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Literature review on the use of water mist system for the protection of wood frame buildings

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Executive Summary

Fire safety in tall wood buildings, especially those using mass timber as structural elements is a challenge, with the advent of new regulations including proposed changes for tall wood buildings, which allow/propose to allow the use of uncovered mass timber for various occupancies as long as protected with sprinkler systems. Water mist systems are considered for the protection of timber buildings because the system provides the advantage of minimal amount of water used, less water damage and easier cleanup compared to sprinkler systems.

This report reviews current building regulations and standard requirements for the use of water mist systems for the protection of wood frame buildings. To identify research gaps, previous experimental studies were also reviewed. It is found that there are very limited studies conducted to develop guidelines or design methods for water mist systems in protection of buildings. Although several water mist standards provide test protocols for using water mist systems in residential and light hazards scenarios, none of these standards considered the use of water mist systems in wood frame buildings. Therefore, without verifications, these existing standards and test protocols should not be incorporated in the use of water mist systems in protection of timber buildings.

In addition, development of new test protocols is in need since building codes are evolving to allow various occupancies for timber buildings. Test protocols need to be developed to address important design parameters, such as compartment conditions, fire scenarios and water delivery systems including nozzles. It should be noted that the occupancy, volumes of compartments, ventilation conditions need to be considered in selection of the nozzles and designing layouts of water delivery systems.

1 Overview

In recent years, Canadian building regulations and codes have begun allowing the construction of wood frame buildings of up to six stories in height. With the advancements in new technologies and mass timber products, such as Cross Laminated Timber (CLT), the allowable height of wood frame buildings is expected to exceed six stories, which may aggravate fire safety concerns. These tall wood buildings require automatic sprinkler protections, as specified by 2015 NBC in order to limit the severity and effect of fire and limit fire spread. In wood frame buildings, the installation of sprinkler systems would achieve the above objectives of the NBC as effectively as in concrete or steel frame buildings. However, there are still concerns that sprinkler systems could create post-fire water damage and mold problems in wood frame buildings, although such damage would be significantly less severe than fire damage that would occur in the absence of a sprinkler system.

To minimize the potential post-fire water damage in the wood frame buildings, water mist systems have been considered as an alternative solution to sprinkler systems since water mist systems use 50 to 90 percent less water than the traditional sprinkler systems (NFPA, 2015). Because of this benefit, a high pressure water mist system was installed to protect the glulam timber structures in the Credit Valley Hospital/Peel Region Cancer Centre in Mississauga, for the first time (Stanwick, 2003). Developed for industrial applications for asset protection, water mist systems have been proven to be effective in the protection of electronic equipment and machinery rooms in ships and industrial buildings. However, when it comes to the protection of residential and office buildings, water mist systems are still emerging technologies. In particular, there is currently no Canadian technical guide specifically addressing the design requirements for water mist systems in the protection of mid/high rise wood frame buildings, in terms of both protecting occupants as well as minimizing post-fire water damage of the wood structure.

Research is needed to evaluate the performance of water mist systems in comparison to conventional sprinkler systems in wood frame building fire scenarios, and to substantiate potential benefits of water mist systems in minimizing post-fire water damage. As an initial step, NRC conducted a literature review on the current regulations and standards that cover applications of water mist systems in the protection of timber buildings.

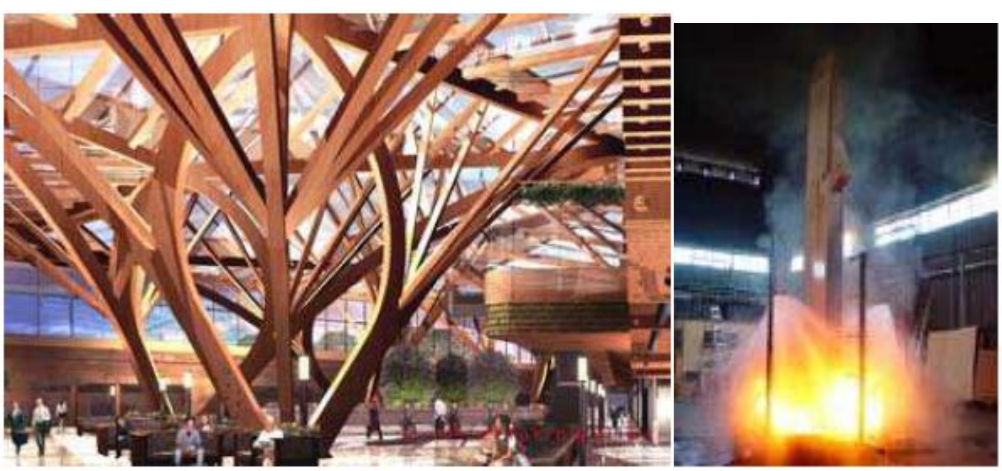

Figure 1 Network of curving glulam beams in the Credit Valley Hospital/Peel Region Cancer Centre in Mississauga and the fire suppression test conducted for the glulam structure using high pressure water mist system (Stanwick, 2003)

1.1 Objectives

The objectives of this literature review are as follows:

1) To understand the current regulations and code requirements for the use of water mist systems for the protection of wood frame buildings
2) To identify research gaps in the use of water mist system for the protection of wood frame buildings. Scope

This literature review focuses on the use of water mist systems for the protection of mass timber buildings to house residential or light hazard occupancies.

The review was also conducted in an attempt to answer the following questions;

(1) Are there any codes, regulations and standards addressing design requirements for the use of water mist system for the protection of wood frame buildings?
    If there are none, could the existing norms be applicable to wood frame buildings?
(2) Have there been any studies about the following aspects:
    a. design requirements for water mist systems or active fire suppression systems that can be employed in protection of wood frame buildings;
    b. benefits of active fire suppression systems in minimizing the contribution of wood structural elements to the severity of the fire;
    c. benefits, such fire protection efficacy and cost effectiveness, of water mist systems in comparison to conventional sprinkler systems, in the application to wood frame buildings
    d. problems with post-fire water damage in wood frame buildings, detailing the extent of water damage and evaluation methods ;
(3) Are there any test methods to evaluate the performance of water mist system and are they applicable to fire scenarios involving wood frame buildings?

2 General Background

2.1 Water mist systems

Water mist systems discharge fine water sprays (i.e., water mist) to control, suppress or extinguish fires[1]. Water mist systems control/suppress/extinguish fire with the fine water mist by three principal mechanisms:

1) First, the fine droplets effectively absorb heat from smoke since the total surface area of the atomized droplets are much larger than the droplets from the conventional sprinkler system.
2) Second, as the fine droplets evaporates, the volume of the water increases up to 1700 times which can eventually smother the fire in an enclosure if properly designed.
3) Third, attenuating the radiant heat from the fire due to the small size of the droplets that block and scatter the radiation of the heat.

A typical water mist system consists of the fully essential components: automatic fire detectors and actuators; water supply and delivery components (such as pumps, pipes and water atomising nozzles).

Water mist systems are distinguished from the conventional sprinkler systems in that they use water atomization technologies to produce fine water mist at high pressure through using specialized nozzles. In general, there are four types of water mist systems defined by the operating pressure: high pressure water mist system operates at pressure of 34.5 Bar (500 psi) or greater, and intermediate pressure water mist system and low-pressure water mist system operates at pressure greater than 12.1 bar (175 psi) but less than 32.5 bar (500 psi); and pressure at 12.1 bar (175 psi) or less, respectively.

The higher the operating pressure, the finer the droplet sizes. By definition in National Fire Protection Association 750 (NFPA, 2015), water mist systems discharge droplets less than a diameter of 1000 microns with Dv0.99 (i.e., 99% of the total volume of water being discharged is in drops with small diameters less than 1000 microns). One study reported that the median droplet diameters for high and low pressure water mist systems were approximately 110 microns and 230-300 microns, respectively (Mawhinney & Back, 2016). In comparison, conventional sprinkler systems generate water droplets with a mean diameter of approximately 700-1000 microns or greater, depending on its operating pressure (Mawhinney & Back, 2016). Therefore, the main benefit of water mist systems is the minimal amount of water used by the system, which is known to be only 10-50% of the water employed by a conventional system.

In application of water mist systems, four types of protection strategies can be considered;

1) Local-application: designed and installed to protect an object or a target hazard in an open or enclosed condition.
2) Total compartment application: designed and installed to provide complete protection of an enclosure or space by simultaneous operation of all nozzles in the enclosure. For example, a total flooding system is designed to extinguish fire in a machinery compartment.
3) Zoned application: designed and installed to provide complete mist distribution throughout a predetermined portion of an enclosure or space. For example, in tunnel fire protection, a deluge system consisting of a network of dry pipework and open nozzles is desirable to provide protection and fire control in a certain portion of a tunnel.

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[1] Fire control means resisting fire development and holding the fire to an area; fire suppression means reducing heat release rate of fire by lowering down the fuel burning rates; and fire extinguishment means putting out fire.

4) Occupancy protection: designed and installed to provide automatic fire protection throughout a building or occupancy. Thermally activated nozzles will be used, which utilize fusible links or glass bulbs to actuate the nozzle at a predetermined temperature.

In each protection strategy, the main suppression mechanism employed (e.g., gas phase cooling, oxygen displacement and radiation attenuation) by the water mist system would vary.

In comparison to conventional sprinkler systems, water mist systems are known to be more suitable for liquid pool fires (Class B fires) due to their gas phase cooling capability. However, sprinkler systems are effective in wetting and cooling combustible fuel surfaces. Water mist systems are more sensitive to ventilation conditions and openings in the spaces being protected than sprinkler systems. Experiments showed that water mist systems may not extinguish small fires in an enclosure with a large opening yet the system may provide fire control (Mawhinney & Back, 2016). Intermediate and high pressure water mist systems require pumping systems to provide pressurized water supply. Due to its complicated water supply system including pumping systems, the reliability of water mist systems would be subjected to questions. Arvidson (Arvidson, 2015) concluded that when the system is maintained on a monthly basis, the reliability of water mist systems could be close to that of the conventional sprinkler system. However, when maintained on a yearly basis, the reliability of water mist systems would be 10% less than the conventional sprinkler system. In some cases, redundant pumping systems should be arranged to provide robust water supply for continuous firefighting through multiple nozzles.

2.2 Wood frame buildings

Wood frame buildings are very popular across Canada and are the typical construction in low-rise residential dwellings. This section reviews light-frame wood and mass timber (with a focus on Cross-Laminated Timber) constructions.

2.2.1 Light-Frame Wood Buildings

Light-frame wood construction is widely used in North America. Typically, light-frame wood construction utilizes dimension lumber (nominally 2-inches thick), I-joists, trusses, structural composite lumber, as well as oriented strand board decking and sheathing for floors, walls and roof decks.

For finishing, fire protection and other reasons, light-frame constructions are typically sheathed with lining material such as the most commonly used gypsum plasterboard. The most common section sizes are nominal 2”× 4” [actual size 1 ½ x 3 ½ inches (38 x 89 mm)] and 2”× 6” [actual size 1 1/2 x 5 1/2 inches (38 x 140 mm)].

2.2.2 Mass Timber Buildings

Panels of mass timbers have been used as structural elements in many buildings, including tall buildings across Canada. In mass timber frame buildings, sometimes also called heavy frame, or heavy timber construction, beams and columns with timber section sizes that are greater than 6” × 6” [150 mm × 150 mm] are used. The main benefit of engineered timber products is their strength and design flexibility. Generally, engineered timber/wood consists of derivative timber products that are manufactured to increase the strength and stiffness of the engineered timber element. This includes, glulam, laminated veneer lumber, Nail-Laminated Timber (NLT), and Cross-Laminated Timber (CLT). CLT, which is in the focus of this report, refers to engineered wood panels manufactured by cross laminating lumber. Typically, CLT panels comprise several layers of softwood wood boards, either glued or nailed together as illustrated in Figure 2.

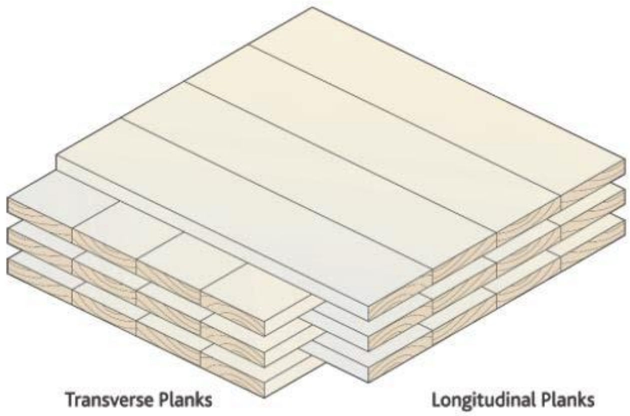

Figure 2. Illustration of a CLT panel configuration (McGregor, 2013)

2.2.3 Fire safety of Wood frame buildings

Fire safety is an important aspect to consider in wood frame buildings. In light-frame wood frame buildings, which are typically four stories high or less, fire safety is typically achieved by protecting the combustible material with non-combustible sheathing material such as gypsum board. Gypsum board is also used to protect mass timber by encapsulation as well. However, in mass timber constructions, fire protection through other means, such as sprinkler systems, is admissible in some cases (see Section 3 for an overview of some regulatory requirements). Therefore, the following sections discuss the contribution of unprotected mass timber structural elements to room fires.

Contribution of unprotected mass timber structural element to room fires

Unlike light-frame wood buildings, mass timber construction assemblies are not always fully encapsulated by fire resistant materials (see Section 3 for a review of code requirements). The fire performance of unprotected non-engineered lumber is well understood. When exposed to fire, the outer layer of lumber will burn and consequently char. The char creates a protective layer that contributes to wood's inherent fire resistance, particularly for heavy timber frames. However, fire behavior of engineered wood products is not well understood. Frangi et al. (Frangi, Fontana, Knobloch, & Bochicchio, 2008) conducted full-scale testing of CLT fire performance and revealed that fire behavior of CLT panels varies from solid timber and depends on the properties of the individual CLT layers. In particular, the authors observed that charred layers fell off faster during fire testing compared to charring on solid timbers. Consequently, the inherent protection provided by char was lost. The same effect was observed for CLT panels that initially were lined with fire protection, after the protective lining had fallen off.

In another study, several full-scale fire tests were conducted to compare furniture and propane fires in rooms manufactured from either completely unprotected, partially protected or fully protected CLT, as well as rooms using light timber and steel frames. For the CLT built rooms, the authors used 105 mm thick 3-ply CLT panels for wall and roof panels in each test room. The outer laminations were made from SPF 1950Fb MSR 35 x 89 mm members with the centre lamination made from SPF No 3/Stud 35 x 89 mm at a 90 degree offset orientation (SPF refers to lumber made from a combination of spruces, pines and firs). Where protection was used in the CLT rooms, the walls and ceiling were lined with two layers of gypsum boards. Table 1 reports the heat production in the CLT room fires reported. The tabulated results demonstrate that unprotected CLT panels can contribute to fire development in a room. The authors concluded that variations in exposure of unprotected areas influences fire contribution of CLT panels but also the occurrence of fire re-growth and secondary flashover (Li et al., 2016).

Table 1. Heat production in CLT room fires measured in Li et al. (2016); see reference for more details on fire size and experimental setup.

Tested furniture fires	Heat produced in first 26 minutes of testing (MJ)	Ratio compared to fully protected testing
Fully protected CLT room	4581	1
2 adjacent walls unprotected	5275	1.15
2 facing walls unprotected	6702	1.46
1 side-wall unprotected	4383	~1
Completely unprotected CLT room	9864	2.15

Another study reported on the heat release rate (HRR), room temperatures, and charring in five tests of for rooms which consisted either of protected or unprotected CLT panels (McGregor, 2013). The author found the protection of CLT panels through encapsulation with gypsum board highly effective so that the panels themselves did not contribute significantly to the fire severity. Unprotected CLT panels, however, as can be expected, did contribute to total fire load and fire severity. In particular, the author observed that delamination had the effect of exposing previously uncharred surfaces and consequently increasing the intensity and duration of the fire (McGregor, 2013). In a similar series of tests, fire severity was associated with proportion of unprotected wall in a room (Medina Hevia, 2015).

These findings are in line with previous research that show that exposed CLT can contribute to the fuel load in room fires and consequently may result in increased fire severity (e.g., Frangi et al., 2008). The effects of delamination were further explored in a recent study, which replicated the finding that delamination impacts fire development. Moreover, the study found that the type of adhesive used plays an important role. In fact, the authors reported complete and partial delamination in three out of ten tests conducted (Johansson & Svenningsson, 2018). Improved adhesives may therefore improve the fire performance of CLT plates (Barber, Crielaard, & Li, 2016), by contributing to the self-extinction of CLT (however, results are mixed and self-extinction seems to be connected to charring as well as delamination, among others (Barber et al., 2016; Crielaard et al., 2016; Hadden et al., 2017)).

Some research has been conducted regarding fire protection by sprinklers and non-combustible lining materials. One study demonstrated that encapsulation is an effective approach to delay the time at which the wood structural elements are affected by and eventually contribute to the growth and spread of fire, if at all.(Su & Lougheed, 2014). A series of full-scale tests on modular wooden hotels were performed under natural fire conditions by Frangi and Fontana (Frangi & Fontana, 2005). In scenarios in which sprinklers were used to provide fire protection the results showed that sprinkler systems were able to quickly control the fire in various conditions. When sprinklers were deactivated they observed faster times to flashover (ca. 4 minutes for walls with combustible lining; 6-7 minutes for walls with non-combustible linings). In addition, for the module with combustible wall and ceiling linings, the external burning outside the window was much more severe than for the modules with non-combustible wall and ceiling linings (Frangi & Fontana, 2005). Similarly, several other studies found sprinklers to be effective in combatting fires in wooden structures (Wei et al., 2011).

A recent project ran a series of six large CLT compartment fire tests without sprinklers (Su, Lafrance, Hoehler, & Bundy, 2018). The CLT surfaces in the compartments were fully or partially protected with multiple layers of 15.9-mm Type X gypsum board, and typical residential movable furnishings provided the fuel load in the compartment tests. The baseline testing with fully protected compartment found that the physical barriers employed were an effective in means to protecting the structural CLT elements, thus limiting and/or eliminating their contribution to the fires. In line with previous findings reported earlier, they showed that the amount and orientation of exposed CLT effected the extent of the contribution of CLT to the fire. Although the maximum temperatures measured were comparable to baseline, significantly higher HRR and heat fluxes to the exterior façade were observed when CLT was partially exposed (Figure 3; please see original report for more details on severity variables such as theoretical HRR and room size). In the latter tests, the authors observed delamination, which then contributed to the fire growth. The use of simulated thermal elements suggested that sprinklers would have been activated well before flashover (Su et al., 2018).

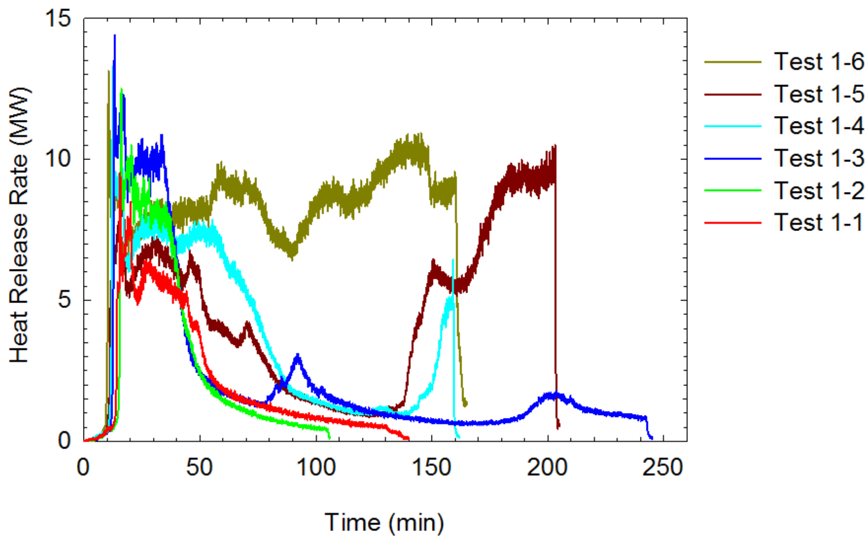

Figure 3. Heat release rates (HRR) in CLT compartment tests (Su et al., 2018). T1-1 and T1-2 were fully protected; In T1-3 and 1-5, one wall was exposed; in T1-4 the ceiling was exposed; In T1-5 the ceiling was exposed; in T1-6 ceiling and one wall were exposed. Tests 1-2 and 1-3 had an opening roughly twice as wide the other tests.

A study involving 20 CLT compartment fire tests found that the fire did not exhibit self-extinguishment in most of the tests (Barber, 2018). In these tests, fire regrowth (in terms of HRR) was observed after an initial fire decay (similar to Test 1-3 in (Su et al., 2018), see Figure 3). In those tests, in which sustained burning was observed, multiple surfaces had been exposed together with an increase in HRR as fuel was being consumed, followed by a more steady-state HRR (Barber, 2018).

A recent literature review summarized findings from 45 compartment fire tests comprising exposed and protected wood constructions as well as non-combustible constructions. The authors summarize from these tests that *protected* CLT panels may not contribute or only to a negligible degree to room fires (Östman & Brandon, 2016). If CLT is not protected or protection fails, however, the consequences in terms of fire development can be serious (e.g., risk of second flashover (Medina Hevia, 2015)). Studies consistently found that unprotected CLT panels are connected to higher HRRs. However, findings regarding compartment temperature levels were not conclusive (Östman & Brandon, 2016).

Based on the literature reviewed, it can be concluded that exposed surface area, configuration, reliability of protection, compartment ventilation, and CLT delamination behavior are important parameters that influence how compartment fires will progress. It should be noted that none of the tests reviewed here reported on fire behavior of loaded structural elements. All in all, some of the research gaps regarding charring, delamination, and fire behavior of exposed and protected CLT have been addressed, but many questions remain open. This is, for example, illustrated in the development of computational models of CLT fires. A recently developed computational model was demonstrated to be able to provide conservative predictions regarding protected and unprotected CLT fires as part of an engineering analysis. However, these models are still in relatively early stages and do not accurately describe fire development after delamination occurred. Yet, they are able to predict the onset of delamination (Wade, Spearpoint, Fleischmann, Baker, & Abu, 2018).

3 Current building regulations for fire suppression systems

The following section reviews current building regulations for fire suppression systems with regard to wood frame building. The review is restricted to two model building codes, the International Building Code (IBC) and the National Building Code (NBC). In general, all codes reviewed state to some extent that wood materials can be protected with non-combustible lining materials and/or sprinkler systems to resolve issues associated with flame spread. On the one hand, codes typically require fire suppression systems based on occupancies, construction material and building heights (e.g., see Table 3). On the other hand, standards use hazard classification systems for approvals of fire suppressions, which are mainly based on occupancies, not the construction type.

The introduction of automated sprinkler systems and other fire protection technologies allowed the construction of high rise wood buildings. Such protective technologies are required by building codes as integral parts of fire protection systems for wood buildings. Initially introduced in the 1990's, provincial and national building codes were changed to allow multi storey wood-frame constructions for residential and office occupancies. Since then national and international building codes have gradually increased the height of permitted tall wood buildings. The current edition of NBC and IBC will be updated again in the coming years and some key changes regarding encapsulated mass timber have been proposed; in both model codes, new building type categories that include encapsulated mass timber structures as well as means of protecting them are being introduced. It is important to note that the recent changes discussed in this section contemplate the use of standard light-frame construction methods/materials which is a fundamentally different construction system than the mass timber system design (mgb ARCHITECTURE + DESIGN, 2012).

3.1 National Building Code (NBC)

One of the principal roles of the model building code (National Building Code) of Canada is to regulate the size/height of built structures relative to fire safety (Canadian Commission on Building and Fire Codes & National Research Council Canada, 2015). This is primarily achieved by limiting the area and height of buildings incorporating combustible construction materials, and by requiring incrementally higher fire-resistance ratings for mid-to high-rise buildings of non-combustible construction (mgb ARCHITECTURE + DESIGN, 2012).[2] The NBC is organized into three divisions:

- Division A (Compliance, Objectives and Functional Statements) defines the scope of the NBC and presents the objectives that the Code addresses and the functions the building must perform to help to satisfy those objectives.
- Division B (Acceptable Solutions) refers to the technical provisions contained in the code.
- Division C (Administrative Provisions) contains administrative provisions relating to the application of the code.

NBC further differentiates between five groups of buildings depending on the type of occupancy.

- A1-4: Assembly (differentiated in 4 subdivisions)

[2] Combustible construction refers construction that does not meet the requirements for non-combustible construction. Combustibility of materials is assessed via CAN/ULC-S114 Test for Determination of Non-Combustibility in Building Materials.

- B1-3: Detention, Treatment and care
- C: Residential
- D: Business and personal services
- E: Mercantile
- F: Low, medium and high-hazard industrial

Fire safety is enhanced by incorporating passive measures to elements as well as active measures where required. . Subsection 3.2.2 of NBC specifies admissible use of combustible constructions as a function of occupancy (i.e. Group A-F) and building height (in terms of the number of storeys). Table 3 provides an overview of allowable combustible construction. Note that this table does not cover all the details and the reader is referred to the NBC for further details. NBC 2015 allows combustible construction up to 6 storey for residential and business occupancies when protected with sprinkler systems and achieved the fire resistance and fire separation requirements.

3.1.1 Proposed changes

The Canadian Wood Council submitted a code change request to the standing committee on Fire Protection for the 2020 iteration of the NBC, containing a list of 25 potential issues and concerns (Alam, 2018). These proposed changes are currently available for public review (National Research Council Canada, 2017). The general premise these proposed changes was to develop a set of provisions that achieves the current level of fire safety when wood structural elements are substituted for structural elements of non-combustible materials.[3] At the core of the proposed changes, *encapsulated mass timber construction* is proposed as a third category of construction type, in addition to non-combustible and combustible construction together with an associated *encapsulation rating*. Encapsulation rating refers to the time at which the ignition and combustion of encapsulated mass timber elements will be delayed when exposed to fire under specific conditions. To be considered mass timber, structural elements would have to meet minimum size requirements.

It is proposed to permit this type of construction in sprinklered buildings, complying with NFPA 13 (National Fire Protection Association) up to 12 storeys (compared to 6 storeys in NBC 2015) high for occupancy Group C (6,000 m^2) and D (7,000m^2). Additional requirements are proposed within Group C for Group A and E occupancy and within Group D for Group A, E, and F respectively. In addition the uppermost floor is proposed to be limited to 42 m. Further changes for damaged/removed encapsulation material, exterior cladding, as well as construction site fire safety requirements are proposed.

One notable change is the permission of *exposed* mass timber surfaces in encapsulated mass timber constructions (see Table 2).

Table 2. Permitted exposure of encapsulated mass timber, proposed for NBC 2020 (Alam, 2018)

Exposed mass timber element	Max aggregate surface of total wall area of the perimeter of the suite or ceiling area	Flame Spread Rating	Other requirements
Beams, columns, arches	10%	150	Also permitted in a fire compartment
Walls	35%	150	Surfaces face the same direction
Combined beams, arches, and walls	35%	150	Wall surfaces face the same direction
Ceilings (Option 1)	10%	150	-
Ceilings (Option 2)	25%	75	No exposed walls

[3] Additional potential future changes are not considered in this report.

3.1.2 Use of sprinklers

Section 3.2.5.12 addresses automatic sprinkler systems. Note that the sprinkler requirements change according to the occupancy type and that NBC refers to NFPA 13, NFPA 13R, and NFPA 13D for sprinkler requirements. The objectives of the sprinkler requirements specified by NBCC are (1) to limit the severity and effects of fire and (2) to retard the effects of fire on areas beyond its point of origin.

3.1.3 Alternative solutions

According to NBC, compliance with the code can be achieved by complying with applicable solutions in Division B, or by using alternative solutions that will achieve at least the minimum level of performance required by Division B. For example, water mist systems can be considered as an alternative solution to sprinkler systems when there are challenges to designing conventional sprinkler systems for a building. The suggested alternative solution; however, should offer demonstrated levels of protection equivalent to the conventional sprinkler system.

Table 3. Allowable use of *combustible* construction in NBC 2015

Group	Occupancy	Storeys	allowable *un-sprinklered* area (m²)	allowable *sprinklered* area (m²)	Additional requirements	NBC sections
A-1	Assembly	1	-	600	Additional fire separation and fire resistance rating requirements apply	3.2.2.22
A-2	Assembly	1 2	2,400⁺ 1,200⁺	4,800 2,400	Additional fire separation and fire resistance rating requirements apply; ⁺ if facing 3 streets; less if facing 1 or 2 streets	3.2.2.25 3.2.2.26
A-3	Assembly	1	3,600	7,200	if facing 3 streets; less if facing 1 or 2 streets	3.2.2.32 to 3.2.2.34
B-2	Treatment	1 2	- -	2,400 1,600	Additional fire separation and fire resistance rating requirements apply;	3.2.2.40
B-3	Care	1 2 3	- - -	5,400 2,700 1,800	Additional fire separation and fire resistance rating requirements apply; different allowable area if up to 2 storeys, and 1 storey buildings	3.2.2.44 to 3.2.2.46
C	Residential	1 2 3 4 5 6	3,600⁺ 1,800⁺ 1,200⁺ - - -	9,000 4,500 3,000 2,250 1,800 1,500	Additional fire separation and fire resistance rating requirements apply; different requirements for buildings up 4 storeys and lower ⁺ if facing 3 streets; less if facing 1 or 2 streets	3.2.2.50 to 3.2.2.52
D	Business and personal services	1 2 3 4 5 6	7,200⁺ 3,600⁺ 2,400⁺ - - -	18,000 9,000 6,000 4,500 3,600 3,000	Additional fire separation and fire resistance rating requirements apply; different requirements for buildings up 4 storeys and lower ⁺ if facing 3 streets; less if facing 1 or 2 streets	3.2.2.58 to 3.2.2.62
E	Mercantile	1 2 3 4	1,500⁺ 1,500⁺ 1,500⁺ -	1,800 1,800 1,800 1,800	Additional fire separation and fire resistance rating requirements apply; different requirements for buildings with fewer storeys ⁺ if facing 3 streets; less if facing 1 or 2 streets	3.2.2.65 to 3.2.2.68
F-1	High hazard industrial	1 2 3	800 - -	3,600 1,800 1,200	Heavy timber construction only; Additional fire separation and fire resistance rating requirements apply; different requirements for buildings with fewer storeys	3.2.2.71 to 3.2.2.73
F-2	Medium hazard industrial	1 2 3 4	1,500⁺ 1,500⁺ 1,500⁺ **-**	9,600 4,800 3,200 2,400	Additional fire separation and fire resistance rating requirements apply; different requirements for buildings with fewer storeys ⁺ if facing 3 streets; less if facing 1 or 2 streets	3.2.2.76 to 3.2.2.79
F-3	Low hazard industrial	1 2 3 4	7,200⁺ 3,600⁺ 2,400⁺ 1,800⁺	14,400 7,200 4,800 3,600	Additional fire separation and fire resistance rating requirements apply; different requirements for buildings with fewer storeys ⁺ if facing 3 streets; less if facing 1 or 2 streets	3.2.2.83 to 3.2.2.88

Note: A-4 (outdoor assembly), B-1(Detention) not considered; any type requiring use of non-combustible construction not considered (see NBC 2015)

3.2 International Building Code (IBC)

The International Building Code (IBC) is developed by the International Code Council (International Code Council, 2015). Chapter 6 of the IBC defines five construction types in which a building can be categorized (Table 4):

- Type I and II: buildings using mostly non-combustible materials.
- Type III: constructions with non-combustible exterior walls, but interior walls can be of any material permitted by the code. This type is primarily sued for multifamily residential buildings.
- Type IV: Constructions of non-combustible exterior walls and interior walls made of solid wood, laminated wood, heavy timber, or structural composite lumber (such as CLT, which were first introduced in the 2015 edition of the IBC) without concealed spaces (see section 602 IBC).
- Type V: Structural elements, exterior and interior walls are of any materials permitted by the code. This category differentiates between Type VA (requires 1-hour fire-resistance-rated structural members) and Type VB (no required fire-resistance rating)

Table 4. Simplified reproduction of 2015 IBC Table 601 and proposed changes of 2021 IBC

IBC edition	Type I		Type II		Type III		Type IV				Type V	
2015	A	B	A	B	A	B	HT				A	B
2021	A	B	A	B	A	B	A	B	C	HT	A	B

A, B, C, HT refer to differences fire resistance rating, allowable height, area and number of storeys (see below); HT = Heavy Timber

The IBC describes fire protection requirements to ensure life safety of occupants in case of fire. It specifies access and equipment for firefighters, as well as preventive measures against fire spread to neighboring buildings. In general, requirements for the protection of the building structure varies with building type and height.

Chapter 23 refers to wood as a construction material. Structural glued CLT has to be manufactured and identified as required in a specified ANSI standard (ANSI/APA PRG 320-2011). CLT is defined as a prefabricated engineered wood product consisting of at least three layers of solid-sawn lumber or structural composite lumber where the adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element.

IBC limits the use of CLT by construction type, occupancy, building height, number of storeys and building area. For example, Tables 504.3 and 504.4 of IBC 2015 allow up to 65 ft (ca. 19.8 m; 4 storeys) for non-sprinklered and 85 ft (5 storeys) for sprinklered Type IV construction for Type R and M occupancies (Note that slight differences for other types of occupancies need to be considered). Barber (2018) reviews IBC code requirements regarding the use of mass timber, such as CLT (Barber, 2018). Up to four storeys, the use of timber for residential buildings is fairly unrestricted, as was the case in previous editions of the NBC. Above 85 ft (25.9 m) building height, timber is not permitted. Additional fire protection and structural performance is required for high-rise buildings (higher than 75 ft/22.9m). Further, IBC specifies when sprinklers (Section 903.2), fire-blocking and draft-stopping are required in concealed spaces (Sections 718.2 and 718.3). IBC differentiates between ten groups of buildings depending on the type of occupancy.

- A: Assembly (differentiated in 5 sub-divisions)
- B: Business
- E: Educational
- F: Factory and Industrial (differentiated in 2 sub-divisions)
- H: High Hazard (differentiated in 5 sub-divisions)
- I: Institutional (differentiated in 4 sub-divisions)
- M: Mercantile
- R: Residential (differentiated in 4 sub-divisions)

- S: Storage (differentiated in 2 sub-divisions)
- U: Utility

Proposed changes

Recently, 14 changes have been proposed for the 2021 IBC cycle (IBC, 2018). The present report focusses on the proposed changes regarding type IV construction (G108-18) and in addition to tables 504.3 (building height), 504.4 (number of storeys), and 506.2 (building area). Note that change G28-18 addresses changes regarding redundant water supply in super high-rise buildings (420 feet or taller). These changes propose three new types of constructions, defining allowable building heights, fire safety requirements, and number of storeys for mass timber constructions up to 18 storeys. The newly proposed building types fall into category IV:

- Type IV-A: 100% non-combustible protection on all surfaces of mass timber
- Type IV-B: non-combustible protection on all surfaces of mass timber except for limited exposed areas
- Type IV-C: exposed mass timber, except shafts, concealed spaces, and outside of exterior walls

The proposed changes permit the use of CLT for structural building elements as well as non-loadbearing interior and exterior walls. Table 5 shows the proposed changes to IBC 2021, which allow the maximum of 18, 12 and 9 storeys for Type IV-A, IV-B and IV-C, respectively, for residential and business occupancies with sprinkler protection. The proposed changes also allow heavy timber construction with exposed mass timber (Type IV-C) for all occupancies with sprinkler protection. The proposed changes for Type IV-A, IV-B, and IV-C are the same as the ones allowed for non-sprinklered Type IV constructions in IBC 2015. Further it is proposed that unprotected mass timber, such as CLT, is required to provide at least a two hour Fire Resistance Rating (FRR). It is important to note that unlike for constructions of type IV-HT in IBC 2015, no one-hour reduction in FRR is allowed for supervised sprinkler valves.

Table 5. Proposed changes to IBC 2021 compared to IBC 2015 (IBC change proposals G75-18, G80-18, G84-18)

Building type	IBC edition	Maximum Storeys*	Avg. area per storey (square feet)	Height (feet)	Exit and Hoistway Enclosures	FRR (hours)***
IV-HT	2015	6	54,000	85’		2+
IV-A	2021	18	54,000	270’	NC or protected MT**; NC above 12 storeys or 180’	3
IV-B	2021	12	54,000	180’	NC or protected MT**	2
IV-C	2021	9	45,000	85’	NC or protected MT**	2

*Notes: *May be less for certain occupancies; ** more detailed requirements apply;* *** more detailed requirements apply; No FRR reduction for sprinkler; +See table 601 IBC 2015
NC = non-combustible; MT = mass timber

Use of sprinklers

Chapter 9 of the 2015 IBC addresses fire protection systems. Sections 903.2 of the IBC specifies the use of approved automatic sprinklers. Note that the sprinkler requirements change according to occupancy type and that IBC references to NFPA 13, NFPA 13R, and NFPA 13D for sprinkler requirements.

Alternative solutions

Section 904 of the 2015 IBC describes alternatives solutions, and “shall be designed, installed, tested and maintained in accordance with the provisions and the applicable referenced standards” (904.1). Among others, the IBC refers to NFPA 750 {NFPA, 2015 #4} for standards for the design and installation automatic water mist systems. In general, supervision and alarm of water mist systems need to comply with section 903.4 (same as for sprinklers), whereas testing and maintenance needs to comply with the International Fire Code.

4 Water mist system standards

Water mist systems could be considered as an alternative solution for the protection of timber buildings, for which NBCC requires sprinkler protection. In adopting water mist systems, one question that must first be answered is how water mist systems should be designed, installed and maintained in particular for the protection of timber buildings. Currently, there are various standards available, such as NFPA (National Fire Protection Association), UL (Underwriters laboratories), FM, BS (British Standards), and DIN (Deutsches Institut für Normung)/ CEN (Comité Européen de Normalisation)/ EN (European Norm). This chapter provides a brief description of each standard. Water mist system performance objectives and design methods specified in these standards are also reviewed to check if these standards are applicable to timber buildings.

4.1.1 Hazard classifications

The approaches to water mist system design employed in the standards are fundamentally different from those established for conventional sprinkler systems. For conventional sprinkler systems, hazard classification systems are utilized, which categorize fire loads and degree of hazards based on occupancies. The rationale of this approach is to link levels of fire hazards to the intended use of a space (NFPA, 2016a).

In general, water mist standards also adopt part of the hazard classifications established for conventional sprinkler systems. Table 6 compares the hazard classification system used in each standard. The hazard classifications vary between different standards, yet they are all based on occupancies. For example, NFPA 13 (NFPA, 2016a) hazard classification identifies five occupancy hazards (i.e. Light Hazard, Ordinary Hazard 1, Ordinary Hazard 2, Extra Hazard 1 and Extra Hazard 2) whereas NFPA 750 (NFPA, 2015) identifies three of the five hazards, which include Light Hazard, Ordinary Hazard 1 and Ordinary Hazard 2.

The intent of adopting the existing hazard classification system to water mist systems should be carefully examined based on good understanding of the differences in design approaches between sprinkler systems and water mist systems:

- The purpose of the hazard classification system for the conventional sprinkler system is to provide design bases, such as by means of the area/water density curve, which provides a required water spray rate for each of the five hazard levels in NFPA 13 Following the generic design methods in NFPA 13, sprinkler system design including water spray rates and installation requirements would be set to provide required protection for the corresponding occupancy.
- Water mist standards, however, require the system to be designed based on verifications through full-scale fire tests as part of listing process for a particular hazard scenario. Thus, the hazard classification system used in each standard is to set bases for identifying a degree of hazards in designing water mist systems. Thus, it should be noted that, all the occupancies outlined in the standards for each hazard classification could not be properly protected by water mist systems unless the effectiveness of the system is proven by evaluations through full-scale tests designed to represent a particular occupancy.

Table 6 Scopes of hazard scenarios covered by water mist system standards

NFPA 750	**UL 2167**	**FM 5560**	**BS 8458**
Hazard Classifications			
Light Hazard- churches, hospitals, museums, offices, schools, residential	Residential-hotels, dorm, apartment, condo, nursing homes Light hazard	Hazard category 1-apt, atrium, church, gym hospital, hotel, institutions, libraries, hotels, museums, nursing homes, offices, schools	Domestic occupancy-single family dwelling, multi-family houses, flats 18 m or less in height. Residential occupancy-residential care premises, dorm, hostels, Up to the maximum height of 45 m
Ordinary Hazard 1-stockpiles not exceeding 2.4 m-automobile parking and showrooms, bakeries, electronic plants, laundries, restaurant service areas	Ordinary hazard 1		
Ordinary Hazard 2-stockpiles not exceeding 3.66 m-Agricultural facilities, dry cleaner, mercantile, post offices, repair garages, tire manufacturing, wood assembly facilities	Ordinary hazard 2		
Specific applications			
-machinery spaces -combustion turbines -wet benches and other similar processing equipment -local application -industrial oil cookers -computer room raised floors -chemical fume hoods -continuous wood board press	-shipboard machinery space -shipboard passenger cabin -shipboard public space	-combustion turbines -industrial oil cookers -Machinery in enclosures -computer room subfloors -indoor transformers -wet benches in cleanrooms	

NFPA 750 Standard on Water Mist Fire Protection Systems (2015 Edition)

NFPA 750 (NFPA, 2015) contains the minimum requirements for the design, installation, maintenance and testing of water mist fire protection systems. It does not provide definitive fire performance criteria or offer specific guidance on how to design a system to control, suppress or extinguish a fire. It states that listed systems that have demonstrated the performance through fire tests should be installed. As per NFPA 750, water mist systems do not currently have a listing for Extra Hazard 1 and Extra Hazard 2 areas, which include occupancies where quantity of combustibles is very high, combustibility of contents is very high, and high rates of heat release is expected. Nonetheless, NFPA 750 identifies specific applications of water mist system to spaces such as machinery rooms and combustion turbines.

Applications to residential and light and ordinary hazard occupancies are addressed in NFPA 750 Chapter 10. The chapter covers the design and installation of occupancy protection system for residential buildings up to and including four stories in height. The chapter also covers applications to one- and two-family dwellings.

NFPA 750 does not provide any generic test protocols; however, examples of other fire test protocols developed in IMO (International Maritime Organization), FM approvals, UL (Underwriters Laboratories, Inc.) and CEN are introduced in Appendix C.

UL 2167 the Standard for Safety of Water Mist Nozzles for Fire-Protection Service

UL 2167 (UL, 2017) sets out UL requirements for water mist systems intended for the protection of residential, light and ordinary hazard areas. UL 2167 provides generic test protocols developed for shipboard applications as well as land applications including residential, light and ordinary hazard areas.

ANSI/FM 5560 American National Standard for Water Mist Systems

FM 5560 (FM, 2017) provides the performance requirements for water mist systems for use as fire control and and/or extinguishing systems. Examinations are limited to use in occupancies such as machinery, combustion turbine rooms. FM 5560 also covers applications to non-storage and non-manufacturing occupancies designated as Hazard Category 1 as per FM Data sheet 3-26, fire protection water demand for non-storage sprinklered properties. For light hazard occupancy, the applications are limited to a ceiling heights of 2.4 m for restricted areas and 5 m for unrestricted areas. FM 5560 provides testing protocols for the light hazard occupancy.

BS 8458 Fixed fire protection systems – Residential and domestic water mist systems –code of practice for design and installation

While the British Standard covers water mist systems in industrial commercial buildings in BS 8489 (BS, 2016), applications to residential and domestic occupancies are covered in BS 8458 (BS, 2015). BS 8458 provides recommendations for the design, installation, and other technical requirements for water mist nozzles in protection of residential and domestic occupancies up to a maximum ceiling height of 5.5 m and in a building with a maximum height of 45 m. The domestic occupancy includes single family dwellings and boarding houses. The residential occupancy includes blocks of flats greater than 18 m in height, residential care premises, dormitories and hostels. Design objectives of water mist systems for residential domestic premises are specified, but design parameters are required to be established by carrying out fire tests. Annex C of the standard provides detailed test protocols developed for residential fire scenarios.

DIN CEN/TS 14972 Fixed firefighting systems – Water mist systems – Design and installation

DIN CEN/TS 14972 (DIN, 2011) provides performance requirements for water mist systems, describes a number of test conditions (1) to set test criteria for fire extinction capabilities of water mist installations, (2) to classify and set the appropriateness of a specified water mist installation, and (3) provides minimum standards for sufficient performance and safety. Annex A.3 of the standard provides detailed test protocols for office use.

4.1.2 Design objectives

Design objectives of water mist systems are also specific to hazard scenarios. Chapter 9 in NFPA 750; Design objectives and fire test protocols states that water mist systems shall be designed and installed for the specific hazards and protection objectives specified in the listing. NFPA 750 also states that “the fire performance objectives of a mist system shall be described using at least one of these terms: fire control, suppression and extinguishment” and listing shall be “obtained through full scale fire tests and system component evaluations conducted by internationally recognized laboratories to demonstrate that performance objectives can be met”.

Among various applications and hazard scenarios, water mist systems for the protection of residential and light hazard spaces are of interest. BS 8458 clearly states that “water mist fire suppression system for residential and domestic applications are designed to provide an additional degree of protection of life and property”. Its focus is primarily on providing life safety for domestic and residential premises, and BS 8458 comments that “water mist systems for domestic and residential occupancies are designed to suppress and control fires”. FM 0402 also states that water mist systems for light hazard occupancies are to control fires with less water than standard automatic sprinkler systems.

These objectives of water mist systems in BS 8458 and FM 5560 are in line with the system performance objectives of conventional sprinkler system specified in NFPA 13 (NFPA, 2016a) and NFPA 13 R (NFPA, 2016b), which are controlling fire to limit the effect of fire by decreasing the heat release rate while wetting combustibles and controlling ceiling gas temperature. In fact, the concept of fire control meets directly the objectives of sprinkler system defined in NBCC, which are to limit the severity of fire and to prevent flashover in an enclosure of fire origin. Chapter 10 in NFPA 750 refers to occupancy protection systems and says that water mist systems shall be designed to protect against a fire originating form a single ignition location.

4.1.3 Design methods

Due to the technical complexities of water mist systems, the standards do not provide generic design methods such as the area/density curve in NFPA 13. The area/density curve, which was developed based on a large empirical database and engineering principles of the conventional sprinkler system, provides a nominal water spray density for different hazard levels.

For water mist systems, however, it is still difficult to stipulate design methods sufficiently covering wide-ranging water mist systems. This is mainly because there are many technical factors other than water spray densities affecting the efficiency of water mist systems. These factors include water droplet atomization, spray cone angle, spray velocity and mixing ability, which all depend on manufactures’ individual system (Mawhinney & Back, 2016). In addition, sprinkler systems are designed specifically to a hazard classification and fire loading in a fire room, whereas water mist systems design needs to take into account room conditions in addition to fire loading in the room, such as the volume, ceiling height and ventilation conditions including sizes of open doors and windows.

Therefore, instead of providing definite design methods, these water mist system standards (e.g., NFPA 750, UL 2167, BS8458, FM5560 and DIN CEN/TS 14972) require a water mist system to be evaluated through full-scale fire tests by qualified testing laboratories as part of listing process. As an initial step, fire hazard assessment should be conducted to identify a hazard classification and to develop test protocols that represent the hazard scenario. Then, following the developed test protocols, each system will be verified for the design objectives and specifications (e.g. the layout of mist system, nozzle locations, installation details, water spray rates and pressure) for each respective hazard scenario. NFPA 750 states that fire test protocols shall be designed to address performance objectives of the application specified in the listing and the application parameters. Application parameters shall include compartment variables, such as height, volume, obstructions, and ventilation, fire hazard fuel type and configuration, and occupancy, with consideration of performance objectives specific to the application (NFPA, 2015). The layout of water mist systems, for example nozzles spacing, water flow rates and pressure should be accepted based on full-scale tests for each respective application.

The absence of a generic design method is in fact a barrier of water mist system to apply to buildings beyond marine and industrial applications (Mawhinney & Back, 2016).

4.1.4 Test protocols

Some of the water mist standards provide generic test protocols that are developed to verify design calculation, component functionality and the stated performance objectives for a specific hazard scenario. This section discusses the protocols provided by FM 5560, UL 2167 and BS 8458 for testing water mist suppression systems designed for residential/light hazard areas. The details of the standard tests are summarized in Table 7.

FM 5560 classifies the tests for light hazard occupancies into a small compartment, large compartment and open space. UL 2167 provides different tests for residential and light hazard areas. The room dimensions in the 3 standard tests (FM 5560, UL 2167 and BS 8458) depend on the maximum nozzle spacing .The maximum ceiling height is 2.4±0.1 m in different tests except for the open space test provided by FM 5560. Both UL 2167 and BS 8458 state specific finishing materials for the room walls while FM 5560 just requires a minimum fire-resistance rating of 30 minutes for the room walls. The room temperature is 27°C, 24°C, 20°C and non-specified in UL 2167 residential hazard, UL 2167 light hazard, BS 8458 and FM 5560 standards; respectively.

FM 5560 differentiates between the room height for pendent nozzles test (< 5 m), and sidewall nozzles test (< 2.4 m). UL 2167 provides separate details about the room dimensions and nozzle locations for testing pendent style and sidewall style nozzles. Nonetheless, BS 8458 doesn't mention any specific differences between testing these two nozzle styles. All the tests use simulated furniture made up of polymeric foam in addition to a wooden crib or frame as sources of fuel in the test. The source of ignition in UL 2167 and BS 8458 is a pan of heptane; however FM 5560 doesn't state any characteristics for the igniter. In all the tests, at least one target (dummy) nozzle is used .This nozzle shouldn't get activated during a successful test.

The BS 8458 procedures involve 6 different tests; a)fuel placed at room corner, b)fuel placed between two nozzles, c)fuel placed beneath a nozzle, d)the worst of a,b or c should be repeated with ambient air having minimum velocity of 1 m/s at 1 m above the floor inside the room. The air velocity is provided by 5 m diameter fan, e) the worst two tests from a,b & c to be repeated with only 2 walls in place (open room test), f)higher ceiling test if approval is required. Moreover, BS 8458 provides the most stringent evaluation criteria where it requires that the nozzles should be capable of suppressing the test fires for a discharge duration of 30 min, measured from nozzle operation. In addition, the maximum allowable temperatures at 75 mm below the underside of the ceiling and at 1.6 m above the floor are 320°C and 95°C; respectively and shouldn't exceed 55°C for more than any 2 min at 1.6 m above the floor. However, ceiling temperature must not exceed 260°C in FM 5560 and UL 2167 tests. In addition to the ceiling temperature, the UL 2167 standard for residential areas requires the temperature at 76 mm below ceiling to be less than or equal 316°C, temperature at 1.6m above the floor ≤ 93°C, and ≤ 54°Cfor more than 2 min period at the same location. For a nozzle intended for use in light hazard areas according to the UL 2167 test, the average loss of weight of 3 wood cribs to max of 35%.

DIN CEN/TS 17972 describes, among others, test procedures for office type setups. The test procedure requires comparing the performance of a water mist system to a sprinkler system (complying with EN 12845) in four tests (water mist and sprinkler system, each with both one and four ignitions). Each test setup consists of a wooden desk, wall, drawers and chair, with some paper, polyethylene foam items, and electronics placed on the table. The performance of the water mist system has to be analyzed in comparison to the sprinkler system. Given the complexity of the setup, the material and items burned in the test need to be described in the results. To pass, performance needs to be demonstrated for both sprinkler and water mist system.

Table 7.Test protocols for some water mist standards

	FM 5560			UL 2167			BS 8458	
	Small compartment	Large compartment	Open space	Pendant nozzle	Sidewall nozzle	Light hazard	Nozzle spacing 2-4 m	Nozzle spacing 4-5 m
Dimensions (m)	3×4×2.4	Square room, side is double nozzle spacing	Height ≥5	Height ≥ 2.4, length and width depend on nozzle coverage		Square room, side is spacing of 4 nozzles	4×8; height 2.5	5×10; height 2.5
Illustration	Figure 4.			Figure 5.			Figure 6.	
Ventilation	1 door	2 doors	Open	2 doors		2 doors	A door and porch	
Fuel	2 bunk beds	Crib+2 pieces of simulated furniture	4 sofas	Wood crib+simulated furniture		Wood crib	Crib+2 pieces of simulated furniture	
Active nozzles	1	2	4	2		4	2 or more	
Target (dummy) nozzles	2	2	8	1		-	1	
Duration	10 min from activation of nozzle			30 min after ignition of wood crib		10 min after ignition	30 min after activation of nozzle	
Evaluation criteria	Ceiling temp.≤260°C			Only 1 nozzle activated. Ceiling temp. ≤ 316°C. Temp. at 1.6m above floor≤93°C		35% loss of weight of crib	Nozzles should suppress the fire. Ceiling temp. ≤ 320°C.	

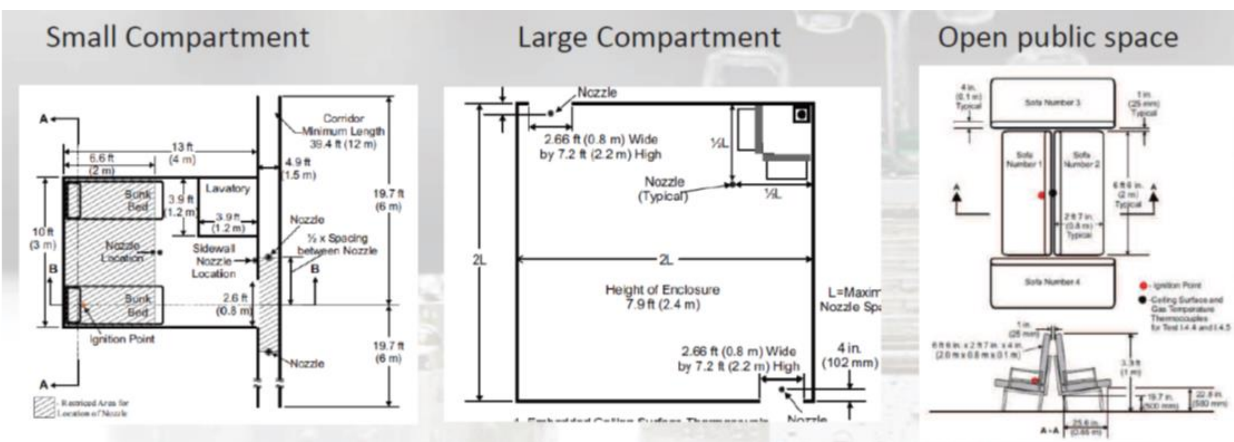

Figure 4. Test rooms for testing water mist systems under FM 5560 standard

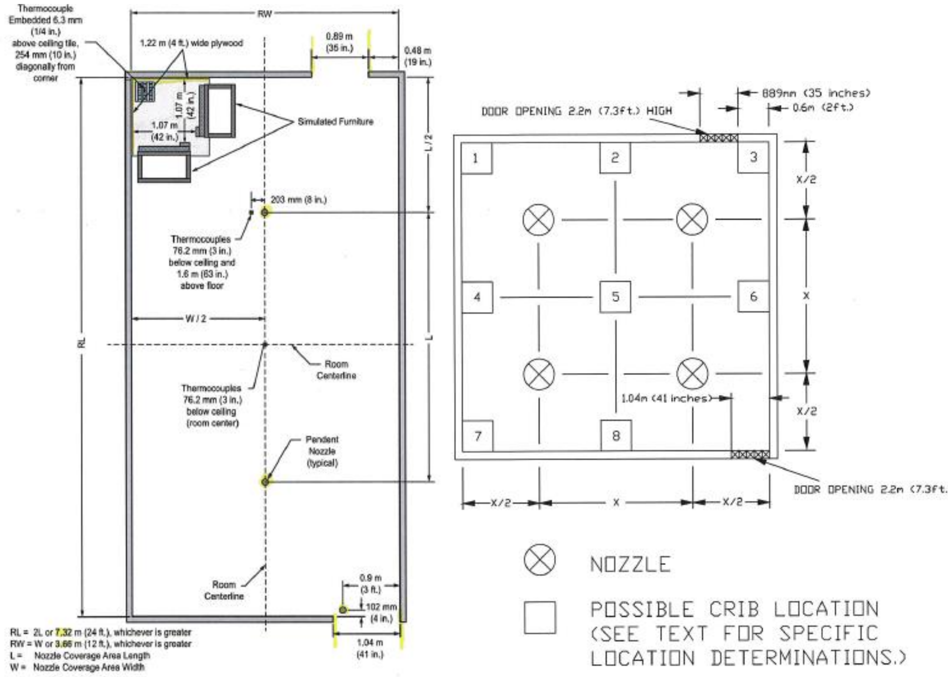

Figure 5. Test rooms for testing water mist systems for residential area hazard (left) and light hazard (right) under UL 2167 standard

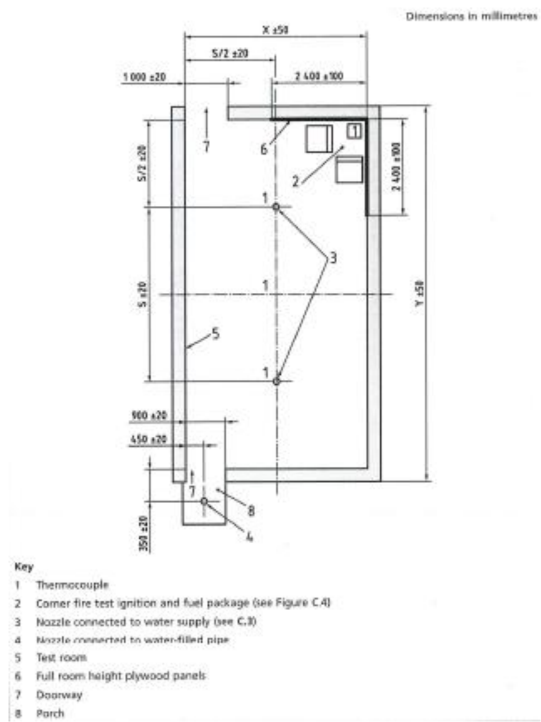

Figure 6. Test room for testing water mist systems for residential area hazard under BS 8458 standard

5 Experimental studies on fire suppression in wood buildings

In recent years, timber buildings (both light-frame and heavy timber buildings) have been studied widely through numerous fire tests to examine the fire performance and to develop design requirements. However, only a few fire suppression tests have been reported particularly with conventional sprinkler systems. These tests were mainly to demonstrate the effectiveness of sprinkler systems in limited applications to timber buildings. There was no test reports in the literature discussing the effectiveness of water mist systems in heavy timber buildings. Nonetheless, some water mist tests were conducted against residential fire scenarios, and this section will discuss these tests.

5.1 AHC TWB fire suppression tests for heavy timber buildings

A series of 5 full-scale apartment fire tests (Zelinka, Hasburgh, Bourne, Tucholski, & Ouellette, 2018) were conducted by the Ad Hoc Committee on Tall Wood Buildings (AHC-TWB) formed by the International Code Council to address proposed changes to the IBC 2021 code (Zelinka et al., 2018). The main objective of the tests was to demonstrate the fire performance of a heavy timber building in support of the proposed changes. A two-storey apartment building with one furnished unit on each floor was built using CLT assemblies with and without gypsum board protection. Each unit had one bedroom and a living/kitchen area. Two tests (Test 4 and 5) were conducted with a sprinkler system, and in these tests, the fire was initiated in a base kitchen cabinet in the unit on the first floor. The walls and ceiling of the unit were protected with gypsum boards, yet one side wall and the ceiling of the living area and the bedroom were unprotected, exposing the CLT members. Sprinkler systems were designed as per NFPA 13 with a water spray discharge density of 2.0 $l/min{\cdot}m^2$, which is specified for light hazard occupancies. A total of sprinkler 9 nozzles were installed in various locations in the unit.

In Test 4, a pendent type nozzle having a temperature rating of 68.4°C installed close to the ignition source was activated at 2.5 minutes and quickly extinguished the fire within about 2 minutes from the activation. The temperature in the living area and the bedroom did not exceed 80°C during the test. Thus, the exposed CLT walls and ceilings were not damaged, and no extra sprinkler head presumed (based on the ceiling temperature measurements) to be activated in the living area and the bedroom. In Test 5, the sprinkler system was manually activated 23 minutes after ignition, by which time the fire had spread to the living area and the bedroom with measured hot layer temperatures exceeding 600°C. With all 9 sprinkler heads activated, the fully-developed fire in the entire unit was effectively suppressed within approximately 10 min; however, the fire damaged the exposed CLT members severely.

The test results from Test 4 showed that sprinkler systems designed and approved by NFPA 13 would effectively control a residential kitchen fire scenario and prevent the fire spread to adjacent rooms. The tests also demonstrated that with sprinkler protection, the heavy timber member could be exposed without gypsum board protections. However, when sprinklers fail to operate, the entire unit can be engulfed in fire very quickly (i.e., without sprinkler system, the flashover occurred at 11-13 minutes in the kitchen/living area, and the measured peak heat release rate was about 20 MW). The report does not provide rationales why the kitchen fire scenario was selected for the tests. Kitchen fires are frequent but not most challenging scenario involving the exposed CLT members. The initial HRR development was not as fast as a living fire scenarios involving upholstered furniture, which could results in flashover within 4-5 minutes in some cases.

5.2 SFIT fire suppression tests for timber buildings

Swiss Federal Institute of Technology (SFIT) conducted full-scale fire tests of modular wooden hotel room to verify the efficiency of sprinkler systems (Frangi & Fontana, 2005). The room dimensioned with 6.6 m (L) ×X 3.1 m (W) ×X2.8 m (H) was built with light-frame construction. The interior of the room was lined with Oriented Strand Board (OSB) panels. The floor was covered with linoleum, and the ceiling was lined with timber boards. The room was fully furnished with a bed, tables and cabinets. Ceiling type and wall type sprinkler heads with the activation temperature of about 68°C were tested for the room fire started from the mattress. Sprinkler systems were activated within 2-3 minutes in all the three tests, and opening the window did not influence the activation of the sprinklers. No significant differences were observed between ceiling and wall sprinkler systems and on the ceiling and the wall, and sprinkler systems extinguished the fire before it could spread to the combustible surfaces of the wall and ceiling. However, water sprayed from sprinkler systems pooled on the floor. The tests confirmed that with fast response sprinkler system the influence of a combustible structure on the fire safety was compensated and the fire safety objective can be fulfilled with combustible timber structures.

5.3 SP fire suppression tests for living room fire scenarios

The Swedish National Testing and Research Institute tested high pressure water mist nozzles and three different types of residential sprinklers (a recessed pendent, concealed pendent and a horizontal wide wall, listed per NFPA 13R) for a living room fire scenario (Arvidson & Larsson, 2001). The primary objective was to provide guidance regarding the appropriate water discharge densities as a function of the type of residential sprinklers used and its coverage area. A living room was constructed using wood studs and ceiling joists. Dimension of the living room was 4 m wide by 5 m long, and it was connected to a bed room dimensioned with 3 m by 3m through a doorway. The living room also had a doorway opening to outside. Two ceiling heights of 2.5 m and 5.0 m were tested for the living room. With the 5 m height for the living set-up, the bedroom floor was raised to 2.5 m from the living room floor. Lining materials of particle board or gypsum board were used for the walls and ceiling around the fire set-up. A upholstered chair/ simulated upholster chair was placed as a fire source at a corner in the living room, quite close to the combustible walls. The chair was ignited at the side of the char facing the combustible wall, with intention to allow the fire to involve the wall paneling.

Two and three high pressure water mist system tests were conducted in the high ceiling and in the low ceiling living room, respectively. Two high pressure water mist nozzles with a nominal temperature rating of 57°C were installed on the ceiling of the living room to provide a water spray density of 1.1 mm/min, and a dummy nozzle was also installed in the bed room. In general, it was observed that water mist systems drew a larger amount of fresh air to the fire, which resulted in more turbulent burning as compared to the sprinkler test. It was also concluded that high wall wetting is desirable for a water mist nozzle to minimize wall damage. In all the high ceiling living room tests, wall damage was observed and the fire redeveloped and burned continuously even with the mist system active. Consequently, the ceiling temperature in the living room and in the connected bedroom were high, and the dummy nozzle measured the temperature that would have activated the nozzle in the bedroom.

The effect of water spray rates was examined using the high pressure water mist system (75 bar) by testing two different water spray rates of 1.1 mm/min and 1.9 mm/min in the low ceiling living room. Less wall damage and lower ceiling temperature were resulted in the test with the higher water spray.

5.4 RISE fire suppression tests for residential fire scenarios

The Research Institutes of Sweden (RISE) investigated the benefits in using early activation of residential sprinklers with lower Response Time Index (RTI)[4] and activation temperature ratings (Arvidson, 2017). The tests used either a simulated or authentic upholstered chair placed in a corner of the test compartment dimensioned with 3.66m wide, 3.66 m long and 2.5 m high. Two low-pressure and two high pressure water mist systems were also tested for the same fire set-up for comparisons with sprinkler systems. It is reported that the performance of the water mist nozzles were comparable or better than the residential sprinkler system at approximately half the water flow rate for the tested fire scenarios. Figure 7 shows the ceiling temperature measured with sprinkler systems and water mist systems, which confirms that water mist systems is effective in cooling the area. The differences between the low and high pressure water mist systems were small. The smallest fire damages were observed in the tests with high water spray rates.

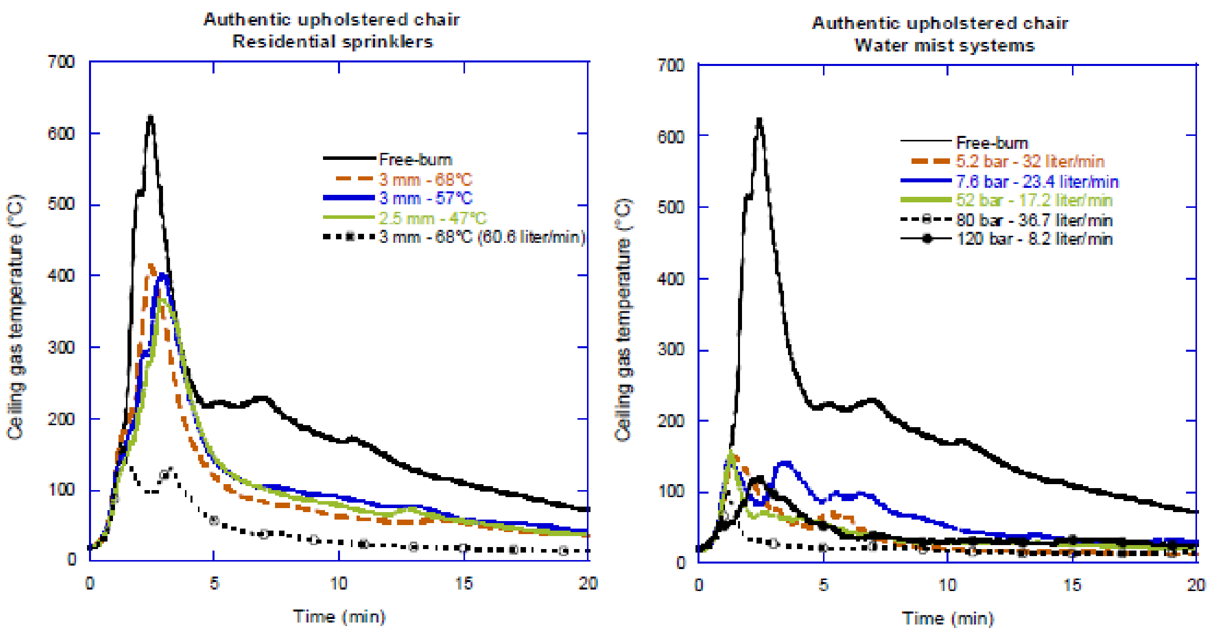

Figure 7. The ceiling temperatures measured with sprinkler systems and water mist systems

[4] RTI is a measure of nozzle sensitivity in responding to gas flow and is correlated with flow temperature and velocity.

6 Discussions

6.1 The effectiveness of water mist systems for protection of wood buildings

The effectiveness of water mist systems depends on various parameters, such as compartment variables, ventilation conditions, fuel types and water spray characteristics.

6.1.1 Compartment volumes and ventilation conditions

In compartment applications, primary fire suppression mechanisms of water mist systems are gas phase cooling and oxygen depletion. Interacting with a hot plume, water droplets extract heat from the plume and evaporate. In turn, the heat transfer process results in cooling the area surrounding the fire. In addition to the heat extraction, the volume occupied by the water mist increases over three orders of magnitude as the water mists evaporate (Mawhinney & Back, 2016). This decreases the volumetric concentration of oxygen in the compartment. Eventually, the suppression system can suffocate the fire in the room when the oxygen level in the room becomes lower than the limiting oxygen concentration required for sustained combustions.

Thus, the volume of the compartment affects the effectiveness of water mist systems in gas phase cooling and oxygen depletion in the compartment. In providing protection for a large volume space, the main mechanism of water mist systems would be flame cooling, radiation attenuation and dilution of fuel vapors rather than suppressing or extinguishing the fire by the oxygen depletion in the space. Thus, in designing water mist systems for the protection of large spaces such as open space offices and halls, experimental assessment of the performance of the system is essential. FM 5560 has developed a test protocol for an open space scenario, which only concerns a residential fire scenarios. Development of new test protocols is in need since building codes evolve to allow various occupancies for timber buildings.

In addition to the volume of the compartment, open doors/windows and mechanical ventilation conditions also affect the oxygen depletion by water mist systems in the compartment. With this regard, the water mist test protocols in FM 5560, UL 2167, BS 8458 consider a test compartment with one or more openings. BS 8458 also includes a test with a forced air flow in the room. These configurations would challenge the system in cooling the area and controlling the fire.

SP 2001 tested water mist nozzles and sprinkler heads for a simulated furniture fire in a living room with varying ceiling heights of 2.5 and 5 m. While the impact of the high ceiling was minimal for sprinkler systems, the effectiveness of water mist systems was affected by the ceiling height. When tested in the high ceiling room, the nozzle activated 16 seconds later than in the low ceiling room, and the maximum ceiling temperature measured during the test (1 m away from the fire) was 170°C greater than in the low ceiling room.

6.1.2 Type of fuel and droplet characteristics

Although the performance of water mist systems are especially suited for liquid fuel (Class B) fire suppression owing to its fine water droplets, water mist systems are known to be also effective on solid combustible (Class A) fires. In general for solid combustible fires, droplet sizes should be large enough to have the momentum to effectively penetrate flames and affect the fuel bed directly. By definition in NFPA 750, water mist systems spray with Dv0.99 of up to 1000 µ. The large water droplets wet the fuel surface while the fine droplets absorb heat from hot smoke and generate vapour. However, the relationship between drop sizes and their effectiveness in controlling fire is complex since there are many other factors affecting the capacity of fire control (NFPA, 2015). The factors include mean droplet size and droplet size distribution, spray velocity (momentum) and spray mixing capacity.

Water mist systems demonstrated successful fire control over a solid combustible (upholstered chair) fire in SP 2001 (Arvidson & Larsson, 2001) and RISE 2017 tests (Arvidson, 2017). RISE 2017 reported that “the lowest ceiling gas temperatures were recorded in the tests with the high-pressure water mist nozzles, illustrating the enhanced cooling of smaller water droplets combined with a strong downward momentum of the water sprays that entrain the hot gases from the ceiling level and push them down”.

FM 5560 ,UL 2167 and BS 8458 test protocols for residential scenarios require solid combustible fuels to be tested, and a simulated furniture padded with PU foam are most comment commonly used as a fire source used in the protocols. In EN, an office desk fire scenario involving materials made of plastics is required to be tested for light hazard scenario. In UL 2167 test protocols for light hazard space, several wood cribs are required to be placed in the testing area.

6.1.3 System actuation

BS 8458 requires a wet pipe system and automatic nozzles with a quick-response thermal element for residential and domestic occupancies. The standard activation temperature required by NFPA is 57 to 77°C for the area with anticipated ambient temperature lower than 38°C. The benefit of fast activation was investigated by SP2017 by testing sprinkler heads with different temperature ratings of 68°C, 57°C and 47°C. The results showed that the earlier activation associated with a lower RTI and operating temperature to certain degrees corresponded to improved performance. However, due to its high sensitivity, sprinkler heads away from the fire origin or in the adjacent room could also be activated. In application to timber buildings with a view to limit unnecessary water discharge, it is ideal to successfully control fire and prevent heat and smoke spread beyond the room or spot of fire origin.

6.1.4 Nozzle spacing and layout

In occupancy protection, water mist systems should provide automatic fire protection throughout the occupancy (NFPA, 2015). This means that water mist nozzles should be laid out such that they provide protection for the entire space in protection. Nozzles are often installed on ceilings or walls so that they can quickly sense the hot gas developed from the fire. The requirements for nozzle spacing and layout should be provided in the listing information for a specific water mist system (NFPA, 2015), which should also include the maximum spacing from walls and the maximum height between ceiling and nozzle tip. The listing information should be re-assessed in application to timber buildings if the listing is particularly developed based on the tests that do not address the issues of combustible wall and ceiling lining materials around the fire. To protect exposed walls and ceilings of mass timber structural elements, minimizing the nozzle spacing from the exposed wall and ceiling minimum could prevent fire damages of the exposed structural elements.

6.1.5 Wall damages

SP 2001 water mist tests reported damages on the wall that faced fire source (i.e., particle board was used for wall lining materials in the fire room). The degrees of the wall damages depended on water spray rates and system pressures. The wall was burnt to a height of approximately 1.5 m above the floor when a water spray rate of 1.1 mm/min was applied, but minor damages were reported for the same test with 1.9 mm/min. SP 2001 concluded that the high wall wetting is desirable for residential scenarios.

6.1.6 Water spray rates and discharge duration

The water spray rate is the most important parameter governing the fire suppression capability of water mist systems. BS 8458, FM 5560 and NFPA 750 requires the water spray rate determined through fire tests for a specific fire scenario and performance objective. For residential and domestic occupancies, the system should be capable of providing pressures and flow rates to permit all the water mist nozzles in an assumed a maximum area of operation of 64 m^2 to operate simultaneously at not less than the nozzle pressure given by the pass criteria determined by the test. NFPA 750 requires the number of design nozzles within a compartment up to a maximum of four adjacent nozzles for residential occupancies and two for one and two family dwellings that require the greatest hydraulic demand in accordance with the requirement of the listing.

Discharge duration is also an important parameter for successful fire control by water mist systems. Particularly to achieve fire extinguishment, which is required for industrial applications, water mist systems entails a certain discharge/hold time of more than 10 minutes. SP2001(Arvidson & Larsson, 2001) test reported that while the simulated furniture fire was under control by water mist systems, the fuel was burning and the fire consumed the entire fuel with the mist system active. NFPA 750 requires the minimum discharge duration of 30 minutes for light hazard occupancies, and BS 8458 requires the minimum discharge duration of 10 minutes and 30 minutes for domestic occupancies and residential occupancies, respectively.

For the protection of timber buildings, it is questionable whether or not the discharge duration requirements are applicable to the same occupancies built with timber structures. The requirements for the discharge duration and water spray rates may need to be enhanced if a hazard assessment shows that extra risks associated with the use of timber frames or special architectural design features, which might adopt non-conventional fire engineering solutions. BS 8458 states that "in special circumstances, enhanced performance, reliability and resilience arrangement should be provided". The special circumstances include when a fire load greater than that which would normally be found in a residential or domestic occupancies or if the fire hazard is greater than that of a conventional residential or domestic occupancy, and when the building houses vulnerable people.

6.2 Water damages

Several sources note that water mist systems are considered to produce less water damage compared to sprinkler systems (Liu & Kim, 1999; Mawhinney & Back, 2016). However, to our knowledge no studies have been conducted to systematically compare water damage from these two systems. In addition, probabilities of accidental discharge of sprinkler and water mist systems are not reported.

6.3 Cost-benefit analyses

In general, installation cost; and operation and maintenance cost are higher for water mist systems than sprinkler systems[5]. However, amounts of water usage are much less for water mist system than sprinkler systems. Thus, this could reduce costs for water tanks and costs for recovering water damages after a fire incident or a false activation, which might affect insurance cost in some circumstances. In fact, cost-benefit analyses should include not only initial installation costs but also long-term operation costs and annual inspection maintenance cost. Moreover, fire protection efficiency in reducing building fire damage, occupant injuries and business interruption should also be considered in cost-benefit analyses.

[5] In the case of a computer data room, it is reported that water mist system could be 10% more expensive than traditional options (King); however, this should not be generalized since each application has different objectives and requirements.

7 Conclusions and further research

- Fire safety in tall wood buildings, especially those using mass timber as structural elements is a challenge. Most of the wood buildings are required to be covered with lining material such as gypsum plasterboard for protection against fire. Nonetheless, new regulations and/or proposed changes will allow the use of uncovered mass timber for tall wood buildings as long as they are protected by sprinklers or water based fire protection systems.
- Water mist systems are considered for the protection of timber buildings because the system provides the advantage of minimal amount of water use, less water damage and easier cleanup compared to sprinkler systems.
- Although water mist systems are widely and efficiently used in marine and industrial fire protection, when it comes to the application to buildings, there are very limited studies conducted to develop guidelines or design methods for water mist systems in protection of buildings. This is mainly because of technical complexities of water mist systems. Due to the complex technical features, water mist systems are also required to be designed based on verifications through full-scale fire tests as part of listing process. Several water mist standards provide test protocols for using these systems in residential and light hazards scenarios. However, none of these standards considered the use of water mist systems in wood frame buildings.
- Therefore, without verifications, these existing standards and test protocols should not be incorporated in the use of water mist systems in protection of timber buildings.
- Thus, in designing water mist systems for the protection of timber buildings, design requirements need to be developed through full-scale fire tests. Development of new test protocols is in need since building codes are evolving to allow various occupancies for timber buildings. Test protocols need to be developed to address important design parameters, such as compartment conditions, fire scenarios and water delivery systems including nozzles. It should be noted that the occupancy, volumes of compartments, ventilation conditions need to be considered in selections of nozzles and designing layouts of water delivery systems. Based on hazard assessment, enhanced design features might be necessary to provide robust and reliable protection.
- Based on the present literature review, the followings are recommend for future studies;
    - Review the existing test protocols to investigate the suitability of the protocols for mass timber building fire scenario.
    - Investigate the performance equivalence of water mist systems compared to conventional sprinkler systems in wood frame building scenarios
    - Investigate the benefits of water mist systems in controlling/suppressing fire and minimizing post-fire water damage.
    - Develop a research plan for numerical modelling and fire experiments for the use of water mist system for the protection of tall wood buildings.

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