm{m}^{1/2}\mathrm{s}^{-1/2}$	✓
Suppression performance	Historically shown to suppress and reduce the HRR of a fire.	Dependent on specific system. Suppression performance in relation to the HRR not necessarily quantified.	Demonstrated to have a similar impact on the HRR to a domestic sprinkler system.	✓
System reliability	In the region of 89 to 91% based on historical studies.	Not historically quantified due to relative novelty of the system(s).	Not historically quantified due to novelty of the system. Estimated from FTA to be in the wide band of 34 (worst-case) to 87%. For open plan design, a reliability required to perform better than a sprinkler system has been conservatively estimated as 60%, with 40-50% generally demonstrating equivalence.	✓
Minimum length of operation	10 min	10 min	30 min	✓
Early warning to occupants	Can be provided separately by an automatic fire detection and alarm system, e.g., an LD1 system designed in accordance with BS 5839-6:2019+A1:2020 [1]. Not typically a key requirement of the suppression system itself.			Not applicable

6. OPEN PLAN PROBABILISTIC MODELLING METHODOLOGY

6.1 Summary of methodology

6.1.1 Comparative analyses have been undertaken in B-RISK [30] to quantitatively assess whether a Plumis Automist system may be able to reasonably support open plan dwellinghouse designs which deviate from the recommendations of guidance. This approach compares open plan three-storey designs to dwellinghouse designs which meet the recommendations of ADB and BS 9991:2015, with an escape stair enclosed entirely in fire-resistant construction.

6.1.2 Demonstrating equivalence or improvement upon an accepted design, such as one proposed in accordance with ADB or BS 9991:2015, is considered a valid means to demonstrate a design achieves an adequate level of safety, as discussed previously in Section 3.2. Similarly, the NF19 [15] study adopted this same comparative approach to demonstrate adequacy of alternative design proposals (see Section 3.1).

6.1.3 Representative parameters for the Plumis Automist suppression system identified in Section 5 have been adopted, which include 'effective' parameters for the RTI and C factor, as well as assumptions on the system's capability to suppress fire growth.

6.1.4 For the comparative study, zone modelling software B-RISK incorporating Monte Carlo method has been used for an FED probabilistic assessment, similar to the work undertaken in NF19 [15]. Inputs for design fire parameters, sprinkler performance, behavioural assumptions, etc., have been taken from the previous studies of Hopkin et al. [38], [39] on *"probabilistic distribution functions for use in the fire safety design of residential buildings"*. Each of the dwellinghouse arrangements have been simulated for 600 iterations.

6.1.5 The simulation outcomes have been considered with respect to the FED for a single evacuating agent. The evacuating agent has been simulated for a fixed pre-evacuation time of 10 min, where the agent is assumed to be sleeping in the bedroom located furthest from the final exit (in the top floor bedroom). By comparing scenarios, it can be determined whether a design is more or less likely to result in unfavourable conditions when compared to guidance expectations (i.e., injury or fatality).

6.1.6 The analyses also exclude the effect of automatic detection and alarm system on the waking of occupants. While B-RISK allows for the inclusion of smoke and heat detectors in the model to generate detection times, it is not possible to incorporate these values into the egress path calculation automatically for use in the Monte Carlo simulations. The modelling is therefore limited to a comparison of arrangements based on internal layouts and suppression performance. A constant pre-evacuation time of 10 minutes have been chosen for both system arrangements.

6.2 Modelling tool and Monte Carlo simulations

6.2.1 The comparative analyses have been undertaken using zone modelling software B-RISK version 2021.2 [30]. B-RISK is a fire modelling software developed by BRANZ with support from the University of Canterbury, New Zealand. Incorporated into B-RISK is an underlying zone model used to calculate fire dynamics, smoke dispersion and temperature throughout compartments, with each compartment divided into two (upper and lower) gas layers. The fundamental equations are implemented as a system of differential equations which are solved to give outputs such as layer height, visibility and temperature, with respect to time. An example visualisation is presented in Figure 4.

6.2.2 The B-RISK software has been benchmarked against a series of experimental measurements from published literature and is regularly updated and tested to consider new developments. The simulated fire scenarios and geometries fall within the recommended geometric limitations of BRANZ document TR17 [40], implying that a zone model is an appropriate assessment tool for the given fire and enclosure size. B-RISK is also able to accommodate the impact of changes in enclosure temperature and the upper layer temperature, in contrast to simpler calculations methods such as directly using Alpert's ceiling jet correlation [41] alongside the differential equation of Heskestad and Bill [42]. Specifically, the NIST/JET ceiling jet model [43] has been employed within B-RISK to capture the impact of the enclosure temperature variations.

6.2.3 More detailed discussion on the validation of B-RISK for application in representing suppression systems can be found in publications by others [25], [44], [45], including for the electronically controlled water mist system nozzles used as part of the Plumis Automist system [2], [20].

6.2.4 For the probabilistic simulations, the Monte Carlo method has been applied. The Monte Carlo method involves the repeated sampling of inputs from mathematical distributions with the aim to generate a desired output distribution [46]. The Monte Carlo method has been adopted due to B-RISK allowing for an efficient method of selecting input values and its capacity to run thousands of simulations / iterations within a short timeframe.

6.2.5 Three different arrangements of open plan dwellinghouses have been simulated, each for 600 iterations, determined as an appropriate number of realisations for the outcomes to be independent of sample size when observing convergence of mean and standard deviation values of the FED.

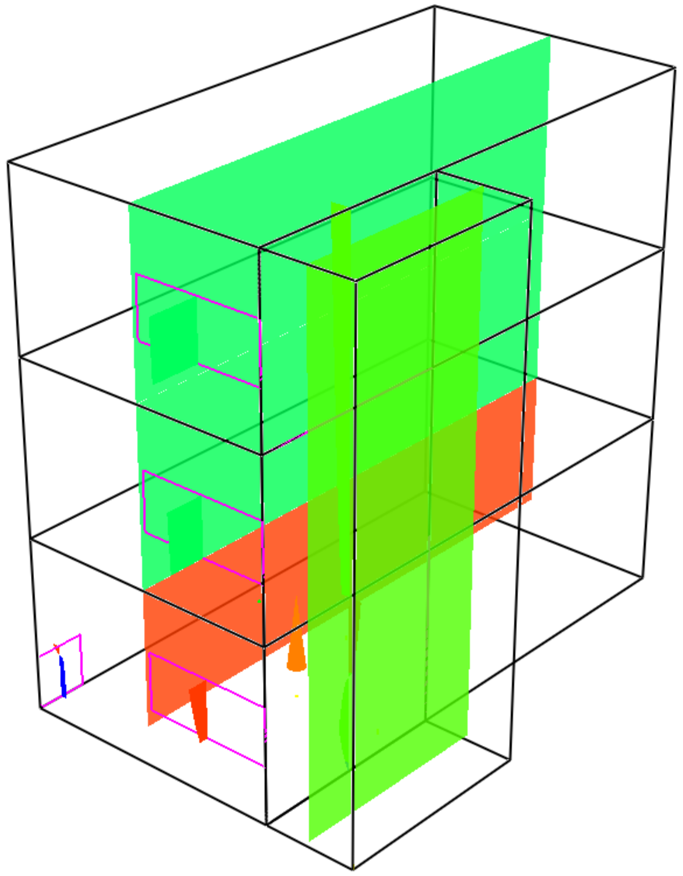


Figure 4 – Example zone model visualisation in Smokeview

6.3 Modelled dwellinghouse arrangements and fire scenarios

6.3.1 To determine a range of representative dwellinghouse arrangements, data has been reviewed from 1152 three-storey houses where the Plumis Automist suppression system has been installed to date. The coverage area, room size, ceiling height, and total room area have been assessed. The minimum, maximum, mean, and standard deviation of each of these datasets has been calculated and a normal distribution has been estimated from these parameters.

6.3.2 It is proposed that the following percentiles provide a reasonable representation of the range of three-storey dwellinghouses in which the Plumis system might be expected to be installed:

- **20th percentile** – 12.5 m^2 per storey (37.5 m^2 total) and a floor to ceiling height of 2.6 m.
- **50th percentile (mean)** – 23 m^2 per storey (69 m^2 total) and a floor to ceiling height of 2.6 m.
- **99th percentile** – 54 m^2 per storey (162 m^2 total) and a floor to ceiling height of 2.6 m.

6.3.3 In comparison, when analysing English Housing Survey (EHS) data, Hopkin et al. [47] identified that an average one-bedroom house has a mean floor area of 50.1 m^2 (from 2227 samples), compared to 88.7 m^2 for a three-bedroom house (26,678 samples). Therefore, it is considered that the arrangements assessed herein are sufficient to capture a broad representation of dwellinghouse dimensions in England.

6.3.4 A fixed floor to ceiling height of 2.6 m has been adopted throughout, which is the mean ceiling height from the full dataset. This ceiling height also broadly aligns with the 2.5 m test enclosure height for the experiments discussed previously in Section 5. As noted in the work of Hopkin et al. [20], *"by representing the water mist nozzles as equivalent to sprinkler heads which are mounted at the ceiling, there are limitations in how these assumptions can then be applied in enclosures with different ceiling heights"* (see Section 6.5). Hopkin et al. go on to hypothesise that *"taller ceilings would not significantly slow the system's activation, or alter its performance, when compared to ceiling mounted sprinkler heads. However, this would need to be verified through further experimentation."* Given these modelling limitations, no variation in the ceiling height has been applied for the different dwellinghouse arrangements.

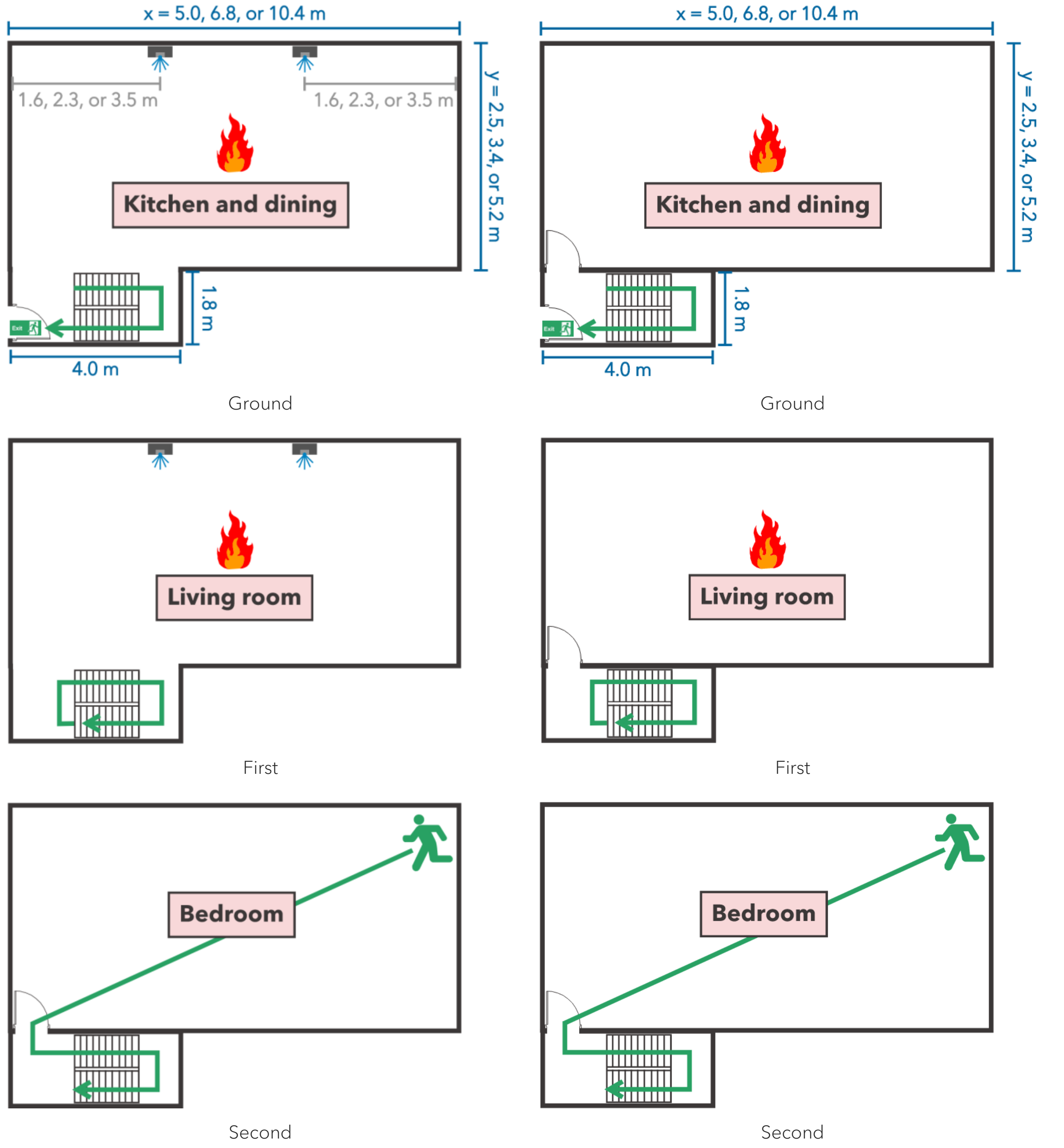
6.3.5 In each of the three above arrangements, it is assumed that a kitchen and dining area is located on the ground floor, a living room on the first floor, and a bedroom on the second (top) floor (see Figure 5). Locating the bedroom at the top floor is considered the worst-case for smoke spread and smoke filling within the dwelling while occupants may be sleeping, and it also represents the worst-case for the distances which occupants may have to traverse down the stairs to reach a place of ultimate safety.

6.3.6 For the open plan design incorporating the Plumis Automist system, an open plan dwellinghouse has been simulated for the ground and first floors, i.e., an open stair with no fire separation, as this is the worst-case for the potential for smoke spread into the stair and between storeys. The bedroom is simulated to be enclosed, since this is where sleeping occupants are located and hence ideally should be afforded fire separation from the access and egress route. This also aligns with the open plan flat arrangements described in NF19, where it is assumed in all scenarios that the bedroom is separated from the access room (living and kitchen areas).

6.3.7 In the open plan arrangement, it is assumed that the Plumis Automist system will be provided on each level where the stair is not separated (ground and first floor), with sufficient coverage area for each nozzle head in line with the DIOM manual (refer to Section 6.5).

6.3.8 For the comparative guidance-based cases, each room of the dwellinghouse has been simulated as separated from the stair, with the stair enclosed in 30 min fire-resisting construction and FD20 doors. In this arrangement, no AWFSS is incorporated into the simulations.

6.3.9 For application in zone models, the geometries have been simplified such that they can be uniformly represented in the two-dimensional plane (i.e., each zone must be resolved as a cuboid). The design fire parameters and the simulated location of the fire for the fire scenarios are discussed in Section 6.4.



(a) Open plan arrangement with Plumis Automist system

(b) Protected stair with no suppression system provided

Figure 5 – Simulated arrangements

Table 2 – Modelled geometry dimensions for three arrangements

Floor level	Room	X (m)	Y (m)	Z (m)
Arrangement 1 – 5.0 m by 2.5 m three-storey dwellinghouse (20th percentile)				
Ground	Kitchen and dining	5.0	2.5	2.6
First	Living room	5.0	2.5	2.6
Second	Bedroom	5.0	2.5	2.6
All	Stair	4.0	1.8	7.8
Arrangement 2 – 6.8 m by 3.4 m three-storey dwellinghouse (mean, 50th percentile)				
Ground	Kitch and dining	6.8	3.4	2.6
First	Living room	6.8	3.4	2.6
Second	Bedroom	6.8	3.4	2.6
All	Stair	4.0	1.8	7.8
Arrangement 3 – 10.4 m by 5.2 m three-storey dwellinghouse (99th percentile)				
Ground	Kitchen and dining	10.4	5.2	2.6
First	Living room	10.4	5.2	2.6
Second	Bedroom	10.4	5.2	2.6
All	Stair	4.0	1.8	7.8

6.4 Design fire properties

6.4.1 Table 3 provides a summary of the key design fire properties used as part of the modelling.

6.4.2 The scenarios have been considered for a fire in the ground floor kitchen and dining area, and a fire on the first floor living room area, as these fire locations are the most probable. Fires from other areas, such as bathrooms and bedrooms, have been excluded to simplify the analyses and because fires in these locations would similarly affect the open plan and guidance-based arrangements.

6.4.3 As summarised by Spearpoint and Hopkin [48] in their assessment of West Midlands Fire Service (WMFS) data, approximately 82% of fires in 'non-flats' occurred in the kitchen (71%) and living room (11%), and they therefore represent the most probable location of a dwelling fire. During typical sleeping hours, this changes to 73% of fires (52% kitchen fires, 21% living room fires).

6.4.4 The distribution function parameters in Table 3 have been largely reproduced from a recent study by Hopkin et al. [39] on *"using probabilistic zone model simulations to investigate the deterministic assumptions of UK residential corridor smoke control design"*.

Table 3 – Probabilistic design fire properties

Parameter	Value	Comments
Room of fire origin	Kitchen and dining = 71% Living room = 29%	Room of fire origin has been estimated from the work of Spearpoint and Hopkin [48] for 'sleeping hours'. B-RISK cannot yet accommodate a probabilistic approach on the fire location. Therefore, based on the percentages, 426 iterations have been simulated for the kitchen and dining area fire, and 174 iterations for the living room fire, amounting to a total of 600 iterations.
Fire growth rate	Dist: Lognormal Mean: 0.0060 kW/s^2 Std dev: 0.0145 kW/s^2 ($\mu = -2.84$, $\sigma = 0.24$)	From Hopkin et al. [49] for residential fire incidents in houses (combined room types).
Maximum fuel-bed controlled HRR	Capped based on Plumis Automist performance, otherwise: Dist: Lognormal Mean: 1200 kW Std dev: 2400 kW ($\mu = 6.29$, $\sigma = 1.27$)	
HRRPUA	Dist: Uniform Min: 320 kW/m^2 Max: 570 kW/m^2	A uniform distribution for residential occupancies has been applied from the recommendations of Hopkin et al. [50] in their review of design values for HRRPUA.
Soot yield	Dist: Lognormal Mean: 0.034 kg/kg Std dev: 0.036 kg/kg ($\mu = -3.76$, $\sigma = 0.04$)	Expanding on the work of BRANZ Study Report 185 [51], the distribution function has been estimated from a collation of 66 furniture fire experiments detailed in 'combustion behaviour of upholstered furniture' (CBUF) [52], Babrauskas and Krasny [53], Gann et al. [54], and Fang and Breese [55]. It is important to note that the selected soot yield will have a negligible impact on the sprinkler activation time, estimated HRR, and production of CO. As such, it would not be anticipated to alter the outcome of the assessment.
Carbon monoxide (CO) yield	0.04 kg/kg to 0.3 kg/kg Automatically calculated as a function of the global equivalence ratio (GER)	B-RISK incorporates an automatic calculation to estimate the CO yield as a function of the GER, where the GER is the ratio of fuel mass loss rate within the compartment to the air flow rate into the compartment, normalised by the stoichiometric ratio for the fuel. Therefore, the fuel yield can vary as a function of the ventilation conditions of the fire, where a well-ventilated fire produces less CO compared to an under-ventilated fire. B-RISK applies a linear correlation adapted from the work of Gottuk et al. [56] for various fuels (hexane, polymethyl methacrylate [PMMA], spruce, and polyurethane). For a GER of 0.6 or less, a CO yield of 0.04 kg/kg is estimated within B-RISK, and this value linearly increases to 0.3 kg/kg up to a GER of 1. Beyond a GER of 1, the CO yield remains fixed at 0.3 kg/kg.
Effective heat of combustion	Dist: Truncated normal Mean: 18.3 MJ/kg Std dev: 5.4 MJ/kg Min: 11.9 MJ/kg Max: 35.1 MJ/kg	A normal distribution function has been estimated from 13 experiments of upholstered furniture fires by Babrauskas et al. [57].
Radiative fraction	Dist: Uniform Min: 0.31 Max: 0.59	A uniform distribution function has been specified for a range of cellulosic and non-cellulosic fuel types detailed in PD 7974-1:2019 [29].
Elevation of the fuel bed	Dist: Fixed Value: 0.0 m	In the absence of a distribution function for the elevation of the fuel bed available in research literature, the fuel bed is assumed to be fixed at floor level.

6.5 Plumis Automist system properties

6.5.1 Table 4 provides the modelling inputs adopted for the Plumis Automist nozzles in the room of fire origin. Spearpoint et al. [2] propose that the activation of the electronically controlled water mist nozzles can be represented by thermal sensitivity parameters for an 'equivalent' sprinkler system. That is, the system can be represented as a series of ceiling-mounted sprinklers with effective parameters for the RTI, C factor, rated temperature, and offset below the ceiling. For the radial distance, Spearpoint et al. estimated this by using the distance between the centreline of the fire and the detection element (i.e., the nozzle). Therefore, the same approach to representing the system activation has been adopted in the modelling presented herein.

6.5.2 Where a suppression system successfully activates but 'suppression' does not occur, B-RISK adopts a method consistent with that shown in Figure 3 previously where, upon activation, the fire is capped at a constant HRR. When applying a value for suppression likelihood, B-RISK can also simulate the impact of suppression on the reduction in the HRR using an algorithm developed by Evans [33] for unshielded furniture fires (also presented in Figure 3). Both methods have been represented in the modelling depending upon the reliability and suppression likelihood. In the case of a failure in reliability, the fire is allowed to continue to grow to either its fuel-bed or ventilation-controlled state.

6.5.3 As discussed in Section 5.3, Hopkin et al. identified that applying the Evans model for a 0.07 mm/s equivalent sprinkler spray density provided closest agreement between zone model simulations and experimental data, and hence this has been captured in the modelling methodology. This value is not intended to be representative of the discharge rate of the Plumis Automist system and is only used as a means of assessing the impact of the system on the HRR.

Table 4 – Probabilistic modelling inputs for the Plumis Automist system

Parameter	Value	Comments
Offset below ceiling	50 mm	From the calibration studies of Hopkin and Spearpoint [25].
Shortest radial distance of Automist nozzle from axis of fire	Dist: Truncated normal Mean: 1.5, 2.1, or 3.2 m Std dev: 0.7, 0.9, or 1.4 m Min: 0.0 m Max: 3.1, 4.1, or 6.2 m	The Plumis Automist system is designed to protect an area within 6 m of each nozzle for 90° radius, which an objective to achieve coverage of all area within the room with an allowance of up to 1.1 m^2 of unprotected space per room [20]. The shortest radial distance (r, m) has been estimated for each arrangement for the arrangements shown in Figure 5. This has been determined using the principles given by Fraser-Mitchell and Williams [60], by applying the Pythagorean theorem: $r = \sqrt{x^2 + y^2}$ where x (m) and y (m) are the distance of the flame centreline to the nozzle in the x and y directions, based on the nozzle location(s) given in respective flat arrangements.
Ambient temperature	20 °C	For a typical indoor temperature.
Rated temperature	68 °C	Based on the work of Spearpoint et al. [2] for electrically controlled water mist nozzles.
RTI	$20\ m^{1/2}s^{1/2}$	
C factor	$0.25\ (m/s)^{1/2}$	
Equivalent discharge density	0.07 mm/s	As discussed by Hopkin et al. [20], this equivalent sprinkler discharge density was found to provide reasonable agreement with experimental data for the Plumis Automist system. It is not intended to be representative of the actual discharge rate achieved by the system.
Reliability (System actuation and controlled fire)	Dist: Truncated normal Mean: 60% Std dev: 13% Min: 34% Max: 87%	A distribution has been approximated from the discussion provided in Section 5.4.
Suppression likelihood (following successful actuation)	70%	A fixed likelihood of 70% has been applied from the tests detailed in Hopkin et al., where it was found that in 3 of the 11 fire tests the heat output did not reduce upon system activation, but was more akin to a 'steady state' fire. Elsewhere, the HRR was shown to decay following the Evans model.

6.6 Ventilation and window properties

6.6.1 Table 5 provides the window dimensions for all scenarios. These are windows situated in the kitchen and dining area, living room, and bedroom, and these have been estimated based on approximately 1/20th of the floor area of each room, as per Approved Document F [61] for purge vent.

6.6.2 The glass of the windows is simulated to break using the glass fracture model built into B-RISK. This model is based on the work of Parry et al. [62] and the fracture time estimations of the model have been benchmarked against experimental data. The model simulates the entire failure of a window area once the glass has reached its point of fracture.

6.6.3 The window area and associated breakage has the potential to affect the HRR by limiting the available oxygen for the fuel to burn. Within B-RISK, the fire is capped at the point in time when the HRR first diverges from the specified input HRR due to insufficient oxygen for complete combustion. The design fire parameters are discussed in Section 6.4.

6.6.4 The B-RISK software provides an idealised representation of air flow within the domain, i.e., it considers that the enclosure is perfectly sealed aside from any user specified openings. In practice, the enclosures will incorporate natural air flow resulting from factors such as leakages through wall and ceiling construction, around window gaps (and through any open windows), through door gaps, etc. Therefore, to represent this, openings have been provided within the simulations to support the onset of combustion prior to any fire-induced glazing failure. This initial opening is positioned at low level, with an area of circa 2 m^2, to allow for enough oxygen to reach the fuel bed to sustain the HRR development while minimising smoke and heat losses from the room of fire origin. This is consistent with the approach adopted in BD 2410 [63] and is a method also recommended in SCA guidance [64].

6.6.5 A limitation of this approach is that the assumed low-level vent has been specified independently of the window area of the dwelling. This vent area could subsequently have an impact on the estimated conditions within the enclosure of fire origin and any connecting rooms.

6.7 Surface properties

6.7.1 Table 6 provides the surface properties adopted for the modelling geometry. All wall, ceiling, and object construction has been modelled as 15 mm thick gypsum plasterboard surfaces based on properties defined by Hopkin et al. [65] and slabs have been simulated with concrete properties estimated from BS EN 1992-1-2:2004+A1:2019 [66].

6.7.2 It is acknowledged that adopting the properties given in Table 6 is a considerable simplification of the wider range of building materials which could be used in practice. However, the intention of adopting these properties is not to provide a detailed representation of the building materials but instead to produce a more representative estimation of temperature losses at the boundaries than if fixed temperature Dirichlet boundary conditions were adopted (i.e., using an inert boundary).

6.8 Internal door closing behaviours

6.8.1 As discussed by Hopkin et al. [67], internal doors are not expected to include self-closing devices under contemporary fire safety guidance. This change to guidance was made in 2006, where work by Andrew Irving Associates [68], [69] and Colwell [70] identified that a significant proportion of occupants either propped open, disabled, or tampered with self-closing devices for a variety of reasons. It was concluded that *"there* [is a] *consensus that self-closing devices could be a nuisance…"*, it was *"fairly common practice to wedge doors open more or less permanently"* [68] and *"for the majority of those properties where self-closing devices are provided, users are likely to disable them to meet family needs"* [70]. Subsequent work by McDermott et al. [71], which described 40 interviews with occupants inhabiting new homes, concluded that in all private dwellings with self-closing fire doors, the occupants reported interfering with the self-closing mechanism. In reviewing these previous studies and analysing survey responses from a wide range of individuals in the UK, Hopkin et al. concluded that *"the analyses […] ultimately point towards the potential for daily household activities to take priority over the safety benefits which internal doors can provide"*, suggesting that designers should consider fire safety measures (such as suppression and smoke detection) which do not noticeably affect the daily needs and activities of households.

6.8.2 Therefore, the influence of occupant door closing habits and behaviours can play a key role in smoke spread and have been incorporated into the modelling, consistent with the methodology of NF19. The probabilities of doors being open or closed have been sourced from the work of Hopkin et al. [67] on internal door closing habits in domestic premises, for the door closing probabilities of respondents who lived in houses (shown in Table 7). The door habits for sleeping occupants have been adopted, based on the behavioural assumptions discussed in Section 6.9. All doors have been modelled with dimensions of 0.8 m wide by 2.0 m high.

Table 5 – Window dimensions adopted for modelling

Window	Location	Window dimensions	Total area
1	Kitchen and dining	Sill height: 1.1 m Opening width by height: 2.5 m by 1.1 m	2.75 m^2
2	Living room	Sill height: 1.1 m Opening width by height: 2.5 m by 1.1 m	2.75 m^2
3	bedroom	Sill height: 1.1 m Opening width by height: 2.5 m by 1.1 m	2.75 m^2

Table 6 – Surface properties

Parameter	Materials	
	Concrete	Gypsum plasterboard
Surface	Slabs	Walls, ceilings, and other obstructions
Thickness	100 mm	15 mm
Density	2300 kg/m^3	780 kg/m^3
Specific heat	0.90 kJ/kg/K	0.95 kJ/kg/K
Thermal conductivity	1.40 W/m/K	0.25 W/m/K
Emissivity	0.7	0.7

Table 7 – Probability of doors being closed while dwelling occupants are sleeping [67]

Room	Probability closed
Kitchen	49%
Living room	52%
Bedroom	47%

6.9 Tenability, evacuation and other behavioural assumptions

6.9.1 The analyses consider the tenability of a single agent located in the bedroom on the top storey of the dwellinghouse. Only a night-time scenario has been considered, where the agent is assumed to be sleeping. This represents the period where occupants may be most vulnerable and are more likely to produce prolonged pre-evacuation times [72], and therefore may be subject to fire and smoke conditions for a greater period than if they were awake.

6.9.2 The analyses consider agents to initially be located in the bedroom for a 10 min (600 s) period. This represents the time required for occupants to wake up and begin evacuation, consistent with the methods adopted in NF19. The 10 min pre-evacuation time is also consistent with PD 7974-6:2019 [73], in which it represents the 99th percentile pre-evacuation time for sleeping and familiar occupants in dwellings (A1 alarm system and M2 management level).

6.9.3 The analyses do not take into consideration the impact of automatic detection and alarm on the waking of agents, with the focus of the study being placed on the performance of the Plumis Automist suppression system.

6.9.4 B-RISK can calculate the FED along a defined egress path, where the egress path adopts a fixed monitoring height in a specified room. To represent movement from room to room, egress path segments can be defined by assuming a time interval, used to represent the period the agent is within each enclosure.

6.9.5 FED is typically a measure of airborne pollutants (irritants and asphyxiants) inhaled by occupants, where toxins, such as CO, accumulate over time during occupant evacuation in a building impacted by fire. The results focus on FED of gases for CO, consistent with NF19, at a height of 2 m from floor level at values above 0.3 and equal to 1.

6.9.6 PD 7974-6 [73] suggests a tenability limit of 0.3 for FED for populations, not including vulnerable sub-populations, representative of *"incapacitation of <1% of the exposed population"*. In addition, an FED of 1 is described as *"representing the dose statistically estimated to result in incapacitation of 50% of the exposed population"*.

6.9.7 For the time spent within each room, agents are assumed to be sleeping and initially located in the bedroom, with a pre-evacuation time given previously. In addition to this, agents have a travel time in the bedroom, plus a travel time in the stair. This is a simplified representation of evacuation, where in reality it may be expected that occupants perform multiple action tasks in different rooms as part of the evacuation, such as investigating the situation, fighting the fire, dressing and gathering family members and belongings [74]. The egress path for the arrangements is given in Table 8.

6.9.8 Travel times within rooms have been calculated using travel distance and a fixed travel speed. From a collation of empirical evacuation studies with non-irritant smoke, Fridolf et al. [75] proposes a minimum walking speed of 0.2 m/s (for a visibility of 0 m). In comparison, the SFPE Guide to Human Behaviour in Fire [76] specifies *"for non-irritant and moderately irritant smoke, the minimum speed in darkness is 0.3 m/s"*. This 0.2 m/s minimum walking speed has been universally adopted for the representation of movement along the egress path, with no variation in walking speed because of changes in visibility. In practice, it would be expected that the walking speed would be faster for higher visibilities. However, due to limitations in the representation of human behaviour and interaction with fire and smoke in the chosen model, variable walking speed cannot yet be incorporated in this manner.

Table 8 – Egress path for each arrangement

Phase	Occupant location	Distance	Elapsed time in room
Arrangement 1 – 5.0 m by 2.5 m three-storey dwellinghouse (20th percentile)			
Pre-evacuation (sleeping)	Bedroom	–	600 s
Evacuation from bedroom	Bedroom	~ 5.6 m	+ 28 s
Evacuation via stair	Stair	~ 13.5 m	+ 68 s
		Time to a place of ultimately safety	**696 s**
Arrangement 2 – 6.8 m by 3.4 m three-storey dwellinghouse (mean, 50th percentile)			
Pre-evacuation (sleeping)	Bedroom	–	600 s
Evacuation from bedroom	Bedroom	~ 7.6 m	+ 38 s
Evacuation via stair	Stair	~ 13.5 m	+ 68 s
		Time to a place of ultimately safety	**706 s**
Arrangement 3 – 10.4 m by 5.2 m three-storey dwellinghouse (99th percentile)			
Pre-evacuation (sleeping)	Bedroom	–	600 s
Evacuation from bedroom	Bedroom	~ 11.6 m	+ 58 s
Evacuation via stair	Stair	~ 13.5 m	+ 68 s
		Time to a place of ultimately safety	**726 s**

7. OPEN PLAN PROBABILISTIC MODELLING RESULTS AND CONCLUSIONS

7.1 FED analysis outcomes

7.1.1 Figure 6 shows the comparison of results for the open plan arrangement with Plumis Automist and the guidance-based, protected stair arrangement with no suppression. This is considered in terms of the FED (CO) exceedance probability at 0.3 and 1. These probabilities are broadly representative of the likelihood of an injury and the likelihood of a fatality from the inhalation of toxic gases (see Section 6.9).

7.1.2 In all instances, the open plan arrangement with the Plumis Automist system is shown to produce fewer incidents which result in injury or fatality compared to the guidance-based design with a protected stair enclosure and no suppression:

- For **Arrangement 1**, an FED of 1 is shown to occur in 1% of simulations for the open plan arrangement and this increases to 1.6% for the guidance-based arrangement. Inclusive of cases where the FED is ≥0.3, this rises to 5.3 and 6.1%, respectively.
- In the case of **Arrangement 2**, the difference in the results is more pronounced, with an FED of 1 in 0.8% for the open plan arrangement and 2.1% for the guidance-based arrangement. For an FED ≥0.3, it is 4.8% and 10.8%, respectively.
- Finally, for **Arrangement 3**, a lower likelihood of injury and fatality is observed overall, likely owing to the larger volume dimensions and a greater reservoir available for smoke spread and dispersal. The open plan arrangement is shown to produce an FED of 1 in 0.2% of instances and ≥0.3 in 2.3%, compared to 0.8% and 4.1% for the guidance-based arrangement.

7.1.3 The findings of the comparative analysis highlight that the Plumis Automist suppression system has the potential to adequately accommodate a representative range of open plan, three-storey dwellinghouse arrangements which deviate from the recommendations of guidance.

7.2 Conclusions

7.2.1 In carrying out a review of both the performance objectives of suppression systems in dwellinghouses and the Plumis Automist documentation and research to date, sufficient evidence has been found to indicate that the system can typically perform equivalent to or better than the minimum expectations of a domestic sprinkler system conforming to BS 9251:2021. By extension, it therefore appears reasonable to assume that the Plumis Automist system can adequately support any applications which are otherwise in line with guidance expectations.

7.2.2 Consideration has also been given to more 'open plan' designs which deviate from guidance, through a probabilistic computational fire modelling assessment of a series of representative dwellinghouse arrangements. Overall, the inclusion of a Plumis Automist suppression system in a three-storey dwellinghouse arrangement with an open plan stair is shown to produce a design scenario which is no more likely to result in injury or fatality during a fire than an accepted design that follows recognise fire safety guidance, such as ADB [6] or BS 9991:2015 [8]. As such, it appears a reasonable approach for the Plumis Automist system to be adopted as part of a performance-based, fire-engineered solution where a three-storey dwellinghouse arrangement deviates from the guidance recommendations.

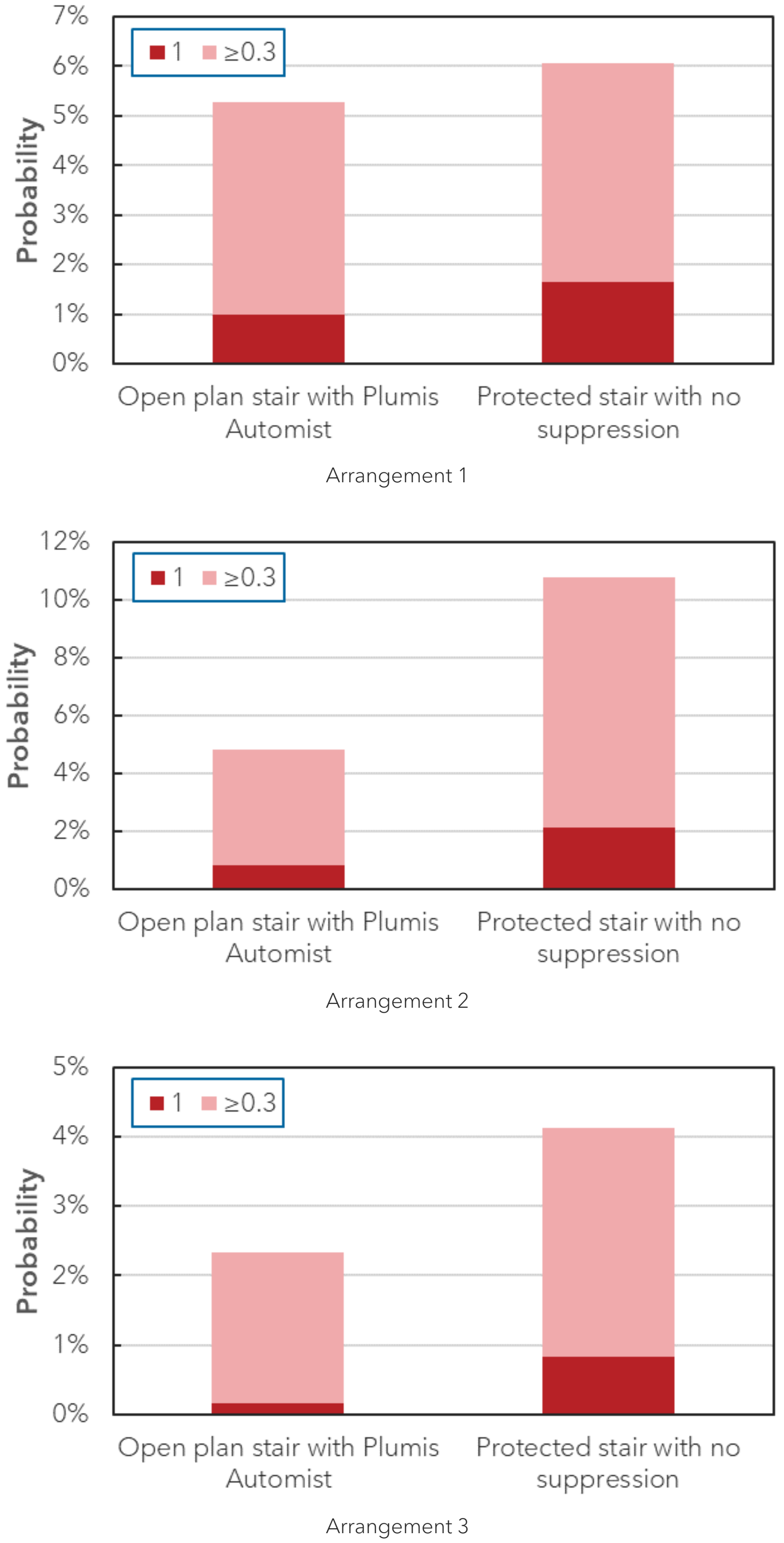


Figure 6 – FED (CO) outcomes of the comparative probabilistic assessment

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