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Plumis Suppression System Reliability Research

Reliability Target of the Plumis Suppression System

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Registered Office | 30-32 Gildredge Road, Eastbourne, East Sussex, BN21 4SH
Telephone | 0203 9956 600 | 0121 8099 700
Email | enquiries@ashtonfire.com
Website | www.ashtonfire.com
Company Number | 12044770

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JHL	Jun Heng Low BEng (Hons) MSc AIFireE MSFPE	Fire Engineer CFD
CGH	Charlie Hopkin MEng (Hons) PhD CEng MIMechE MIFireE PMSFPE	CFD Lead / Associate

The checker has provided an internal review of the technical content of the report.

The approver confirms the report has received quality assurance in accordance with the principles of ISO 9001 and authorises external release of the document on behalf of Ashton Fire.

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1. INTRODUCTION

1.1 General

1.1.1 Ashton Fire have been commissioned by Plumis to undertake further research on the reliability and performance of the Plumis suppression system(s).

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1.1.3 This document outlines the studies of reliability and performance for the Plumis suppression system by benchmarking to a residential sprinkler system in its performance for open plan apartments. The purpose of the comparative study is to identify a system reliability (or 'target reliability') necessary for the Plumis suppression system to achieve equivalent estimated performance to a sprinkler-protected arrangement in terms of fractional effective dose (FED) assessment, which meets the recommendations of contemporary guidance.

1.2 Reference information

1.2.1 This document primarily based on information produced in the first phase of the research. This includes 'effective' parameters for the response time index (RTI) and conductivity factor (C factor), as well as assumptions on the system's capability to suppress fire growth. Such work has been published by Spearpoint et al. [1] on the activation of electronically controlled watermist system in the *Fire Safety Journal*.

1.2.2 Elsewhere, reference is made to relevant standards, research publications and online resources. These are cross-referenced throughout the document and a list of all citations can be found in Section 5.

1.2.3 The Plusmis Automist system layout provided by Plumis to Ashton Fire for this analysis is listed in Table 1.

Table 1 – Reference documentation

Description	Reference	Revision	Author
NF19 Case 1c – Using fire protection from Plumis	164509781759	-	Plumis
NF19 Case 2 c – Using fire protection from Plumis	164509822959	-	Plumis

1.3 System description

1.3.1 The Plumis Automist Smartscan Hydra system (referred to hereafter as the 'Plumis Automist' system for brevity) is a residential watermist system. The system does not operate in the same way as traditional mist systems but instead is activated by a wireless / wired smoke or heat (or combined smoke and heat) detector.

1.3.2 Following this activation, the system uses an infrared (IR) thermopile sensor located within the nozzle head(s) to scan the room. When scanning the room, 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 temperature exceeds a given threshold, the head is deemed to have successfully located a fire and discharges water droplets in the direction of where the high temperature readings have been observed. The water is discharged by the activation of a high-pressure pump, driving mains-linked water through the nozzle unit, with the nozzle achieving a water rate discharge of around 5.6 L/min.

1.3.3 The Plumist Automist spray nozzles are wall mounted and positioned around light switch height, e.g., 1.45 m from floor level. In positioning the heads at this height, the intent is for the water spray to be entrained in the fire plume and to minimise what Plumis deems to be 'ineffective' evaporation in the upper, hot smoke layer.

1.3.4 Visualisations of the system configuration are presented in Figure 1, taken from the official Plumis website [2]. Full design information of the system can be found in the DIOM manual.

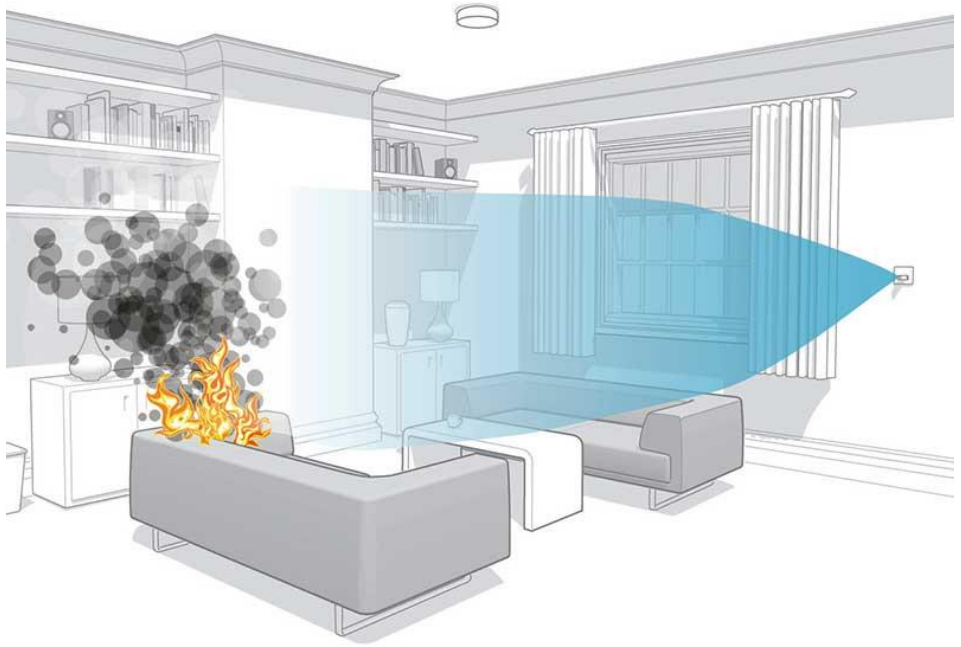

Figure 1 – Visualisation of the Plumis Automist system configuration with a nozzle discharging water towards a fire.

1.4 Purpose of research

1.4.1 As discussed in Section 1.3, the Plumis Automist system is a new innovative suppression system that does not behave the same way as a sprinkler or watermist system. However, fire engineers require input parameters and assumptions necessary to represent these systems in performance-based assessments.

1.4.2 The two main elements of estimating activation time for sprinkler heads are RTI and C factor. They are empirical parameters specified for sprinklers, where the RTI represents the thermal time constant for the heat-responsive element in relation to velocity and convective heat transfer, while the C factor characterises the heat loss to the sprinkler housing due to conduction [2].

1.4.3 Given the complexities associated with representing the Plumis Automist system in a simple zone model, an approach has been taken whereby it is assumed the system operates in a similar fashion to a sprinkler system. As such, the first phase of the research was to determine 'effective' parameters for the RTI and C factor of a Plumis Automist system. Such work has been carried out by Spearpoint et al. [1] to determine the 'effective' values for RTI and C factor to provide reasonable agreement to the experimental data using B-RISK modelling software.

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

1.4.5 To address this issue, a fault tree analysis (FTA) or failure modes and effects analysis (FMEA) is to be undertaken by another party, while the work detailed in this report is intended to determine a target reliability for the Plumis Automist system. This research work is essentially to establish how well the performance of the Plumis Automist system must be in order to be comparable to a residential sprinkler system with concealed sprinkler heads, in terms of system reliability.

1.4.6 The reliability target determined in this document focusses exclusively on the use of suppression systems in accommodating open plan living in residential apartments. It does not consider the potential impacts the adopted suppression system can have on building design and fire safety strategies, such as occupant travel distances, compartmentation, smoke control, structural fire resistance ratings, etc.

1.4.7 This report outlined the methodology, selected parameters, results and conclusion of the studies. It is anticipated that the target reliability identified in the FED assessment will be used to compare to the probability range estimated in a fault tree analysis, to determine whether the level of performance needed by the system to achieve adequate safety is similar to that which might be expected in practice.

2. METHODOLOGY

2.1 Summary of methodology

2.1.1 Comparative analyses have been undertaken in B-RISK [3] to demonstrate the system reliability equivalency of the Plusmis Automist system to a traditional residential sprinkler system. The representative parameters for the Plumis suppression system identified in the first phase of the research 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.

2.1.2 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 the NF19 open plan flats study [4]. Inputs for design fire parameters, sprinkler performance, behavioural assumptions, etc., have been taken from the previous studies of Hopkin et al. [5], [6] on 'probabilistic distribution functions for use in the fire safety design of residential buildings'. Each of the system arrangements have been simulated for 1000 iterations.

2.1.3 The system reliability (or 'target reliability') necessary for the Plumis suppression system has been identified such that it achieves similar performance to a sprinkler-protected arrangement in terms of FED outcomes (see Section 2.10). This is achieved by simulating the sprinkler-protected case with a fixed reliability of 89% from PD 7974-7:2019+A1:2021 [7], and then simulating the Plumis suppression system iteratively, with differing reliabilities, until approximate equivalence is demonstrated.

2.1.4 It is important to note that the analyses only consider the reliability performance and not the suppression performance of the system. The suppression performance is beyond the scope of this study, but ongoing research based on Plumis experimental data has thus far indicated that the application of traditional suppression assumptions of sprinkler-capping and sprinkler-decay can be extended to the Plumis suppression system.

2.1.5 As such, in all cases where a sprinkler system or Plumis Automist system is successfully actuate, the fire is capped at a constant HRR, consistent with Figure 6.4 of CIBSE Guide E [8]. Such approach allows consistent observations of FED along egress path across the two different systems, with variation of system reliability only.

2.1.6 The analyses also exclude the effect of automatic detection and alarm system on the waking of occupants. A constant pre-evacuation time of 10 minutes have been chosen for both system arrangements.

2.2 Modelling tool

2.2.1 The comparative analyses have been undertaken using zone modelling software B-RISK version 2020.03 [3]. 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 2.

2.2.2 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 [9], implying that a zone model is an appropriate assessment tool for the given fire and enclosure size.

2.2.3 Hopkin and Spearpoint [2] identified that B-RISK is able to provide a reasonable but conservative estimation of sprinkler activation times compared to experimental data, and therefore it is considered an appropriate tool for the research problem. 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 [10] alongside the differential equation of Heskestad and Bill [11]. Specifically, the NIST/JET ceiling jet model [12] has been employed within B-RISK to capture the impact of the enclosure temperature variations. For the Plumis suppression system, refer to discussion in Paragraph 1.4.3.

2.2.4 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 [13]. 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.

2.2.5 Two types of open plan flat, 8 m by 4 m one-bedroom flat and 10 m by 8 m two-bedroom flat, have been simulated, each for 1000 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.

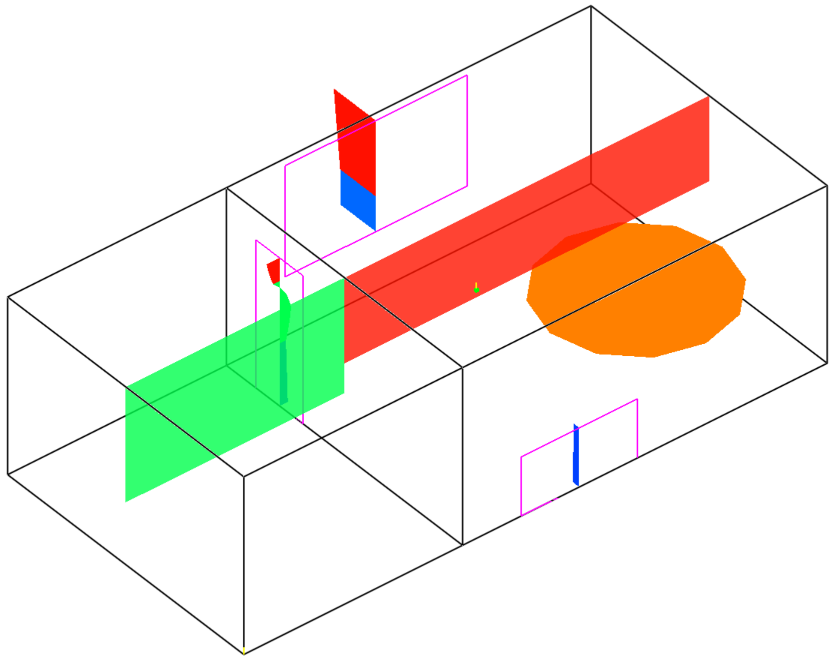

Figure 2 - Zone model visualisation in Smokeview for an 8 m by 4 m flat

2.3 Modelled flat arrangement and fire scenarios

2.3.1 Two flat arrangements have been considered in this assessment, one for an 8 m by 4 m open plan flat with an unenclosed kitchen, another for a 10 m by 8 m open plan flat with an enclosed kitchen. These flat enclosure dimensions align with the NF19 open plan flats study and the recommendations of BS 9991:2015 [14]. When analysing English Housing Survey (EHS) data, Hopkin et al. [15] identified that an average one-bedroom apartment has a floor area of 44.9 m^2 (from 7099 samples), compared to an average of 81.9 m^2 (from 1309 samples) for three-bedroom apartments. Data from Scott Wilson [16] suggests a mean floor area of 46.6 m^2 and 86.5 m^2 for one-bedroom and three-bedroom flats, respectively. Therefore, it is considered that the arrangements assessed herein are sufficient to capture a broad representation of typical flat dimensions in the UK.

2.3.2 Figure 3 presents Arrangement 1, an 8 m by 4 m open plan flat with unenclosed kitchen, Scenario 1 denotes the arrangement simulated with sprinkler protection, whereas Scenario 2 represents the same arrangement simulated with Plumis Automist protection. 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). For all scenarios, the bathroom has been excluded (or captured in the living / kitchen enclosure) for simplification. By excluding the bathroom, this is not anticipated to affect the results when comparing the two systems.

2.3.3 Likewise, Arrangement 2 for a 10 m by 8 m open plan flat with enclosed kitchen is shown in Figure 4. Scenarios 3 and 4 denote the arrangement simulated with sprinkler protection and Plumis Automist protection, respectively.

2.3.4 The design fire parameters and the simulated location of the fire for these fire scenarios is discussed in Section 2.4.

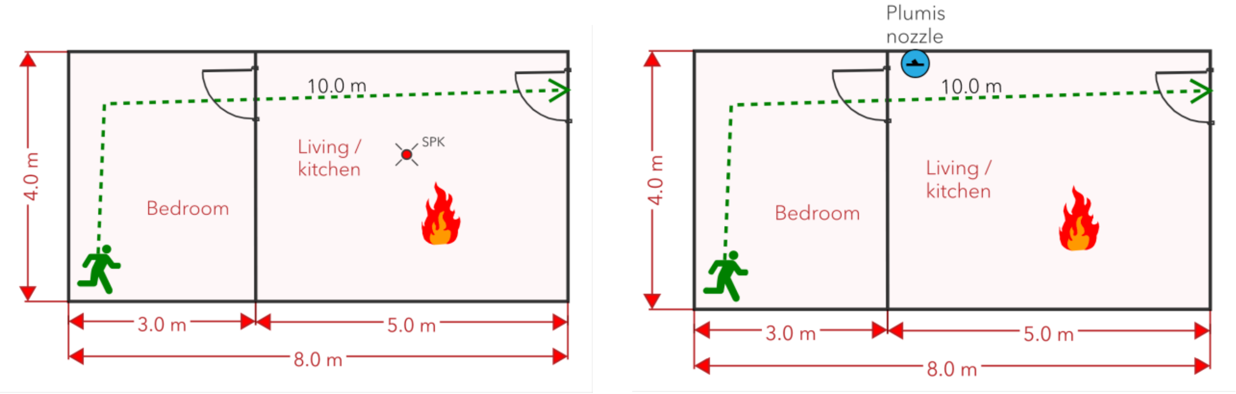

Figure 3 – Modelled geometry layout for Arrangement 1, Scenario 1 (left) and 2 (right)

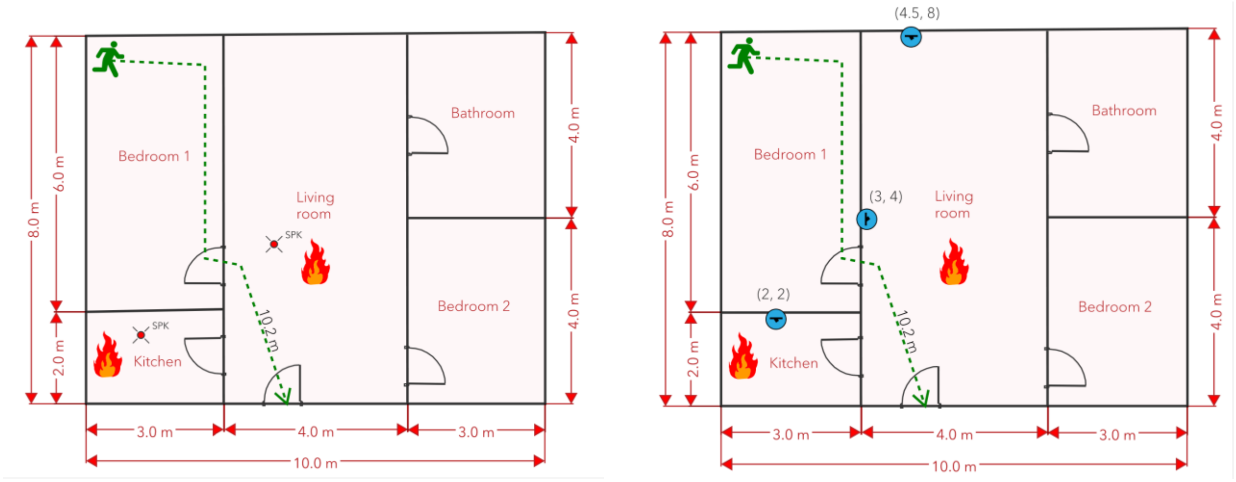

Figure 4 – Modelled geometry layout for Arrangement 2, Scenario 3 (left) and 4 (right)

Table 2 – Modelled geometry dimensions for Arrangement 1 and 2

Room	X (m)	Y (m)	Z (m)
Arrangement 1 – 8 m by 4 m flat			
Living room/kitchen	5.0	4.0	2.4
Bedroom	3.0	4.0	2.4
Arrangement 2 – 10 m by 8 m flat *			
Living room	4.0	8.0	2.4
Kitchen	3.0	2.0	2.4
Bedroom 1	3.0	6.0	2.4

* Bathroom and Bedroom 2 have not been included in the modelling as occupants are assumed to be located in Bedroom 1, for a fire in either the kitchen or living room, and thus the bathroom and bedroom have limited interaction with the fire.

2.4 Design fire properties

2.4.1 Table 3 provides a summary of the key design fire properties used as part of the modelling. The scenarios have been considered for a fire in the living room and/or kitchen as these fire locations are far more 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 both arrangements.

2.4.2 As summarised by Spearpoint and Hopkin [17] in their assessment of West Midlands Fire Service data, approximately 88% of fires in flats occurred in the kitchen (76%) and living room (12%), and they therefore represent the most probable location of a dwelling fire. While occupants are sleeping, this changes to 83% of fires (66% kitchen fires, 17% living room fires).

2.4.3 B-RISK cannot accommodate probabilistic approach on the fire location, therefore for the 10 m by 8 m flat (Arrangement 2). Therefore, based on the above statistics, 136 iterations have been simulated for living room fire, and 864 iterations simulated for kitchen fire, amounting to a total of 1000 iterations.

2.4.4 The distribution function parameters have been largely reproduced from a recent study by Hopkin et al. [6] 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
Fire growth rate	Dist: Lognormal Mean: 0.0062 kW/s^2 Std dev: 0.0140 kW/s^2	From Hopkin et al. [18] for residential fire incidents in flats.
Maximum fuel-bed controlled HRR	Capped based on sprinkler performance, otherwise: Dist: Lognormal Mean: 1000 kW Std dev: 2300 kW	
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. [19] in their review of design values for HRRPUA.
Soot yield	Dist: Lognormal Mean: 0.034 kg/kg Std dev: 0.036 kg/kg	Expanding on the work of BRANZ Study Report 185 [20], the distribution function has been estimated from a collation of 66 furniture fire experiments detailed in 'combustion behaviour of upholstered furniture' (CBUF) [21], Babrauskas and Krasny [22], Gann et al. [23], and Fang and Breese [24]. It is important to note that the selected soot yield will have a negligible impact on the sprinkler activation time and estimated HRR.
Carbon monoxide (CO) yield	Pre-flashover: 0.04 kg/kg Post-flashover: 0.4 kg/kg	Selected from the recommendations of C/VM2 [25] for pre- and post-flashover design fire characteristics. These values are broadly derived from the work of Wade et al. [26] and Robbins and Wade [27], where the CO yields are for a 100% polyurethane fire and therefore represent conservative values.
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. [28].
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: Truncated normal Mean: 0.5 m Std dev: 0.6 m Min: 0.0 m Max: 2.2 m	From the work of Hopkin et al. [30] on safety factors, albeit the distribution is described as *"arbitrarily selected (with no known literature available to the authors)"*. For reference, C/VM2 [31] recommends an elevation of 0.5 m from floor level, the mean of the adopted distribution function.

2.6 Probabilistic sprinkler properties and concealed residential sprinkler heads

2.6.1 Table 4 provides the modelling inputs adopted for the sprinkler head in the room of fire origin for the scenario incorporating sprinkler protection (Scenario 1 and 3). A fixed reliability value of 89% has been assigned to the sprinkler to consider its effect on the HRR of the fire. In the case of sprinkler failure, the fire is allowed to continue to grow to either its fuel-bed or ventilation-controlled state.

2.6.2 Where sprinklers successfully actuate, B-RISK adopts a method consistent with Figure 6.4 of CIBSE Guide E [8] where upon actuation, the fire is capped at a constant HRR.

2.6.3 It is common for sprinkler heads in residential buildings to be of the concealed type, and a practical approach to estimating their activation time is to assume that the concealed sprinkler can be represented by an exposed pendent head with appropriate effective values for the RTI ($m^{\frac{1}{2}}s^{\frac{1}{2}}$) and C factor ($[m/s]^{\frac{1}{2}}$).

2.6.4 BS 9252:2011 [32] and BS EN 12259-14:2020 [33] outline test methods to determine whether sprinkler heads achieve adequate thermal sensitivity, stipulating that a room test be undertaken for concealed heads. In carrying out this test, neither an RTI nor a C factor are defined. Hopkin and Spearpoint used a combination of deterministic and probabilistic simulations, in FDS [34] and B-RISK [3] computational models, to estimate the relationship between RTI and C factor (C) necessary to pass the room test. As a result, it has been proposed that this relationship can be represented using a simple power law equation of:

$$\text{RTI} = 100\,(5.4 - C)^{2/3}, \text{ where } C < 5.4 \qquad (1)$$

2.6.5 The results of the work of Hopkin and Spearpoint indicate that the minimum RTI and C factor values needed to pass the room test are greater than those needed to pass wind tunnel testing methods commonly used for exposed, pendent heads.

2.6.6 In the absence of any detailed specification for sprinkler heads, Hopkin and Spearpoint recommend that an RTI of 290 $m^{\frac{1}{2}}s^{\frac{1}{2}}$ and a C factor of 0.5 $(m/s)^{\frac{1}{2}}$ may be applied for residential design when considering deterministic scenarios. However, data was also presented of the experiments by Annable [35] and Yu [36] where it was shown that values within the acceptable bounds generally ranged from 50 to 300 $m^{\frac{1}{2}}s^{\frac{1}{2}}$ for the RTI and 0.4 to 1.0 $(m/s)^{\frac{1}{2}}$ for the C factor, which was adopted in the probabilistic corridor modelling study by Hopkin et al. [6]. These ranges have therefore been incorporated into the simulations as uniform distribution functions, as discussed in Table 4.

Table 4 – Probabilistic modelling inputs for concealed residential heads

Parameter	Value	Comments
Sprinkler offset below ceiling	50 mm	A sprinkler offset of 50 mm (relative to the ceiling) has been adopted, based on previous model calibration studies carried out by Hopkin and Spearpoint [2]. Hopkin and Spearpoint determined that a 50 mm offset resulted in the best agreement between FDS simulations and B-RISK simulations for the modelling of the BS 9252:2011 [32] BS / BS EN 12259-14:2020 [33] thermal response room test.
Shortest radial distance of sprinkler head from axis of fire	Arrangement 1 Dist: Truncated normal Mean: 2.15 m Std dev: 1.02 m Min: 0.0 m Max: 5.0 m	The shortest radial distance (r, m) has been determined using the principles given by Fraser-Mitchell and Williams [37], 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 sprinkler head in the x and y directions, based on the sprinkler head location given in respective flat arrangement in NF19.
	Arrangement 2 Dist: Triangular Min: 0.00 m Max: 3.89 m Mode: 2.65 m	
Ambient temperature	20 °C	For a typical indoor temperature.
Rated temperature	68 °C	For a red glass bulb, rated temperature specified in BS EN 12259-14:2020 [33], where BS 9251:2021 states that the rated temperature should be *"closest to but at least 20 °C greater than the highest anticipated ambient temperature"*.
RTI	Dist: Uniform Min: 50 $m^{\frac{1}{2}}s^{\frac{1}{2}}$ Max: 300 $m^{\frac{1}{2}}s^{\frac{1}{2}}$	Based on the work of Hopkin and Spearpoint [2] for concealed residential sprinkler heads.
C factor	Dist: Uniform Min: 0.4 $(m/s)^{\frac{1}{2}}$ Max: 1.0 $(m/s)^{\frac{1}{2}}$	
Sprinkler reliability	89%	PD 7974-7:2019+A1:2021 [7] refers to US sprinkler reliability data where, for residential occupancies, 89% of relevant incidents resulted in sprinklers *"operating effectively"*. In comparison, Koffel's [38] 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%"*.

2.7 Plumis nozzle properties

2.7.1 Table 5 provides the modelling inputs adopted for the nozzle in the room of fire origin for the design scenario incorporating Plumis nozzle (Scenario 2 and 4). Four different reliabilities of nozzle are simulated to compare with the performance determined for the sprinkler-protected arrangement. In the case of nozzle failure, the fire is allowed to continue to grow to either its fuel-bed or ventilation-controlled state.

2.7.2 Where nozzle is successfully actuated, B-RISK adopts a method consistent with Figure 6.4 of CIBSE Guide E where upon actuation, the fire is capped at a constant HRR. This approach is consistent with the sprinkler suppression detailed in Section 2.5 and has been demonstrated in yet unpublished work [39] to provide a conservative representation of the system performance based on BS 8458:2015 [40] fire test data.

2.7.3 To represent the Plumis Automist system in B-RISK zone model, it is assumed the system operates in a similar fashion to a sprinkler system. Spearpoint et al. [1] have written a paper on the activation of electronically controlled watermist system in the *Fire Safety Journal*. The results of the work of Spearpoint et al. recommend that an RTI of 20 m^{½}s^{½} and a C factor of 0.25 (m/s)^{½} is suitable for representing the Plumis nozzle to simulate activation time. These values have found to be able to provide reasonable agreement to the experimental data.

2.7.4 A ceiling offset of 50 mm has been adopted throughout, consistent with the concealed sprinkler heads, noting that this is not representative of the actual configuration. It has been assumed that the 'effective' rated temperature of the Plumis Automist system corresponds to the rated temperature of 68 °C for the concealed sprinkler head, which aligns with the 'effective' rated temperature used in work of Spearpoint et al

Table 5 – Probabilistic modelling inputs for Plumis Automist nozzle

Parameter	Value	Comments
Nozzle offset below ceiling	50 mm	A nozzle offset of 50 mm (relative to the ceiling) has been adopted, consistent with the concealed sprinkler heads
Shortest radial distance of nozzle from axis of fire	Arrangement 1 Dist: Truncated normal Mean: 2.65 m Std dev: 1.31 m Min: 0.0 m Max: 6.0 m	The shortest radial distance (r, m) has been determined using the principles given by Fraser-Mitchell and Williams [37], 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 arrangement as provided by Plumis.
	Arrangement 2 Dist: Truncated normal Mean: 2.14 m Std dev: 1.06 m Min: 0.0 m Max: 5.38 m	
Ambient temperature	20 °C	For a typical indoor temperature.
Rated temperature	68 °C	Corresponds to the rated temperature of 68 °C for the concealed sprinkler head, as adopted by Spearpoint et al. [1].
RTI	20 m^{½}s^{½}	Based on the work of Spearpoint et al. [1] for electrically controlled watermist nozzles.
C factor	0.25 (m/s)^{½}	
Nozzle reliability	20%, 30%, 40% and 50%	Four different reliability values have been selected to compare with the performance determined for the sprinkler-protected arrangement. Initial sensitivity analyses were carried out to identify this range.

2.8 Ventilation and Window Properties

2.8.1 Table 6 provides the window dimensions for both scenarios. These are windows situated in the living room presented in NF19 and therefore may be impacted by fire or influence fire development.

2.8.2 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. [41] 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.

2.8.3 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 2.4.

2.8.4 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 1.3 m^2 (approximately 1/20th of the room of fire origin floor area, as per Approved Document F [42] for purge vent), 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 [43].

2.8.5 A limitation of this approach is that the assumed low-level vent has been specified independently of the window area of the apartment. This vent area could subsequently have an impact on the estimated conditions within the apartment.

2.9 Geometry and surface properties

2.9.1 Under current guidance, doors within apartments are not expected to incorporate self-closing devices. Therefore, the influence of occupant door closing habits / behaviours can play a key role in smoke spread and have been incorporated into the modelling, consistent with the methodology of NF19.

2.9.2 The probabilities of doors being open or closed have been sourced from the work of Hopkin et al. [44] on internal door closing habits in domestic premises, for the door closing probabilities of respondents who lived in apartments (shown in Table 7). The door habits for sleeping occupants have been adopted, based on the behavioural assumptions discussed in Section 2.10. All doors have been modelled with dimensions of 0.8 m wide by 2.0 m high.

2.9.3 Table 8 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. [45] and slabs have been simulated with concrete properties estimated from BS EN 1992-1-2:2004+A1:2019 [46].

2.9.4 It is acknowledged that adopting the properties given in Table 8 is a considerable simplification of the wider range of building materials which will 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 the default 'INERT' boundary of FDS).

Table 6 – Window dimensions adopted for modelling

Window	Location	Window dimensions	Total area
1	Living room	**Sill height:** 0.8 m **Width by height:** 2.5 m by 1.5 m	3.75 m^2

Table 7 – Probability of doors being closed while occupants are sleeping [44]

Room	Probability closed
Bedroom	73%
Kitchen	38%

Table 8 – 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

2.10 Tenability, evacuation and behavioural assumptions

2.10.1 The analyses consider the tenability of a single agent located in the bedroom. 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 [47], and therefore may be subject to fire and smoke conditions for a greater period than if they were awake.

2.10.2 The analyses consider agents in the bedroom for 10 minutes (600 s). This representing the time required for occupants to wake up and begin evacuation, like the methods adopted in NF19. The 10 minutes pre-evacuation time is also consistent with PD 7974-6:2019 [48], in which it represents the 99th percentile pre-evacuation time for sleeping and familiar occupants in dwellings (A1 alarm system and M2 management level).

2.10.3 The analyses do not take into consideration the impact of automatic detection and alarm on the waking of agents. This is expected to have a negligible impact on the outcomes as the scenarios focus on the performance study of suppression systems, where an equivalent detection and alarm system would be provided in both scenarios.

2.10.4 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 space.

2.10.5 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 0.1 and 0.3 and equal to 1. NF19 refers to an FED of 0.1 as "almost certainly" to be recorded as an injury in the fire statistics for a real fire incident and PD 7974-6 [48] 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".

2.10.6 For the time spent within each room, agents are assumed to be sleeping and initially located in the bedroom, with a pre-evacuation time previously given. In addition to this, agents have a travel time in the bedroom, plus a travel time in the living room. 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 [49]. The egress path for Arrangement 1 and 2 is given in Table 9 and Table 10, respectively.

2.10.7 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. [50] 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' [51] 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 9 – Egress path for Arrangement 1 (8 m by 4m flat)

Phase	Occupant location	Distance	Elapsed time in room
Pre-evacuation (sleeping)	Bedroom	–	600 s
Evacuation from bedroom	Bedroom	~ 5 m	+ 25 s
Evacuation via living room	Living room	~ 5 m	+ 25 s

Table 10 – Egress path for Arrangement 2 (10 m by 8 m flat)

Phase	Occupant location	Distance	Elapsed time in room
Pre-evacuation (sleeping)	Bedroom	–	600 s
Evacuation from bedroom	Bedroom	~ 6.7 m	+ 34 s
Evacuation via living room	Living room	~ 3.5 m	+ 18 s

3. RESULTS

3.1 FED outcomes for Arrangement 1 (8 m by 4 m flat)

3.1.1 Figure 5 shows the comparison between the sprinkler and Plumis system in terms of FED (CO) exceedance probability at 0.1, 0.3 and 1. Figure 6 provides the average FED (CO) with respect to sprinkler and Plumis system with various reliabilities. The sprinkler system arrangement has been simulated with a fixed reliability of 89%, whereas Plumis Automist system has been simulated with a fixed reliability of 20%, 30% and 40%.

3.1.2 The probabilities of the Plumis system with 40% reliability exceeding 0.1 FED, 0.3 FED and FED = 1 were 4% to 24% less than the sprinkler system. The average FED for Plumis system with 40% reliability was 20% less than that compared to the sprinkler system.

3.1.3 When the reliability of Plumis system is 30%, the probabilities exceeding 0.1 FED and 0.3 FED were found to be 17% less than the sprinkler system. However, the probability of FED = 1 for Plumis system was about 10% higher than that compared to the sprinkler system. The average FED for Plumis system was found to be 9% less than the sprinkler system.

3.1.4 For a reliability of 20% for Plumis system, the probabilities exceeding 0.1 FED and 0.3 FED were found to be 9% less than the sprinkler system. However, the probability of FED = 1 for Plumis system was about 26% higher than that compared to the sprinkler system. The average FED for Plumis system was found to be 1% more than that compared to the sprinkler system.

3.2 FED outcomes for Arrangement 2 (10 m by 8 m flat)

3.2.1 Figure 7 shows the comparison between the sprinkler and Plumis system in terms of FED (CO) exceedance probability at 0.1, 0.3 and 1. Figure 8 provides the average FED (CO) with respect to sprinkler and Plumis system with various reliabilities. The sprinkler system arrangement has been simulated with a fixed reliability of 89%, whereas Plumis Automist system has been simulated with a fixed reliability of 30%, 40% and 50%.

3.2.2 With a 50% reliability for Plumis system, the probabilities exceeding 0.1 FED, 0.3 FED and FED = 1 were found to be 0% to 34% less than the sprinkler system. When the reliability reduces to 40%, the FED exceedance probability at 0.3 and 1 becomes higher than the sprinkler system, this outcome is also consistent with a reliability of 30%.

3.2.3 The average FED at 30% and 40% reliability are up to 10% higher than the sprinkler system. Whereas at 50% reliability, the average FED is about 17% lower than sprinkler system.

3.3 Discussion

3.3.1 Overall, the trends shown in the result are in consistent with expectations, whereby a lower system reliability is expected to produce a higher proportion of FED exceedance, i.e., a system which is more likely to fail leading to an increase of FED for the occupant.

3.3.2 As the Plumis Automist nozzle exhibited much more rapid activation time when compared to the concealed sprinkler heads i.e., lower RTI and C factor, it is anticipated that a lower reliability for Plumis system would achieve an equivalent or similar performance to a residential sprinkler system which meets the recommendations of contemporary guidance such as BS 9991.

3.3.3 The findings from this study show that a reliability range between 40% to 50% for Plumis system achieves a similar or improved performance to the residential sprinkler system utilising concealed sprinkler heads. For conservatism, it is recommended to consider a **fixed reliability target of 60%** for the Plumis Automist system where, at this reliability target, the Plumis system is expected to exceed performance of the sprinkler system for all criteria.

3.3.4 It is important to note that this does not imply the Plumis system should only achieve an overall reliability of 60% to meet adequate safety level. It was noted by Spearpoint et al. [1] that a common expectation that any new system should be able to achieve an equivalent level of safety to an existing system that meets the relevant standard, irrespective of the intended performance target. However, such comparisons tend to be evaluated in the context of 'legacy' hazards, without necessarily considering how hazards may change over time.

3.3.5 Therefore, from a life safety perspective, the Plumis system should be designed, installed and maintained such that it is highly reliable to reflect a necessary safety level in the context of active fire protection measures.

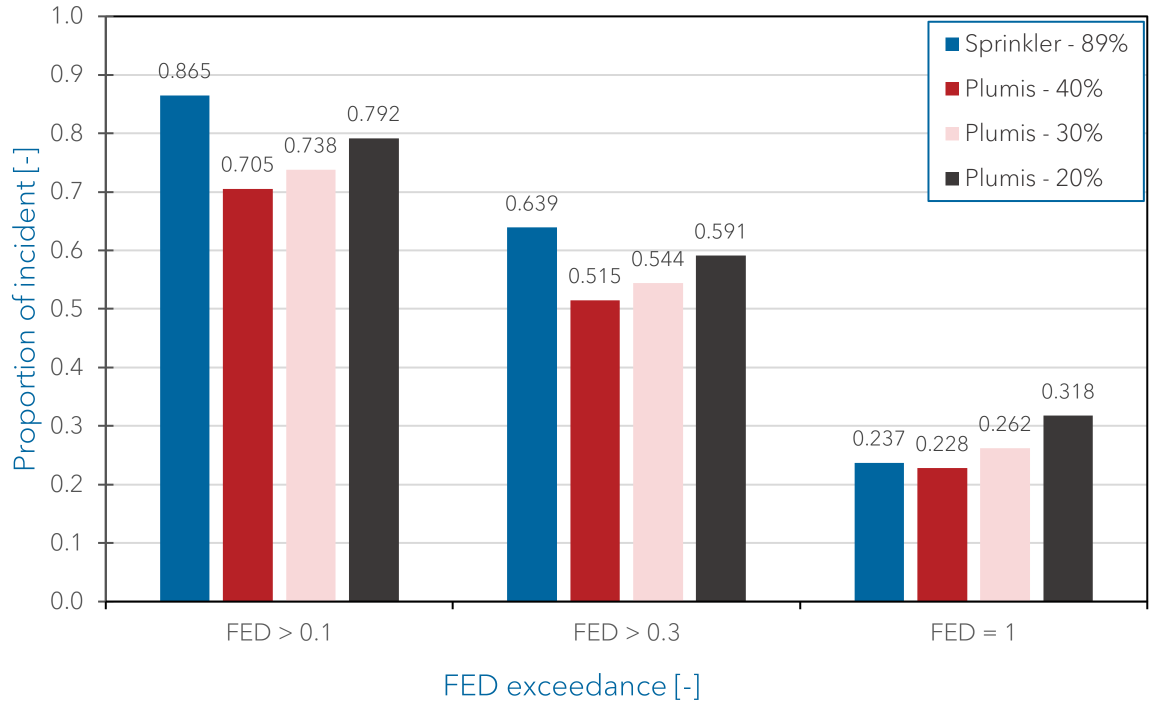

Figure 5 – Arrangement 1, probability of FED exceedance for sprinkler and Plumis system with various reliabilities

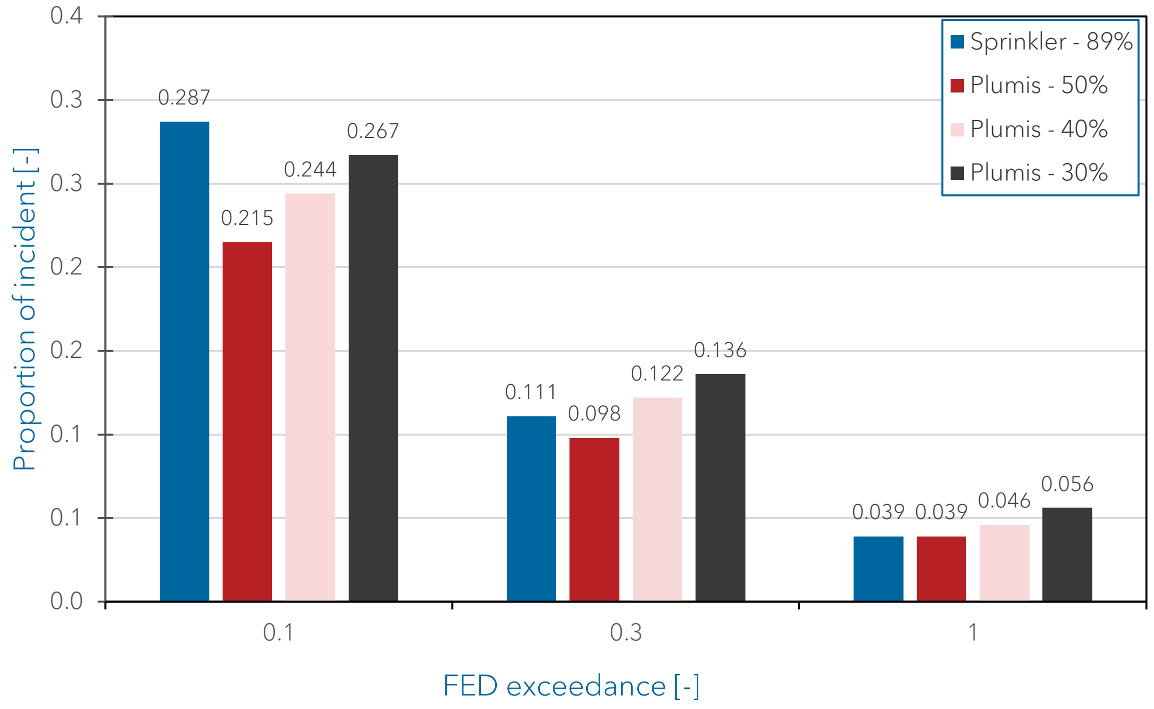

Figure 7 – Arrangement 2, probability of FED exceedance for sprinkler and Plumis system with various reliabilities

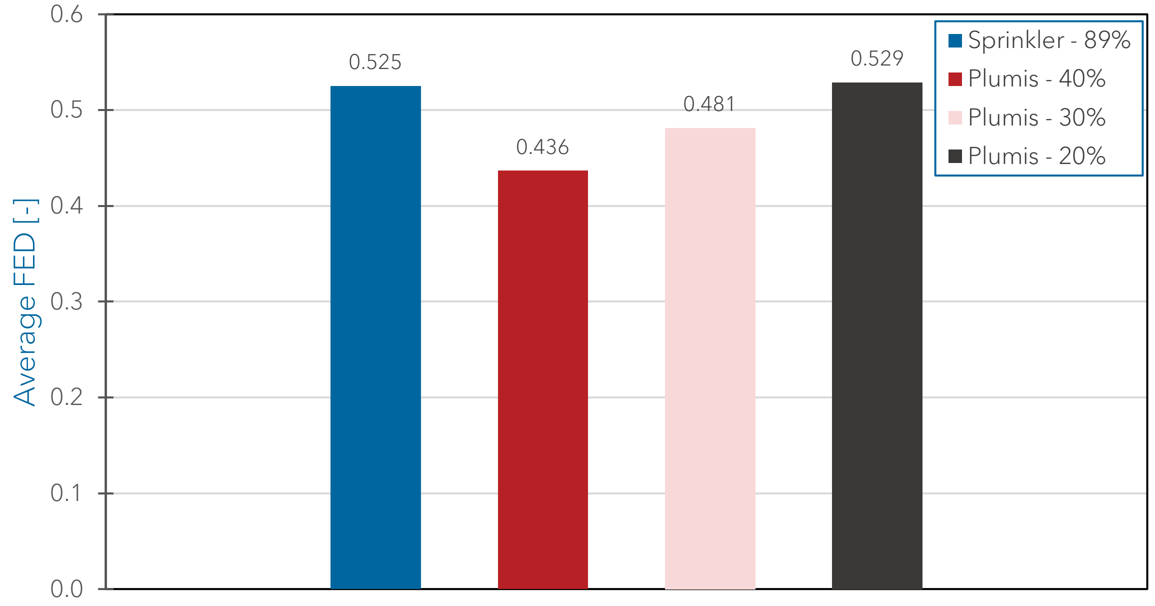

Figure 6 – Arrangement 1, average FED for sprinkler and Plumis system with various reliabilities

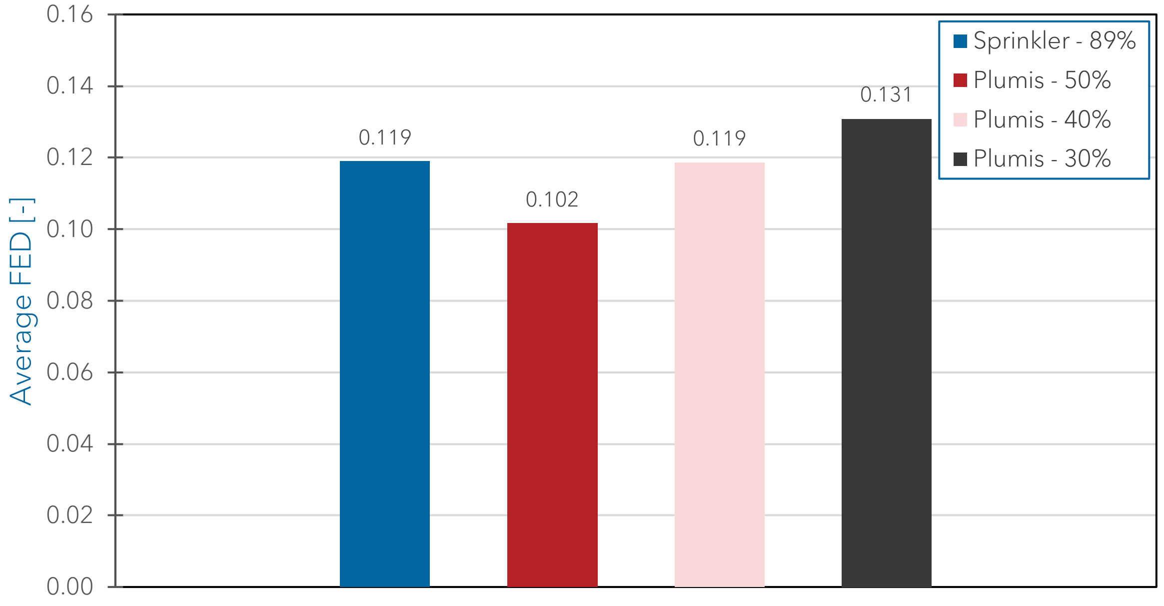

Figure 8 – Arrangement 2, average FED for sprinkler and Plumis system with various reliabilities

4. CONCLUSION

4.1.1 The work presented in this report describes the methodology, selected parameters and results in determining a target reliability for the Plumis Automist system, such that it can be considered to have achieved the same level of safety performance to that of a residential sprinkler system.

4.1.2 A fixed reliability of 60% for Plumis system has been shown to reasonably achieve an equivalent or better performance to a residential sprinkler system which meets the recommendations of contemporary guidance such as BS 9991. Such value can be adopted by fire engineers to reasonably represent Plumis or electronically controlled residential water mist system of similar for probabilistic risk assessment in fire safety engineering.

4.1.3 The above observations are based on the assumption of similar suppression performance between systems, i.e., the impact of the Plumis Automist system on the heat output of the fire is similar to that of a sprinkler system. In addition, given the nature of the study detailed herein, these observations are only relevant to the specific application of the system to open plan flat design.

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