

NRC-CMRC CONSTRUCTION

Technical Best Practice for Use of Water Mist Systems in Mass Timber Residential Buildings

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Report No.: A1-018023.1

Report Date: Jun 5th, 2023

Review/Approval Date: Aug 29th, 2024



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Cat. No. NR24-126/2024E-PDF
ISBN 978-0-660-73529-0



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Program: Codes R&D

55 pages

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Executive Summary

Water mist systems are considered in protection of encapsulated mass timber construction (EMTC), due to their typically low water spray rates. This technical best practice provides an overview of regulatory requirement for the fire protection of residential mass timber buildings including fire suppression systems, and it discusses applicable characteristics and design considerations of water mist systems, which are not addressed in the existing standards and guidelines.

In designing a water mist system, any special hazard of mass timber buildings should be considered, whilst construction materials are not specifically addressed in the hazard categories of the existing standards. The water mist system should be designed to provide enhanced property protection in addition to the typical residential system performance when the hazard assessment indicates relatively large areas of exposed mass timber elements, post-fire retrofit difficulties of damaged mass timber elements or other special hazardous circumstances.

While the evaluated design objectives are the same for water mist and conventional sprinkler systems, the design approach of water mist system is fundamentally different from the prescriptive manner of sprinkler systems. Water mist systems are designed based on acceptable performance demonstrated in full-scale fire tests meeting the specified pass criteria. For the case where the existing standard test protocols are not applicable, test protocols should be developed to represent the actual hazard condition (e.g., fuel loads, ventilation conditions, room dimensions) in the protected area, and to test the performance objectives, design, and component functionality. This technical document provides aspects to take into account in selecting test scenarios, protocols and pass-fail criteria. Technical notes are also provided to design parameters, such as delay times of a dry-pipe/pre-action system, water-spray shape, design area and durations, which are particularly relevant to the fire protection of residential mass timber buildings.

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List of Defined Terms and Acronyms

Authority having jurisdiction: an organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

Approved: acceptable to the authority having jurisdiction.

ANSI: the American National Standards Institute

APA: the Engineered Wood Association

BS: British Standard

Combustible construction: construction that does not meet the requirements for noncombustible construction or encapsulated mass timber construction.

DIOM manual: design, installation, operation and maintenance manual

EMTC (encapsulated mass timber construction): type of construction in which a degree of fire safety is attained by the use of encapsulated mass timber elements with an encapsulation rating and minimum dimensions for structural members and other building assemblies.

EN: European Standards

Encapsulation rating: the time in minutes that a material or assembly of materials will delay the ignition and combustion of encapsulated mass timber elements when it is exposed to fire under specified conditions of test and performance criteria, or as otherwise prescribed, as defined in the NBC 2020.

Fire control: limiting the size of fire by distribution of water or other suppressants so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage.

Fire suppression: the sharp reduction of the heat release rate of a fire and the prevention of regrowth.

Fire extinguishment: the complete suppression of a fire until there are no burning combustibles.

Fire load: the combustible contents of a room or floor area expressed in terms of the potential heat liberation (in MJ/m²), which is calculated based on the calorific value of combustible materials including the furnishings, finished floor, wall and ceiling finishes, trim and temporary and movable partitions.

FM: FM Approvals

IBC: International Building Code

IMO: International Maritime Organization

Listed: meets appropriate designated standards or has been tested and found suitable for a specified purpose.

NBC: National Building Code of Canada

NFC: National Fire Code of Canada

NFPA: National Fire Protection Association

NRC: National Research Council Canada

Residential occupancy: the occupancy or use of a building or part thereof by persons for whom sleeping accommodation is provided but who are not harboured for the purpose of receiving care or treatment and are not involuntarily detained.

Sprinklered or sprinkler protected: the building or part thereof is equipped with a system of automatic sprinklers.

The Conformité Européenne (CE) Mark: the European Union's (EU) mandatory conformity marking for regulating the goods sold within the European Economic Area.

UL: UL Mark for UL Solutions

VdS: Verband deutscher Schadenverhütung, German institution for corporate security and safety, specializing in fire protection, security, and natural disaster prevention. (Subsidiary of the German Insurance Association).

Water mist: a water spray, for which the $D_v 0.99$, (i.e., a drop diameter such that the cumulative volume, from zero diameter to this respect diameter, is the fraction 0.99) is less than 1000 microns at the minimum design operating pressure of the water mist nozzle.

Water mist nozzle: a special purpose device containing one or more orifices designed to produce and deliver an atomized water spray meeting the definition of water mist.

Water mist system: a distribution system connected to a water supply that is equipped with one or more nozzles capable of delivering water mist, intend to control, suppress, or extinguish fires, and that has been demonstrated that to meet the performance requirements of its listings and NFPA 750, "*Standard on Water Mist Fire Protection Systems*" or equivalent.

1 Introduction

In the 2020 edition of the National Building Code of Canada (NBC) (Canadian Commission on Building and Fire Codes, 2022), encapsulated mass timber construction (EMTC) is recognized as a new type of construction, in addition to noncombustible and combustible construction¹. The acceptable solutions in Division B of the NBC permit residential (Groups C) buildings to be constructed of EMTC up to a height of 12 storeys and require the buildings to be protected by an automatic sprinkler system conforming to NFPA 13, *Standard for the Installation of Sprinkler Systems* (NFPA, 2022). Some exposed mass timber surfaces such as walls, ceilings, beams, columns, and arches are permitted in certain conditions.

Post-fire water damage and mold are not addressed in the NBC's fire protection requirements; however, there are concerns of water damage and mold problems with mass timber construction as shown in a survey report (Perkins + Will, 2018), which could be caused by the sprinkler systems (Zurich American Insurance Company, 2016). Thus, water mist systems with the typically lower water flow rates could be considered as an alternative solution to the conventional sprinkler systems (Ko et al., 2019). The NBC references NFPA 13 (NFPA, 2022), for the design, construction, installation and testing of an automatic sprinkler system required for this construction type. Water mist systems as an alternative solution could be pursuant to satisfying the sprinkler requirement of the EMTC provisions in the NBC in accordance with the stated code intents and attributed objectives and functional statements.

There are several water mist protected wooden buildings. [Appendix D](#) presents some of the currently existing exposed wood buildings that are protected by water mist systems. Also, there are a few studies that were conducted for water mist systems (see the NRC study on water mist systems in application to mass timber residential buildings in [Appendix A](#) and other water mist experimental studies in [Appendix C](#)). However, there is no technical guide or standard currently available to directly address the issue of applying water mist systems to mass timber buildings (Ko et al., 2019).

This technical best practice addresses the design objectives and requirements for water mist systems in protection of residential mass timber buildings, in terms of life safety and property protection² in EMTC.

1.1 Scope

This technical document primarily covers fire scenarios involving mass timber construction, where property protection is required along with life safety. Also, it is focused on the effectiveness of water mist system in terms of fire suppression or control performance. Potential water damage assessment related to water mist system and water damage mitigation and control measures are beyond the scope of this document and will be studied in future research. However, it is briefly discussed in this technical document, where relevant, to provide broad design consideration.

¹ *Combustible construction*: construction that does not meet the requirements for noncombustible construction or encapsulated mass timber construction. Combustibility of materials is assessed via CAN/ULC-S114, *Standard Method of Test for Determination of Non-Combustibility in Building Materials* (CAN/ULC-S 114, 2018) or CAN/ULCS135, *Standard Test Method for the Determination of Combustibility Parameters of Building Materials Using an Oxygen Consumption Calorimeter (Cone Calorimeter)* (CAN/ULC-S135, 2022). Subsection 3.2.2. of Division B of the NBC specifies building size and construction relative to occupancy.

² The terminologies of “life safety” and “property protection” are used in this technical note, since they are widely used by engineers and in NFPA standards. However, the NBC uses “Safety” and “Fire and structural protection of the building”.

The rest of this technical document is structured as follows.

Section 2 provides an overview of regulatory requirement for the fire protection of mass timber buildings including fire suppression systems.

Section 3 provides the characteristics and design considerations of water mist systems, which include design objectives; consideration of occupancies and hazard classification; fire fighting mechanisms and protection strategies; design parameters; key system components; and existing standards and guides.

Section 4 discusses the process of designing water mist systems covering fire hazard evaluation, performance objective development, and selection of test scenarios, protocols and pass-fail criteria.

2 Fire Safety in Mass Timber Construction

Mass timber construction uses structural elements such as column, beam, wall, and slab with solid engineered timber sections, the required minimum dimensions of which are prescribed in the NBC. The structural elements of engineered mass timber products include Glue-Laminated Timber (Glulam), Cross-Laminated Timber (CLT), Nail-Laminated Timber (NLT), Dowel-Laminated Timber (DLT) and Structural Composite Lumber (SCL). Fire safety is an important design aspect in mass timber construction on which this technical document is primarily focused.

When unprotected mass timber is exposed to fire, its outer layer will burn and form a char layer, which could act as a protective layer contributing to mass timber's inherent fire resistance yet requires protective measures for life safety and property protection. Various studies showed the effect of the char layer formation on the protection of the residual wood for engineered mass timber products (e.g., CLT, and NLT) during fire, and also showed the burning behaviour influenced by the product configuration (e.g., de-lamination) (J. Su et al., 2019; J. Su, Leroux, et al., 2018). It should be noted that since the 2018 edition of the ANSI/APA PRG 320, *Standard for Performance-Rated Cross-Laminated Timber*, (ANSI/APA, 2019) heat delamination characteristics of CLT previously reported in (Brandon & Dagenais, 2018; J. Z. Su et al., 2018) was significantly reduced (Dagenais et al., 2019). As a result, the 2020 edition of the NBC requires that adhesives used in CLT should conform to the ANSI/APA PRG 320 standard (ANSI/APA, 2019). In addition to the product configuration, a large unprotected combustible surface area in a room could increase the fire severity by contributing to the fuel load, the compartment size, and ventilation conditions are also important parameters—as for any construction type—influencing the progression of compartment fires (J. Su, Lafrance, et al., 2018).

Along with a sacrificial layer of wood to form char and protect the residual wood, fire safety in mass timber buildings is typically achieved by passive means, i.e., by protecting the mass timber elements with noncombustible material (encapsulation) such as gypsum board and/or by active means, such as sprinkler and water-based suppression systems. The reliability of these protection methods is investigated in literature (e.g., encapsulation (Barber & Gerard, 2015; McGregor, 2013) and sprinklers (Frangi & Fontana, 2005; J. Z. Su, 2018; Wei et al., 2011)).

The following section presents an overview of some regulatory requirements for the fire protection of mass timber buildings.

2.1 Current Canadian building regulations

The NBC contains provisions based on the building size and construction relative to occupancy “to prevent fire spread and collapse caused by the effects of fire” (Subsection 3.2.2. of Division B). This is primarily achieved by limiting the area and height of buildings incorporating combustible construction materials, and by requiring higher fire-resistance ratings for mid- to high-rise buildings of noncombustible construction of similar occupancy and area (mgb ARCHITECTURE + DESIGN, 2012).

The NBC states “a degree of fire safety is attained by the use of encapsulated mass timber elements with an encapsulation rating and minimum dimensions for structural members and other building assemblies.” The introduction of automatic fire suppression system (e.g., sprinkler, water mist systems) and other fire protection

technologies allowed the construction of tall³ wood buildings. Such protective technologies are required by national and provincial building codes as integral parts of fire protection systems for wood buildings.

In the 2020 edition of the NBC, EMTC is considered as a third construction type, in addition to noncombustible and combustible constructions. With a degree of fire safety attained by the encapsulation (e.g., encapsulation rating), the acceptable solutions—found in Division B of the NBC—permit buildings of residential (Group C) major occupancy to be constructed of EMTC up to a height of 12 storeys. In particular for residential occupancy buildings, it will allow a building area of up to 6,000 m², sprinklered complying with the NFPA 13 standard (NFPA, 2022).

In addition, exposed mass timber surfaces are permitted in EMTC on walls, ceilings, beams, columns and arches in a suite or compartment in certain conditions (see Table 2-1).

Table 2-1 Permitted exposure of encapsulated mass timber in NBC 2020

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

2.2 Current Canadian building regulations for fire suppression systems

The NBC typically requires fire suppression systems based on building size and construction relative to occupancy. For residential occupancy, a building is permitted to be of EMTC or noncombustible construction complying with the requirements of the maximum height (12 storeys), area (6,000 m²) and sprinkler protection, which include mandatory sprinkler requirements for concealed spaces and balconies (in compliance with NFPA 13 standard (NFPA, 2022)).

The fire safety objective of the NBC is achieved in consideration of sprinkler systems in conjunction with other elements (i.e., passive fire protection, height and area limits, alarm, and detection, etc.)

- *Sprinkler system*

Automatic sprinkler systems are addressed as part of the acceptable solutions in Article 3.2.5.12. of Division B of the NBC. Note that the sprinkler requirements change according to the occupancy type and specific hazards. The NBC refers to NFPA 13 (NFPA, 2022a), NFPA 13R⁴, *Standard for the Installation of Sprinkler Systems in*

³ A tall wood building is a building over six-storeys in height that utilizes mass timber elements as a functional component of its structural support system.

⁴ NFPA 13R, “Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies” is for low-rise residential occupancies.

Low-Rise Residential Occupancies, (NFPA 2019b) and NFPA 13D⁵, *Standard for the Installation of Sprinkler Systems in One and Two-Family Dwellings and Manufactured Homes*, (NFPA 2019a) for sprinkler requirements. The functional statements and objectives attributed to the acceptable solutions in the Code for the sprinkler requirements are provided in Section 4.2.1 of this report, according to Table 3.10.1.1. of Division B of the NBC.

- *Alternative solutions*

As stated in the NBC, “*alternative solutions can be used in lieu of compliance with the acceptable solutions*” (i.e., Division B of the NBC). “*However, to do something different from the acceptable solutions described in Division B, a proponent must show that their proposed alternative solution will perform at least as well as the acceptable solution(s) it is replacing. The objectives and functional statements in the NBC attributed to the acceptable solution(s) identify the areas of performance where this equivalence must be demonstrated*” (Clause 1.2.1.1.(1)(b) of Division A).

Alternative solutions to sprinkler systems will be considered by the authority having jurisdiction (AHJ) confirming they achieve at least the minimum level of performance required by the acceptable solutions. For example, water mist systems could 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 or better to the conventional sprinkler system. If code compliance is demonstrated through equivalency, the alternative solution must also be subjected to the same conditions and limitations of the acceptable solution that it is seeking equivalency to. For example, if the sprinkler system is subjected to requirements on height and area limits, occupancy, passive fire protection, alarm, detection, etc., the water mist system should be subjected to the same conditions and limitations.

⁵ NFPA 13D, “Standard for the Installation of Sprinkler Systems in One and Two-Family Dwellings and Manufactured Homes” is for one- and two-family dwellings and manufactured homes.

3 Overview of Water Mist Systems

Water mist systems produce fine water droplets⁶ using the water atomization technologies motorized typically by higher operating pressures than used in traditional sprinkler systems or by applying compressed gas for atomization. Three types of water mist systems are defined in the NFPA 750, *Standard on Water Mist Fire Protection Systems* (NFPA, 2023):

- low-pressure system (< 12.1 bar / 175 psi)
- intermediate-pressure system (12.1–34.5 bar / 175–500 psi)
- high-pressure system (> 34.5 bar / 500 psi)

Water mist systems can be used in a wide variety of applications, and some cases relevant to this technical document are provided in [Appendix D](#). They can replace conventional sprinklers in certain applications, but experimental proof by full-scale fire testing is needed in general for each application. The current standards for water mist systems require that design parameters are mainly established and verified by carrying out full-scale fire test. This design approach of water mist systems, which is fundamentally different from that of conventional sprinkler systems, are further discussed in this technical document (Sections 3.3, 4.3, and 4.4).

The median droplet diameters reported for high-pressure water mist systems and conventional sprinkler systems are approximately 110–300 microns and 700–1000 microns (or greater), respectively (Mawhinney & Back, 2016). Consequently, the main benefit of water mist systems in comparison to sprinkler systems is a smaller amount of water used by the system, which can be as low as 10% but typically about 50% of the water used by a conventional sprinkler system, in most applications.

Water mist systems can be very different, and the generated water mist varies a lot with respect to

- droplet penetration in the flame zone and coverage of the water mist sprays,
- drop size distribution, and
- total flow rate.

Water mist has several fire fighting mechanisms: (i) cooling and (ii) oxygen depletion related to the rapid evaporation of small droplets, (iii) blocking of radiant heat by the 3-dimensional water mist barrier in the space, and (iv) wetting of surfaces. The relative importance of the mechanisms is entirely system specific and also depends on the fire and fuel type. This leads to the key difference between water mist system and any conventional sprinkler system design and hydraulic dimensioning⁷:

- *Conventional sprinklers* rely primarily on wetting, and their key design parameter is water spray density in mm/min. The design parameter is given in a prescriptive manner in different sprinkler standards, and all sprinkler systems are designed based on the same requirements.
- *Gaseous systems* (inert gas) rely primarily on oxygen depletion, and their key design parameter is gas concentration in volume (%) and room airtightness. The design parameter is given in a prescriptive manner in different gas standards, and all gaseous systems are designed based on the same gas specific requirements.

⁶ By definition in the NFPA 750 standard (NFPA, 2023), 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).

⁷ Hydraulic dimensioning is determined through fire testing protocols.

- *Water mist systems* rely on several suppression mechanisms as described above and in Section 3.2 of this technical document, the relative importance of which varies between systems and applications. Water mist is not a generic fire fighting agent. Therefore, it is not possible to give a single, prescriptive design parameter for all water mist systems, and each design is defined based on required performance in representative full-scale fire tests. Water mist standardization is largely about standardizing full-scale fire tests for different applications.

3.1 Design objectives and consideration for occupancies and hazard classifications

The design objectives of water mist systems are typically the same as for conventional sprinkler systems and specific to hazard scenarios. Chapter 9 in NFPA 750, *Design objectives and fire test protocols*, (NFPA, 2023) states that water mist systems should be designed and installed for the specific hazards and protection objectives specified in the listing. The standard also states that “*the fire performance objectives of a mist system should be described using at least one of these terms: fire control, suppression, and extinguishment*”⁸.

NFPA 750 (NFPA, 2023) is a standard that provides requirements for design, installation, maintenance and testing for water mist fire suppression systems, and requires a “listing”. In the US (the United States of America), listings can be issued for water mist systems by FM Approvals and UL Solutions based on their water mist standards, FM 5560, *Water Mist Systems*, (FM Approvals, 2021) and UL 2167, *Standard for Safety Water Mist Nozzles for Fire Protection Service*, (UL, 2021) respectively. Listings also cover the “*acceptable performance/pass criteria in representative full-scale fire tests*” that was evaluated by standard fire test protocols specified by the approval authorities. The fire performance objective is built into the fire test requirements.

In setting the design basis for a water mist system, the occupancy and level of hazards are first assessed. The hazard classification system in NFPA 750 (NFPA, 2023) for sprinkler-like applications is the same as in NFPA 13 (NFPA, 2022a) for conventional sprinkler systems with the hazard categories of light hazard (LH)⁹, ordinary hazard (OH) 1¹⁰ and others. In addition, many specific applications (typically protected by gaseous systems) like machinery spaces and other hazards with flammable liquids are listed as suitable water mist applications.

The performance objective in LH and OH applications is the same as with conventional sprinklers. Residential applications are a unique application under LH category as the fire should be at least controlled for the main purpose of life safety (i.e., to provide time for escape). These systems are usually called “residential life safety systems” since they are designed mainly for life safety and property protection with a lesser degree. The systems for LH/HC-1 (hazard category 1)¹¹ are usually called “property protection systems.”

3.2 Fire fighting mechanisms and protection strategies

⁸ 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.

⁹ *Light Hazard (LH) Occupancies*: Occupancies or portions of other occupancies where the quantity and/or combustibility of contents is low and fires with relatively low rate of heat release are expected.

¹⁰ *Ordinary Hazard Group 1 (OH 1)*: Occupancies or portions of other occupancies where the quantity and/or combustibility of contents does not exceed the amount of miscellaneous storage.

¹¹ HC-1 (Hazard Category 1): formerly Light Hazard Occupancy, where the quantity and/or combustibility of contents is low and fires with relatively low rates of heat released are expected.

By discharging fine water sprays, water mist systems control, suppress or extinguish fires by the following three principal mechanisms:

- 1) In evaporation, the fine droplets effectively absorb heat from flames and gases, as the total surface area of the atomized droplets is much larger than of the droplets from a conventional sprinkler system per volume of water.
- 2) In evaporation, the volume of the water increases up to 1700 times, which can eventually smother the fire either locally or globally in an enclosure.
- 3) Attenuating radiant heat from the fire due to the small size of the droplets that block and scatter heat radiation.

In comparison to conventional sprinkler systems, water mist systems are generally more effective in cooling gases and less effective in wetting and cooling combustible fuel surfaces simply due to the smaller amount of water. Radiant heat blocking is a unique property of water mist, and surrounding structures may be well protected. For example, in some marine applications where windows need to be protected, dedicated window wetting is required from conventional sprinklers, while not required if the space is protected by a water mist system. But then again, water mist systems may be more sensitive to the ventilation and opening conditions in the protected space than conventional sprinkler systems.

Water mist systems are particularly well suited against flammable liquid fires (Class B fires) due to their gas phase cooling capability. These hazards are typically protected by gaseous systems. In total flooding applications, both systems are sensitive to openings: for gaseous systems, openings may ruin the performance altogether, whereas water mist systems always provide at least cooling or control (Mawhinney & Back, 2016).

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 applications: 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 may be desirable to provide protection and fire control in a certain portion of a tunnel.
- 4) Occupancy protection: designed and installed to provide automatic fire protection throughout a building or occupancy. Thermally activated nozzles will be used, which usually utilize 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 depending on the ignited fuel type, room characteristics and ventilation conditions.

3.3 Design parameters

While the hazard classification provides design bases for water mist systems, the design parameters are established and verified by carrying out full-scale fire tests (i.e., as part of the listing process in the US). This approach employed in the design of water mist systems is fundamentally different from that established for conventional sprinkler systems, which follows the generic design methods in previous editions of NFPA 13 (NFPA, 2022a) providing water spray rates and installation requirements set for the corresponding occupancy. In previous editions of NFPA 13, there was the area/density curve, which provided spray densities required for different hazard classifications (excluding residential hazard classification). The area-density curves were

removed in the current edition of NFPA 13 and replaced by single design points¹² (NFPA, 2022a). On the other hand, water mist systems do not have generic design methods like the area-design curves of sprinkler systems. For water mist systems, full-scale fire test protocols have been and are being developed to be representative of the actual conditions in each application. Test protocols should properly evaluate the performance of a water mist system against the corresponding occupancy and hazards, and to clearly define the limits of the system's application. Key parameters to be considered in test protocols are the following;

- 1) The fire hazards of the fuel (characterized by fuel type, quantity, combustibility and flammability, and arrangement¹³).
- 2) For compartment application, the volume, height, ventilation and opening condition of a test room.
- 3) Any other constraints that are critical to the actuation and operation of a water mist system like the ceiling height, obstructions, and possible area limitations.
- 4) System specifics (operating pressure, spacing, discharge coefficient factor), which are unique from each manufacturer.

To summarize, even though the design objectives are the same for water mist and conventional sprinkler systems, the design basis is different. Conventional systems are designed in a prescriptive manner applying to all systems, whereas the design of water mist system is based on acceptable performance demonstrated in full-scale fire tests meeting the specified pass criteria and is system specific.

3.4 Key components

The key components of a typical water mist system are nozzles, piping and fitting, valves, pump systems and water containers as well as detection and actuation, and alarm control systems where appropriate (e.g., for pre-action systems).

Generally, intermediate, and high-pressure water mist systems require pump systems to provide pressurized water supply. Pumps should be designed with sufficient capacity to exceed the system flow rate and pressure demands. Detailed design and installation requirements for pump systems are provided in the current water mist standards (see Section 3.5). Systems may also utilize gas-driven pump systems or self-contained cylinder systems typically for shorter design duration.

Water mist nozzles spray fine water droplets, the characteristics (e.g., droplet size, spray angle) of which depend on the design and operating pressure. Usually the higher the operating pressure, the finer the droplet sizes. Systems using compressed gas for atomization may generate very small droplets even at lower pressures. In general, nozzles are selected for their intended hazards and protection objectives as well as protection strategy. Nozzle listing provides detailed specifications including operating pressure, water spray rate, spacing, and installation height. Also, for thermally activated nozzles, nozzles' temperature rating should be selected among the standard temperature ratings of ordinary, intermediate, high, extra-high, very extra-high, and ultra-high classifications as per NFPA 750 standard (NFPA, 2023).

In addition to the acceptable fire fighting performance, the listings cover successful component tests for key components: FM Approval covers the full system with all key components whereas UL Listing covers only the nozzles, design, installation, operation and maintenance

Design, installation, operation, and maintenance of water mist systems should follow manufactures' DIOM (Design, Installation, Operation and Maintenance) manuals, which include detailed installation requirements for

¹² It should be noted that the NBC 2020 is not yet updated for this change since it still refers to NFPA 13 2019 edition.

¹³ Humidity limits should also be considered if wood pallets are used.

the system components and may be linked to dedicated operation manuals such as for pump systems. They also include maintenance routines (e.g., weekly, monthly, and annual) that for the US-listed systems should be aligned with the routines given in NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems* (NFPA, 2020) or FM Data Sheet 2-81, *Fire protection system inspection, testing, and maintenance* (FM Global, 2019).

Proper maintenance is crucial for all fire protection systems, but it is particularly important for water mist systems as they differ from conventional systems and may consist of many “unconventional” components including pumping systems, which could impact the reliability of water mist systems. A probabilistic modeling study reported that when the system is maintained on a speculative monthly basis (instead of a yearly basis), the reliability of water mist systems could be close to that of the conventional sprinkler system (Lohrmann et al., 2011) .

DIOM manuals provide the system-specific design parameters that was defined and proven in the full-scale fire tests. Where NFPA 13 (NFPA, 2022a) is the design standard for all conventional sprinkler systems, the DIOM manual is the system specific design standard for each water mist system. For listed water mist systems, the DIOM manual was reviewed and approved by the relevant approval authority, which is part of the system listing process.

3.5 Existing standards and guides

There are currently several types of standards and guides for water mist systems:

- The “umbrella” standards are design and installation standards that provide generic requirements for all water mist systems (i.e., NFPA 750 (NFPA, 2023), UL 2167 (UL, 2021), FM 4-2 *Global Property Loss Prevention Data Sheets* (FM Global, 2022), EN 14972 *Fixed fire fighting systems - Water mist systems* (EN, 2020) Part 1, BS 8489 *Fixed fire protection systems. Industrial and commercial water mist system* (BS, 2016) Part 1, BS 8458 *Fixed fire protection systems - Residential and domestic watermist systems – Code of practice for design and installation* (BS, 2015), VdS 3188 *Water Mist Sprinkler Systems and Water Mist Extinguishing Systems (High Pressure Systems)* (VdS, 2019)).
- The “fire test” standards provide standardized fire test protocols for different applications for defining the system-specific design parameters (i.e., FM 5560 (FM Approvals, 2021) Appendix A-P, UL Ch. 47-48, VdS 3883 *Fire Test Protocol for Water Mist Systems* (VdS, 2020), Part 1-8, EN 14972 Part 2-17 & Annex A (EN, 2021b), BS 8489 (BS, 2016) Part 2-7, BS 8458 (BS, 2015)).
- The “component test” standards provide standardized component test protocols for different components of the system (i.e., UL 2167 (UL, 2021), FM 5560 (FM Approvals, 2021), EN 17450 *Fixed fire fighting systems – Water mist components* (EN, 2021b), BS 8663 *Fixed fire protection systems – Components for water mist systems Part 1*(BS, 2019), VdS 3100 *High pressure water mist system, Requirements and Test Methods* (VdS, 2022)).
- Approval standards (i.e., UL 2167 (UL, 2021), VdS 3188 (VdS, 2019), FM 5560 (FM Approvals, 2021)).

A full system listing requires that the system complies with all the three types of standards as appropriate.

3.5.1 The US and Canada

The water mist standard status in the US is quite well established for many applications, and the following Table 3-1 summarizes the status with respect to residential/LH-type applications in NFPA 750 (NFPA, 2023), UL 2167 (UL, 2021) and FM 5560 (FM Approvals, 2021). FM 5560 refers to LH as HC-1.

In Canada, the design and installation of a water-based special fire suppression system is addressed in Article 2.1.3.5. of Division B of the National Fire Code of Canada (NFC) by referring to NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection* (NFPA, 2022b); but, it should be noted that the scope of the standard does not include water mist systems.

The NBC addresses sprinkler systems referring to NFPA 13 (NFPA, 2022a), NFPA 13R (NFPA, 2019b), and NFPA 13D (NFPA, 2019a). Regarding mass timber construction, however, the objectives and performance requirements for sprinkler systems are not specifically addressed in these standards. In Section 2.2, we discussed the current building regulations of fire suppression requirements for wood construction.

Table 3-1 Water mist standard status in the US with respect to residential/LH-type applications

Design & installation standards / guidelines	NFPA 750 (NFPA, 2023) Standard on water mist fire protection systems		FM Global Property Loss Prevention Data Sheet 4-2 (FM Global, 2022) Water mist systems
Approval standards		UL 2167 (UL, 2021) Standard for Safety Water Mist Nozzles for Fire Protection Service	FM 5560 (FM Approvals, 2021) Approval Standard for Water Mist Systems
Fire test protocols	<i>NFPA 750 does not include fire test protocols but requires listings</i>	Ch.47 Residential Dwelling Units Fire Tests Ch.48 Light Hazard Area Fire Tests	Appendix G Fire tests for water mist systems for the protection of non-storage occupancies, Hazard Category 1 (HC-1)
Component test protocols	<i>NFPA 750 does not include component test protocols but requires listings</i>	Covers only nozzles Other components are tested as per adjusted requirements from other protocols	Covers all critical components in the system Pump units are tested as per adjusted fire pump requirements
Design basis	System specific DIOM manual		
Type approvals / Listings	<i>NFPA does not issue listings but requires them</i>	UL Listing	FM Approval

3.5.2 Europe

In Europe the standardization situation is in a transition stage from a few national guidelines and standards to common European standard series EN 14972, *Design & Installation and Fire test protocols* (EN, 2020)¹⁴ and EN 17450, *Component test protocols* (EN, 2021b)¹⁵.

In general, the European approach is not as straightforward as in the US, as there is no authority in Europe to issue approvals based on EN standards. Depending on the standard, manufacturers may declare conformity via CE (Conformité Européenne) marking, or Technical Assessment Bodies may issue a European Technical Assessment about the compliance but—related to water mist systems in particular—a system-type approval, similar to FM Approval or UL Listing, is not possible. Currently, VdS¹⁶ in Germany is the only European

¹⁴ The first part (Part 16) was published in 2019, and another three parts were published in 2020 and 2021. Other parts are in process.

¹⁵ So far only one part was published in 2021, and other parts are in process.

¹⁶ VdS is the name of a German independent testing and certifying institution.

authority that issues full system-type approvals for water mist systems covering all the necessary aspects (fire testing, component testing and DIOM manual review and assessment).

There is also another difference between the US and European approaches: in the US, a fire test protocol may cover a full hazard classification (like LH/HC-1) but in Europe all fire test protocols are application-specific (like concealed spaces or parking garages). Within one hazard category there may be many different designs, which have benefits (optimized designs for each application) and drawbacks (different designs within one system add to complexity).

The current water mist standards in Europe are shown in Table 3-2 below. For a smooth transition from the national standards and guidelines to a common European standard, practically all fire test protocols in the EN 14972 (EN, 2020) series were adopted from existing national protocols (VdS, BS) or FM Approvals that were widely accepted in Europe. However, there is currently no specific guide or protocol available for mass timber construction in Europe.

3.5.3 General overview of the relevant standards and guidelines

NFPA 750 (NFPA, 2023), FM 5560 (FM Approvals, 2021), EN 14972 (EN, 2020), VdS 3188 (VdS, 2019), VdS 3883 (VdS, 2020), and BS 8489 (BS, 2016) lay out the minimum requirements for the design, installation, and testing of water mist fire protection systems. They require systems with the demonstrated performance through full-scale fire tests and component tests. In the US, the systems must also be listed.

The standards with fire test protocols provide the system-specific design basis for different hazard classifications or applications. All fire test protocols for LH/HC-1 type hazards have the same performance objective, i.e., at least suppression of the fire, and they are intended for property protection. They all (FM 5560 / HC-1 tests, UL 2167 (UL, 2021) / LH tests, EN 14972 – Part 3, 4, 7, VdS 3883- Part 1, BS 8489- Part7) are largely or at least partly based on the first water mist guideline for such applications, i.e., IMO Res.A.800 *Revised guidelines for approval of sprinkler systems* (IMO, 1995)¹⁷. All fire test protocols for residential applications reflect the performance objective of typical residential systems, and hence the requirement in the tests is at least to control fire. They all (UL 2167 (UL, 2021), EN 14972 – 17, BS 8458 (BS, 2015)) are partly based on UL 1626, *Residential sprinkler standard* (UL, 2003)¹⁸.

All these standards require that through fire tests, system specifications (e.g., discharge coefficient factor, pressure, spacing) and limitations for installation (e.g., installation height, vent conditions, obstructions) should be defined and included in the manufacturer's DIOM manual. The DIOM manuals are also required to provide operation and maintenance instructions.

The situation with component test protocols is still largely in a development phase. Only FM 5560 (FM Approvals, 2021) includes component test protocols for most of the critical components in a water mist system. For pump units, FM Approvals applies and adjusts existing fire pump requirements. VdS has also recently published test protocols for critical water mist system components in VdS 3100 (VdS, 2022). For components not covered by VdS 3100, VdS applies and adjusts existing EN standards as appropriate. UL 2167 (UL, 2021) and BS 8663 (BS, 2019) Part 1 include tests only for the nozzles, and the EN 17450 (EN, 2021b) series is still at its very early stages¹⁹.

¹⁷ IMO Resolution A. 800 addressed fire tests covering various of fire load, fuel arrangement, room geometry and ventilation condition typically found on board passenger ships.

¹⁸ In 2020, seven separate UL Standards, including UL 1626 were consolidated into UL 199.

¹⁹ EN 17450 Part 1 (Product characteristics and test methods for strainer and filter components) is published, and EN 17450 Part 2 (Product characteristics and test methods for nozzles) is ready to be released pending the working group's voting.

Table 3-2 Water mist standards in Europe with respect to residential/LH-type applications

	Europe (all EU countries and a few more)	Base document	Germany	UK
Design & installation standards & guidelines	EN 14972 - 1 Design, installation, inspection, and maintenance		VdS 3188 Water Mist Sprinkler Systems and Water Mist Extinguishing Systems (High Pressure Systems) Planning and Installation	BS 8489 - 1 Code of practice for design and installation
Fire test protocols	EN 14972 - 3 Test protocol for office, school classrooms and hotel for automatic nozzle systems	VdS 3883-1	VdS 3883 - 1 Protection of office spaces and accommodation areas	BS 8489 Fixed fire protection systems – Industrial and commercial watermist systems
	EN 14972 - 4 ⁽¹⁾ Test protocol for non-storage occupancies for automatic nozzle systems	FM 5560 Appendix G	VdS 3883 Fire Test Protocol for Water Mist Systems VdS 3883 - 2 Protection of office spaces and accommodation areas with Water Mist Sidewall Sprinklers	
	EN 14972 - 6 Test protocol for false floors and false ceilings for automatic nozzle systems	VdS 3883-3	VdS 3883 - 3 Protection of False Ceilings and False Floor of OH Group 1	
	EN 14972 - 7 Test protocol for commercial low hazard occupancies for automatic nozzle systems	BS 8489-7		BS 8489 - 7 Fire performance tests and requirements for watermist systems for the protection of low hazard occupancies
	EN 14972 - 10 Test protocol for atrium protection with sidewall nozzles for open nozzle systems	New		
	EN 14972 - 17 ⁽¹⁾ Test protocol for residential occupancies for automatic nozzle systems	BS 8458		BS 8458 Fixed fire protection systems – Residential and domestic watermist systems Code of practice for design and installation
Component test protocols	EN 17450 - 1 Product characteristics and test methods for strainer and filter components EN 17450 - 2 ⁽¹⁾ Product characteristics and test methods for nozzles Several other parts in plan		VdS applies and adjusts relevant EN standards for water mist system component testing	
Design basis	System specific DIOM manual			
Type approvals / Listings	Notified Bodies may state compliance with individual EN standards, but there are no system related type approvals linked to EN.		Vds approval (full system)	No water mist system approval scheme available in UK

⁽¹⁾ Not yet published

4 Water Mist Systems in Application to Mass Timber Residential Buildings

4.1 Evaluation of fire hazards in mass timber residential buildings

4.1.1 Residential buildings in general

The NBC 2020 (Canadian Commission on Building and Fire Codes, 2022) defines residential occupancy as *“the occupancy or use of a building or part thereof by persons for whom sleeping accommodation is provided but who are not harboured for the purpose of receiving care or treatment and are not involuntarily detained.”* With its focus on the protection of residential areas, such as bedrooms, living rooms, kitchens and apartment units, this technical document considers typical fire scenarios and hazards associated with residential occupancy.

Typical movable fuel loads involved include upholstered furniture (beds, sofas, chairs), wooden and composite materials (tables, dressers, cupboards), furnishings (curtain, bedding), and other items (TV, computer, clothing, books).

Typical fire scenarios include:

- Kitchen fire
- Living room fire
- Bedroom fire

Among the fire scenarios, kitchen fires are most frequent, yet the living room fires are reported cause of the largest number of fatalities. The NRC analysis, conducted in 2004 with reported residential fire cases in Ontario, over the period 1995–2003, found that most fires occurred in the kitchen and cooking areas (28.6%), then followed by the living areas (12.6%), and the sleeping areas (11.3%) (Bounagui et al., 2004). It also reported that the living areas constitute the deadliest places in Ontario homes. They account for 45.1% of fire fatalities, followed by the sleeping areas (20.0%), and by the kitchen and cooking areas (16.9%). Living room fires are reported to have rapid initial fire development mostly due to upholstered furniture often involved, as shown in the research conducted at NRC (Bwalya et al., 2014).

Water mist systems are designed based on acceptable performance demonstrated in full-scale fire tests meeting the specified pass criteria, so the evaluation of the hazards should consider the protected area and entail potential fire scenarios that the water mist systems should be designed for.

4.1.2 Hazards specific to mass timber construction and compartment conditions

In assessing potential fire scenarios in mass timber buildings, any special hazards including high fire load and particular compartment conditions should be considered. The special hazards of mass timber buildings to be considered in designing any water-based fire protection systems, include the following:

- Unprotected mass timber elements installed as walls, floors, beams and columns, which can contribute to the total fire load and fire severity of a room.
- Encapsulation rating of EMTC.
- Special conditions such as difficulties with post-fire retrofit of damaged mass timber elements.
- Any other added hazardous circumstances such as housing vulnerable people.

Fixed fire protection systems, including water mist system, in application to mass timber residential buildings are required to be capable of intervening fire development in time and limiting involvement of the exposed combustible mass timber elements, which can result in potential fire spread beyond the fire origin. Thus, it is recommended that the fire protection system should be designed considering enhanced property protection with potential suppression capabilities since typical residential systems are mainly designed for life safety (and property protection with a lesser degree) and aim for fire control rather than fire suppression.

In addition, potential water damage to mass timber elements could be addressed together with drainage options, when necessary, while post-fire water damage and mold are not addressed in the NBC's fire protection requirements. In designing water-based fixed fire suppression systems, it becomes an optimization issue with an agreed compromise as the outcome: on one hand, the total water discharge should be minimized but, on the other hand, the fire fighting capability should be maximized. Other post-fire solutions are provided in (Ranger, 2019) for mass timber construction to assess the post-fire water damage and mitigate moisture.

Other compartment hazards generic to residential systems include at least the following:

- The height of the compartment must be within the successfully evaluated limits for water mist systems.
- Ventilation conditions: strong ventilation may affect the effectiveness of water mist systems. Thus, the actual mechanical and natural ventilation condition should be considered in the design of water mist systems.
- System obstruction guidelines must be followed—any obstructions should always be assessed (and avoided) with any sprinkler systems, including water mist systems.

4.2 Evaluation of design objectives

4.2.1 Life safety and property protection

The design objectives of water mist systems should be evaluated based on good understanding of the current building code provisions, which usually set the objectives and minimum requirements. In the context of the NBC, the Code attribute the functional statements and objectives for sprinkler systems (Table 3.10.1.1. of Division B) since automatic sprinkler systems are addressed as part of the acceptable solutions in Article 3.2.5.12. of Division B. Table 4-1 below shows the attributed functional statements and objectives for sprinkler systems.

Table 4-1 Functional statements and objectives of sprinkler systems for Article 3.2.5.12. of Division B of the NBC

	Functional statements	Objectives	
General sprinkler requirement, Sentence 3.2.5.12.(1)	F02, F81, F82	OS1.2, OP1.2	In conformance with NFPA 13
Sprinkler requirement for low rise residential buildings, Sentence 3.2.5.12.(2)	F02, F81	OS1.2, OP1.2	NFPA 13 R is permitted to be used
Sprinkler requirement for one- and two-dwellings, Sentence 3.2.5.12.(3)	F02, F81	OS1.2, OP1.2	NFPA 13 D is permitted to be used
Functional statements			
<i>The acceptable solutions are intended to allow the building or its elements to perform the following functions:</i>			
<ul style="list-style-type: none"> • <i>F02 To limit the severity and effects of fire or explosions</i> • <i>F81 To minimize the risk of malfunction, interference, damage, tampering, lack of use or misuse</i> • <i>F82 To minimize the risk of inadequate performance due to improper maintenance or lack of maintenance</i> 			
Objectives			
<i>Safety: to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire. The risks of injury due to fire addressed is by:</i>			
<ul style="list-style-type: none"> • <i>OS1.2 – fire or explosion impacting areas beyond its point of origin</i> 			

Fire Protection of the building: to limit the probability that, as a result of its design or construction, the building will be exposed to an unacceptable risk of damage due to fire. The risks of damage due to fire addressed in the codes are by:

- *OP1.2 – fire or explosion impacting areas beyond its point of origin*

Note that both “Safety” (of a person in or adjacent to the building) and “Fire protection of the building” objectives are clearly stated for residential sprinkler systems in the NBC²⁰.

The NBC refers to NFPA 13 (NFPA, 2022) (i.e., for all applications), NFPA 13R (NFPA, 2019b) (i.e., for residential buildings up to 4 storeys in building height), and NFPA 13D (NFPA, 2019a) (i.e., for one- and two-family dwellings and manufactured homes) for sprinkler requirements. These NFPA standards elucidate that various levels of sprinkler protection are available to provide “life safety” and “property protection.”

- The objectives specified in NFPA 13 (NFPA, 2022a) are life safety and property protection.
- NFPA 13D (NFPA, 2019a) states that “While the purpose of this standard is to provide improved protection against injury and loss of life, the use of these systems has demonstrated an ability to provide improved protection against property damage.”
- NFPA 13R (NFPA, 2019b) addresses that “this standard is to provide both life safety and property protection, but to a lesser degree than would be achieved by using NFPA 13”.

Water mist systems as alternative solutions to sprinkler systems should provide at least the same levels of protection to those of the conventional sprinkler systems, achieving the same objectives and functional statements.

The design and hydraulic dimensioning of the sprinkler system are based on the hazard categories of the spaces, but the construction material is not specifically addressed in the existing standards. One important question to be raised when designing sprinkler and water mist systems for mass timber residential buildings is:

- The performance objectives of the sprinkler and water mist system be those of typical residential systems. In each case, the fire hazards should be analyzed, considering how the construction material of mass timber and the compartment condition would affect the degree of performance of water mist system both for life safety and property protection with different design parameters including dimensioning for hydraulic design areas.

The water mist system should be designed to provide enhanced property protection in addition to the typical residential system performance when the hazard assessment indicates high fire loading including relatively large areas of exposed mass timber elements or special hazardous circumstances as discussed in Section 4.1.2. While fire control is the least performance objective for fixed fire protection systems in regular residential buildings designed largely for life safety, fire suppression should be the least design objective for property protection systems.

4.3 System design and fire testing

As described in Section 3, water mist systems are currently designed and evaluated through full-scale fire tests. In the tests, system performance limits are found and the design parameters effective to the applications are defined. As introduced in Sections 4.1 and 4.2, the evaluation of the hazards and identification of the

²⁰ In this technical document, the NBC terminologies of “Safety” and “Fire and structural protection of the building” are used when referring to the NBC’s objectives, yet the terminologies of “life safety” and “property protection” are mainly used, since they are widely used by engineers and in NFPA standards.

performance objectives will entail potential fire scenarios that the water mist systems should be designed for. Then, fire testing should be planned, as shown in Figure 4-1.

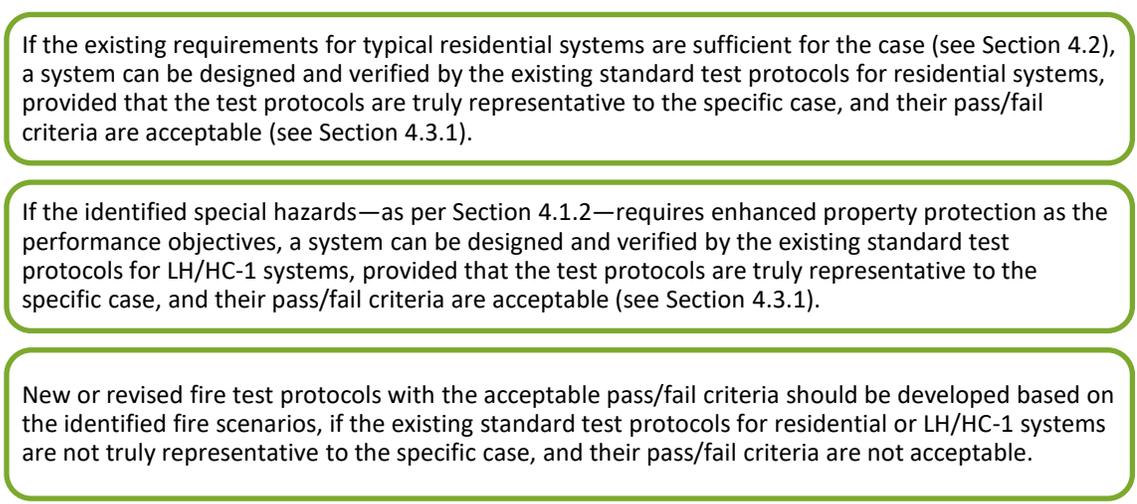


Figure 4-1 Design principle-fire testing

4.3.1 Full-scale fire testing for water mist systems: existing test protocols relevant to residential buildings

For a project related to mass timber residential buildings, one of the key tasks is to evaluate whether already existing standard test protocols would be applicable for the current application, and what would be the appropriate hydraulic dimensioning for the systems. For this reason, this section introduces the existing standard test protocols provided by FM Approvals, UL, and BS for testing water mist systems for general residential areas, which are summarized and compared to other water mist standards in Table 3-1 and Table 3-2.

There are two types of systems for residential applications: (i) systems tested for property protection purposes for all LH/HC-1 type occupancies, including residential, and (ii) systems specifically tested mainly for life safety purposes in residential occupancies. The relevant test protocols are summarized in Table 4-2.

Table 4-2 Generic test protocols for residential and LH/HC-1

		Occupancy	
		LH/HC-1	Residential
Authority	FM Approvals	FM 5560 Appendix G Fire tests for water mist systems for the protection of non-storage occupancies, Hazard Category 1 (HC-1)	(Residential type test – large compartment test – is included in the HC-1 test series)
	UL	UL 2167 Ch.48 Light Hazard Area Fire Tests	UL 2167 Ch.47 Residential Dwelling Units Fire Tests
	BS	BS 8489 - 7 Fire performance tests and requirements for water mist systems for the protection of low hazard occupancies	BS 8458 Residential and domestic water mist systems (Residential type test – large compartment test – is also included in LH test series)

All LH/HC-1 water mist system standard test protocols of FM 5560 (FM Approvals, 2021), UL 2167 (UL, 2021) and BS 8489 (BS, 2016) are at least partly based on the very first fire test protocol for automatic water mist systems. For example, the marine IMO Res.A.800 (IMO, 1995), and the residential water mist test protocols of UL 2167 (UL, 2021) and BS 8458 (BS, 2015) are at least partly based on UL 1626 (UL, 2003) for conventional residential systems. This means that these water mist standard test protocols followed the same considerations, such as for test room, fire scenario, and fuel arrangement, taken in the sprinkler system standard test protocols. Exact acceptance criteria differ and, particularly in the BS protocols, there are additional tests. The FM 5560 HC-1 test protocol has been in widest use. There are about ten different water mist systems FM approved for HC-1 applications, whereas no systems were evaluated against UL 2167 LH test protocol. There is one water mist system listed in UL 2167 for residential applications. BS protocols were used in UK (United Kingdom) only, but there is no established scheme for full water mist system approvals in this country. At least one system was successfully tested according to the BS 8458 residential test protocol. There are also systems successfully tested to BS 8489-7²¹.

The fire scenario commonly considered in the existing residential test methods listed above is a living room fire where a simulated furniture made of foam with plywood backing is consistently used as the main fuel source. The simulated furniture placed in a corner represents the rapid initial fire development due to upholstered furniture, which is the most frequent first-ignited item that results in severe real fires (Bounagui et al., 2004, Bwalya et al., 2014). In addition to the corner fire arrangement of UL 2167 (UL, 2021), FM 5560 (FM Approvals, 2021) and BS 8489 (BS, 2016) Part 7, BS 8458 (BS, 2015) require testing with the simulated furniture fire placed between two nozzles and beneath a nozzle in the test room. It also requires evaluating the impact of airflow (with a minimum velocity of 1 m/s) and high ceiling heights (if approval is required) in the living room scenario. See Appendix B Existing generic testing protocols, for more details.

All LH/HC-1 fire test protocols include tests with the same sofa arrangement in an open space. They also include smaller room tests either by requiring the dedicated residential tests or tests defined under the LH/HC-1 test series. BS 8489 (BS, 2016) Part 7 includes additional office type tests in an open space.

All test protocols address pendent nozzles, and some of them also consider sidewall nozzles in the room tests. Ceiling height is fixed in some of the tests, whereas it is up to the manufacturer in others. The test duration is 10 or 30 min, depending on the test.

The suppression performance evaluation criteria are test specific and vary somewhat even between similar test protocols, but they all include:

- fire damage and the amount of fuels burned
- ceiling surface and gas temperatures
- room temperature

In residential tests, the number of activated nozzles is also pass-fail criteria due to the hydraulic dimensioning of a very limited number of nozzles in real applications.

4.3.2 Full-scale fire testing for water mist systems: new test protocols

As discussed in Section 4.3.1, the existing water mist standards provide generic standard test protocols proven in practice for residential applications. These existing standard test protocols corresponding to the design

²¹ issued for residential buildings (not mass timber construction) higher than 45 m, yet this is an UK specific case, and it should be noted that there are very different views between European countries related to height vs residential applications.

objectives could be applied to water mist systems in application to residential mass timber construction, provided that the protocols are considered truly representative of the specific case and accepted by the AHJ.

For the case where the existing standard test protocols are not applicable, a new or revised testing protocol, representing the actual hazard condition in the protected area, should be developed to test the performance objectives, design, and component functionality as shown in Figure 4-2. Also in Canada, following the alternative solution pathway required by the NBC to demonstrate code compliance, in principle, the performance of water mist system should be demonstrated in comparison to that of a conventional sprinkler system. One method to demonstrate equivalent performance could be through side-by-side testing with the conventional sprinkler system under the same conditions and limitations, but it should be noted that the NBC does not require this side-by-side testing, in general.

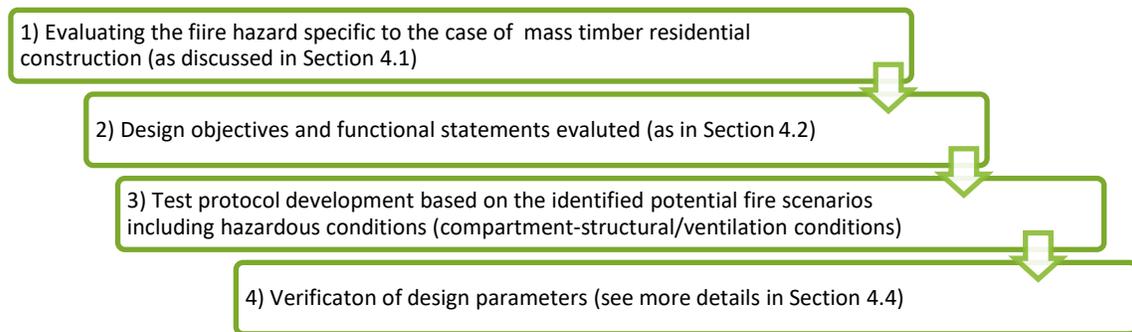


Figure 4-2 Considerations in developing a new test protocol

Pass-fail criteria should be assessed to ensure the suitability of the testing for the mass timber residential construction and developed based on side-by-side testing with conventional sprinkler system, where needed. The recommended pass-fail criteria to be addressed include the following:

- The enclosure tenability (room temperature, visibility, and combustion gas concentrations).
- The level of suppression or extinguishment where enhanced property protection is desired.
- The limited surface temperature and fire damages on any critical exposed mass timber elements where enhanced property protection is desired.

As an example, the water mist fire tests (Ko et al., 2020, 2021; Ko & Elsagan, 2023) that NRC conducted in 2019 are briefly described in Appendix A NRC tests. In the NRC tests, the generic residential test protocol using the living room fire scenario (discussed in Section 4.3.1) was modified by including exposed mass timber elements. The fire corner of the living room fire scenario was built with exposed CLT wall and ceiling panels, and the performance of water mist systems was evaluated by measuring fire temperature, CLT ceiling surface temperature, room gas temperatures (at various heights, including just below the ceiling), gas concentrations (oxygen [O₂], carbon monoxide [CO] and carbon dioxide [CO₂]) and visibility (smoke optical density). Also, post-fire damage and moisture content at a number of locations on the exposed CLT walls and ceiling were assessed.

In essence, the design parameters should be established and verified by carrying out full-scale fire tests. Thus, test protocols should be developed to clearly define the limits of the system's application. All specific parameters verified by the full-scale tests should be provided in the system specific DIOM manuals, as discussed in Section 0. The following Section 4.4 provides guidance on the design parameters including the considerations effective to the particular applications to mass timber residential buildings.

4.4 Consideration for design parameters

4.4.1 General considerations for design parameters

There are several water mist systems listed for LH/HC-1 and residential use, and a few specifically for residential use based on the current test protocols, which do not consider the application of mass timber construction. All system specific parameters are covered by the listing as given in the system specific DIOM manuals. In the following, some parameters are discussed in generic terms.

4.4.1.1 System actuation

In occupancy protection, NFPA 750 (NFPA, 2023) requires water mist systems to provide automatic fire protection throughout the occupancy, and the nozzles should have quick-response thermal sensitivity rating. For residential occupancy, ordinary (57–77°C) or intermediate (79–107°C) temperature ratings are required for sprinklers by NFPA 13 (NFPA, 2022a), NFPA 13R (NFPA, 2019b), and NFPA 13D (NFPA, 2019a), unless ambient temperatures can exceed 37.8°C.

In general, for water mist systems, early activation by typically lower operating temperatures (57°C) provides enhanced fire control to a certain degree in the early stage of a fire, yet due to the high sensitivity, nozzles away from the fire origin or in the adjacent room could also be activated, which might require special water damage control in mass timber buildings.

In practice, all nozzle characteristics, including the temperature rating, are included in the performance evaluation in the full-scale fire tests and are defined in the relevant listing. For residential (mainly for life safety) systems, the acceptable number of activated nozzles in the tests is limited, reflecting the hydraulic dimensioning i.e. 2 or 4 nozzles only, whereas there is no acceptance limit for the number of activated nozzles in LH/HC-1 type property protection systems. But, in practice, the maximum number of activated nozzles in the tests is four. In actual residential occupancies, nozzle activations beyond the fire compartment could occur. Thus, the test protocols should also include limiting the number of nozzle activations. As discussed in Section 4.3.1, the existing standard residential tests include the number of activated nozzles as pass-fail criteria due to the hydraulic dimensioning of a very limited number of nozzles in real applications.

4.4.1.2 Nozzle and water spray characteristics

There are no requirements for nozzle and water spray characteristics as such: any spray patterns, drop size distributions, and pressures are equally acceptable as long as the system performs as required in the full-scale fire tests.

4.4.1.3 Nozzle spacing and layout

In occupancy protection, water mist systems should provide automatic fire protection by laying out nozzles to protect the entire space (NFPA, 2023). While nozzle spacing and layout requirements are provided in the listing information for a specific water mist system, they should be reassessed on-site in application to residential mass timber buildings to address any special hazards and any obstructions.

4.4.1.4 Compartment height and ventilation conditions

Full scale testing evaluates the system performance at fixed installation heights, and the successfully tested height sets the upper limit for the acceptable ceiling height. Depending on the test series and exact tests within them, tests are conducted in a fully open space or in different sizes of rooms. In real installations, fire fighting performance is always better in smaller enclosed spaces, and tests in an open space represent a conservative approach.

In all tests except for the BS 8458 (BS, 2015) residential tests, natural ventilation is usually required. From a purely testing point of view, it is very difficult to arrange repeatable, reproducible, and representative ventilation conditions in a full-scale test arrangement. In practice, all forced ventilation should be avoided or minimized in real fire situations. It is always good to close all windows and doors and shut off any mechanical ventilation in case of fire, as much as possible. Although water mist systems can tolerate natural ventilation, strong forced

ventilation would deteriorate the performance²², the degree of which depends on system parameters (e.g., droplet size, pressure and spray angle etc.). In this regard, the design parameters of water mist systems should be established considering the actual ventilation conditions, and test protocols should be developed to verify the performance insusceptible to given ventilation conditions.

4.4.1.5 Consideration for tenability

The primary objective of the current standards for sprinkler and water mist systems in application to residential occupancy is life safety²³, and thus the system performance should maintain the tenability of the fire room sufficient to allow occupants to escape safely and to allow safe fire rescue and service. The tenability criteria suggested are room temperature, visibility, O₂ and CO concentrations (Bryan, 2007). Also, the fractional effective dose could be considered in predicting the incapacitation or death of occupants with combustion toxic gas data. Evaluating tenability in full-scale tests in an unambiguous manner is challenging, though, as all the parameters should be evaluated in the full context. For example, while the smoke from the fire contributes most to the low visibility in the room, the fine water mist alone could also lower the room visibility²⁴, yet lower visibility in a cool and otherwise more tenable room may be better than full visibility in a hot room.

In general, it is always better to fight the fire as early as possible, and the current test protocols mostly concentrate on tenable temperatures, but residential tests also include assessment of O₂ concentration.

4.4.2 Design parameters to consider with mass timber residential buildings

Different requirements applying to any automatic fire protection systems in residential buildings are discussed below but special attention is given to requirements that are more relevant to the mass timber construction.

4.4.2.1 False activation

Potential water damage in case of false activation or inadvertent discharge would always be a nuisance to the very least and, in particular in mass timber structures. As such, it should be avoided, or the probability should be minimized as much as possible. In general, no heat activating elements activate without sufficient heat and sufficient hot gas flow, and in practice the most conceivable reason for false activation is intentional or unintentional tampering of the nozzle. Many automatic water mist nozzles have a mechanical structure where unintentional mechanical damaging of the bulb is practically impossible but, then again, in some nozzle types, the bulbs may be fully exposed to external tampering (like in conventional sprinklers).

One way of preventing water damage by false discharge is to apply dry-pipe/pre-action systems, which use air or other inert gases to fill the nozzle-pipe network so that initially only gas would come out when the nozzle activates. Water would be supplied only when also the valve to the network is open and the pump started. This would require a signal from a separate fire detection system. The pre-action arrangement is much more complicated (and expensive) than a simple wet system, and in a real fire situation it tends to lead to a delay in water discharge. These dry-pipe/pre-action systems should be designed based on good understanding of potential fire scenarios and the negative consequences from the delay in the water discharge.

²² A water mist system performance test with a forced air flow in the room is provided in BS 8458 (BS, 2015). These configurations would challenge the system in cooling the area and controlling the fire.

²³ As discussed in Section 4.2.1, while the main purpose of typical residential systems is to provide life safety, the use of these systems has demonstrated an ability to provide property protection subsequently.

²⁴ In NRC tests (Ko et al., 2020, 2021), visibility was measured during the water spray tests conducted without fire. While the operation of the sprinkler system did not affect the obscuration in the test room, the water droplets discharged from the LPWM and HPWM significantly affected the obscuration in the room. In particular, the operation of HPWM nozzles with no fire resulted in the optical density in the room much higher than the criterion value of 0.166 1/m.

While there is no specific discharge time requirement for residential occupancy in NFPA 750 (NFPA, 2023), the 2010 and 2019 editions of NFPA 13 and NFPA 13D (NFPA, 2019a) require a maximum time of water delivery of 15 s from the fire detection. In considering a dry-pipe/pre-action system for water mist system, the delay time²⁵ should be evaluated in the full-scale fire testing as part of the listing program. In general, systems protecting residential occupancies are wet systems either because only wet systems are allowed by relevant regulations in some countries or because of the complexity and cost of pre-action systems.

4.4.2.2 Design area and duration

Full-scale fire tests define the system design—but hydraulic dimensioning of the system is a matter of decision supported by field experience. This applies both to the design area and duration of the discharge. For conventional sprinkler systems in the US, NFPA 13 (NFPA, 2022a), NFPA 13R (NFPA, 2019b), and NFPA 13D (NFPA, 2019a) provide the dimensioning rules to be followed. NFPA 750 (NFPA, 2023) requires the same design areas and duration for water mist systems for the same applications. In practice, the dimensioning criteria are covered by the relevant listing and included in the relevant DIOM manuals.

With respect to relevant residential/LH-type applications, the existing standards (as discussed in Section 3.5) provide requirements for design areas and durations. For FM Approved LH/HC-1 type water mist systems, which covers residential applications, the design area is 140 m² or 9 nozzles, whichever is larger, whereas for UL listed LH systems, the design area is fixed to 140 m². The discharge duration requirement is 60 min. For residential water mist systems, the dimensioning is set with four nozzles for 30 min.

However, the minimum design area and hydraulic demand requirements may need to be reassessed for sprinkler and water mist systems in application to residential mass timber buildings where the fuel loading can be greater.

4.4.2.3 Measures to minimize fire and water damage in mass timber

With the performance objectives of life safety and property protection in residential mass timber buildings, water mist systems are required to prevent involvement in fire of exposed mass timber structural elements, such as CLT walls and ceiling. In a residential fire test, the exposed CLT walls placed near a fire source were charred (Ko et al., 2020, 2021; Ko & Elsagan, 2023) although a fixed fire fighting system successfully limited fire development and controlled the fire. The degree of damage on the exposed walls varied depending on the spray characteristics of the tested water mist systems. It is recommended to consider the availability of post-fire retrofit measures for any damaged mass timber. When the architectural and structural design does not permit easy retrofits of damaged mass timber elements, special performance enhancement should be considered for the water mist systems.

Conventional sprinkler systems fight fires primarily by wetting of surfaces and, hence, to protect exposed mass timber elements; wetting is desirable particularly for walls in residential scenarios. On this note, residential sprinklers are required to have water distribution tests to check the wall wetting capability (i.e., wet patterns up to a height not less than 0.7 m, with a minimum of 5 percent of the sprinkler spray rates (UL, 2022)). UL 199 (UL, 2022) and FM 2030 *Approval Standard for Residential Automatic Sprinklers for Fire Protection* (FM Approvals, 2009) include sprinkler system test methods for checking the spray pattern in the vertical and horizontal planes.

Water mist systems rely more on other fire fighting mechanisms (see Section 3.2) than wetting and there are no requirements on spray patterns as such. Instead of wetting, water mist systems can protect adjacent

²⁵ In NRC tests (Ko et al., 2020, 2021), a delay time of 1 min was tested, which allowed rapid fire development and resulted in significant damage on exposed CLT walls and ceiling.

structures by blocking of radiant heat with the three-dimensional water mist barrier in the protected space. The overall performance and design parameters are defined in the relevant full-scale fire tests.

In general, water mist systems are preferred due to reduced water usage with equivalent performance and subsequently, less potential water damage than conventional sprinkler systems (Liu & Kim, 1999; Mawhinney & Back, 2016). In application to mass timber residential buildings, potential water damage assessment²⁶ and water damage mitigation and control measures should be considered, which, however, are beyond the scope of this technical document.

4.5 Summary

Figure 4-3 summarizes the process of designing water mist systems in application to mass timber residential buildings. First, the fire hazards should be evaluated considering not only the residential occupancy hazards, but also special considerations associated with the potential and limited contribution of mass timber elements to the fire severity, as detailed in Section 4.1. Based on the evaluated hazards, design objectives should be established. The performance objectives of the water mist system should at least be those of typical residential systems, and satisfy the objectives of protecting the safety of persons and buildings, yet enhanced property protection should be necessary when the hazard assessment indicates high fire loading and other special hazards, as detailed in Section 4.2. To meet the design and performance objectives, water mist systems are designed and evaluated through full-scale fire tests. As detailed in Section 4.3, test scenarios, protocols and pass-fail criteria should be selected and developed. From the test results, the system performance limits and the design parameters effective to the applications should be defined, and they should be included in the DIOM manual.



²⁶ NRC fire tests (Ko et al., 2020, 2021) reported that after the fire suppression tests, the wet CLT panel surfaces quickly dried, and the level of moisture content measured on the CLT wall surfaces in 24 hours after the fire suppression test was similar to that measured before the test for all systems tested regardless of the water spray rates. However, the suppression systems formed a large water pool on the floor. For this reason, unlike the wall and ceiling surfaces, water penetrated the joints along the bottom edge of the CLT wall panels.

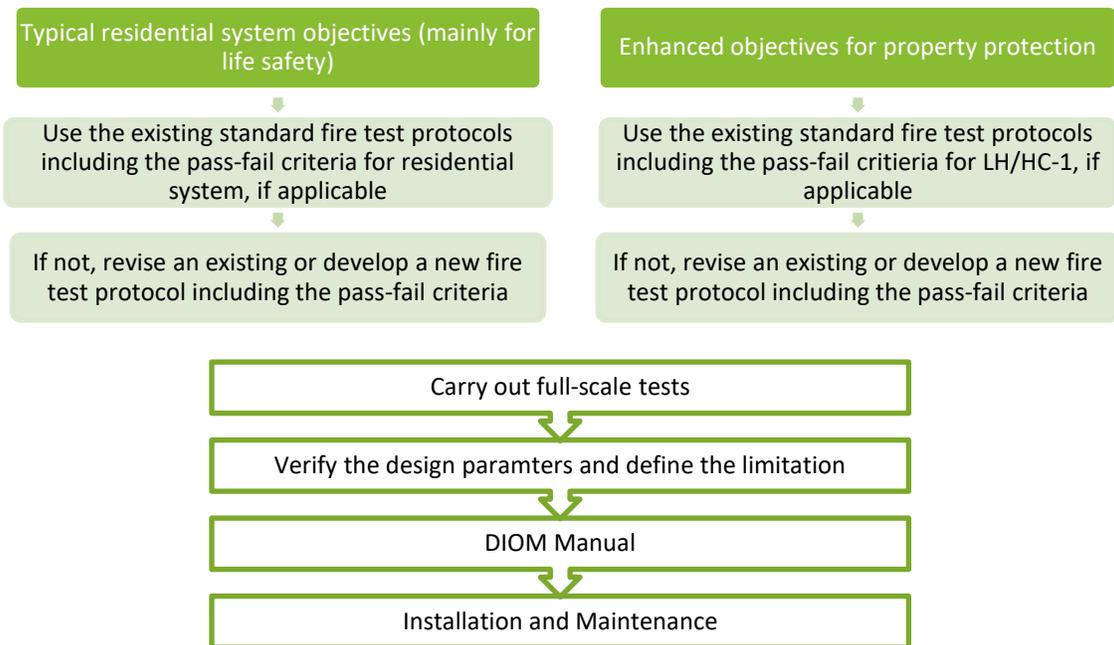


Figure 4-3 Process of designing water mist systems in application to mass timber residential buildings

Appendix A NRC tests

A.1 General

A series of tests was conducted to investigate the performance of water mist systems in protection of residential mass timber buildings (Ko et al., 2020, 2021). The fire suppression tests were conducted using water mist and sprinkler systems in a living room fire scenario involving exposed mass timber wall and ceiling panels.

A.2 Test facility

A.2.1 Test room

Figure A-1 shows a schematic diagram of the test room with all dimensions.

- Room dimensions were approximately 8.53 m (Length) × 4.27 m (Width) × 2.4 m (Height).
- Ventilation was provided by 2 doors of 2.2 m height each. One of the doorways was 1.05 m wide and located at the corner opposite to the fuel package, and the other one was 0.9 m wide and located at the same side of the fuel package.

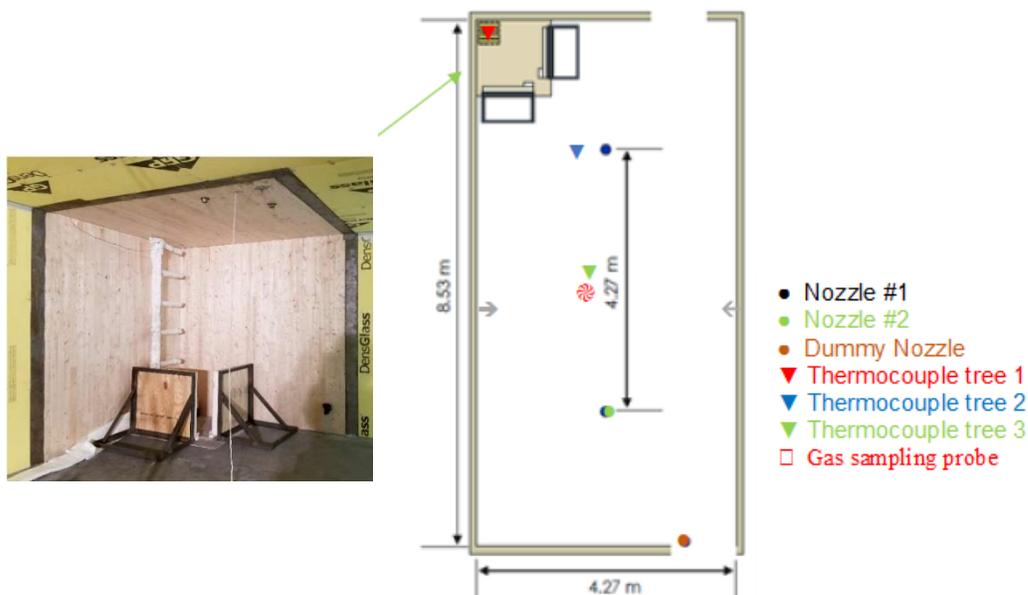


Figure A-1 Test compartment with nozzle layouts and instrumentation (Ko et al., 2020, 2021)

A.2.2 CLT panels

- Placed at the corner where the fuel package
- Dimensions approximately 2.4 m (L) × 2.4 m (W).
- To support the corner, the CLT panels were embraced using steel frames, and the ceiling CLT panel was bolted to the roof joists.

A.2.3 Fuel package

- Wood crib with a cross-sectional area of 0.3 × 0.3 m² and 0.15 m thickness. The wood crib was prepared as per UL 2167 (i.e., The weight was 2.5–3.2 kg, and the crib consisted of four alternate layers of four trade size 38.1 by 38.1 mm, kiln-dried spruce or fir lumber 305 mm long. (i.e., the wood crib dimension,

and weight were prepared as per the UL 2167). The wood crib was placed on top of a heptane pan (0.3 m (W) × 0.3 m (L) × 0.1 m (H)). The wood crib was positioned 50 mm from each wall.

- Simulated furniture built with two foam (pure polypropylene oxide polyol, polyether) sheets with a thickness of 0.076 m, which were adhered to plywood panels. The dimensions of the simulated furniture were 0.84 m width and 0.79 m height. The foam sheets used in the tests have the burning characteristic properties required by UL 2167 (i.e., peak heat release rate of 230±50 kW/m² and heat of combustion of 22±3 kJ/g tested by ASTM E1354²⁷ at a 30 kW/m² heat flux exposure). The simulated furniture was ignited with two cotton wicks soaked in heptane.

A.2.4 Nozzle layout

Three nozzles were used during each test

- Nozzle #1 was installed on the ceiling at a radial distance of 3 m from the fire corner.
- Nozzle #2 was installed at 4.27 m away from Nozzle #1,
- Nozzle #3 was an unpressurized, dummy nozzle and installed near the doorway.

Each nozzle was installed in accordance with the manufacture’s design and installation instructions (i.e., installed to flush with the ceiling as much as possible). The dummy nozzle (Nozzle #3) was installed on the ceiling such that the heat response elements were located 51 mm below the ceiling.

A.3 Fire suppression system

In this testing program, two high-pressure water mist (HPWM) systems, one low-pressure water mist (LPWM) system and one residential sprinkler system were tested. All nozzles were listed for residential or LH/HC-1 applications. Each nozzle contained an automatic fire detector (glass bulb) that in their listing was either 57°C or 68°C but in the tests, they all had 79°C bulbs for a conservative approach in the tests. The nozzle was connected to water supply and delivery components (such as water pipelines and pumps). The specifications of the tested nozzles are listed in Table A-1. In some tests, in addition to the higher temperature bulbs, the activation of the water mist system was manually delayed by approximately 1 min to investigate the effect of the delay.

Table A-1 Specifications of the tested nozzles

Type	Description	Discharge coefficient factor [lpm/bar ^{1/2}]	Max. Spacing [m]	Temperature rating [°C]	Operating pressure [bar]
A	HPWM (Residential)**	2.4	4.27	79	50 or70
B	HPWM (HC-1 / Light hazard) *	4.1	5	79	80
C	LPWM (HC-1 / Light hazard) *	16.5	4.5	79	8
D	Sprinkler (Residential)***	43.2	5.5	79	0.92 bar for spacing 4.3 m

*as per FM 5560

** as per UL 2167

*** as per UL 199

²⁷ A standard test that examines the relationship between the total heat produced during the combustion process and the oxygen needed for that combustion to occur.

A.4 Instrumentation

The test room was instrumented with the following;

- Three thermocouple trees (each with 6 thermocouples at 0.4 m spacing) above the wood crib, beside nozzle #1 and at the centre of the room
- One thermocouple at each nozzle
- Water supply line pressure sensor for the HPWM, LPWM and sprinkler systems
- Pressure sensor at the water supply pumps
- Pressure sensor at the dummy nozzle
- Smoke density measurement across the room at a height of 1.6 m
- O₂, CO and CO₂ concentration measurements at the centre of the room at a height of 1.6 m
- Buckets to measure water spray density on the floor
- Cameras

In addition, the moisture contents of the CLT walls and ceiling were measured before and after each test using a pin-type moisture meter.

A.5 Conclusions

The performance of the investigated fire suppression systems in a residential fire scenario involving exposed mass timber structures (CLT panels) was evaluated based on:

- 1- Maintaining tenable conditions in the test room by controlling/suppressing the fire;
- 2- Minimizing fire and water damage on the exposed mass timber structures

A.5.1 Tenability and life safety

The main design objective of the fire suppression systems for a residential building is life safety. This requires maintaining the room temperature, smoke optical density and gas concentrations below the threshold limits, in order to ensure sufficient evacuation time for the occupants. The tested HPWM, LPWM and sprinkler systems successfully maintained the room temperature (see Figure A-2 for room temperature) and gas concentrations tenable (see Figure A-4 for O₂ concentration), when they were automatically activated. However, the smoke obscuration in the test room deteriorated rapidly and reached the untenable condition within 2 minutes from the ignition in all tests (see Figure A-3).

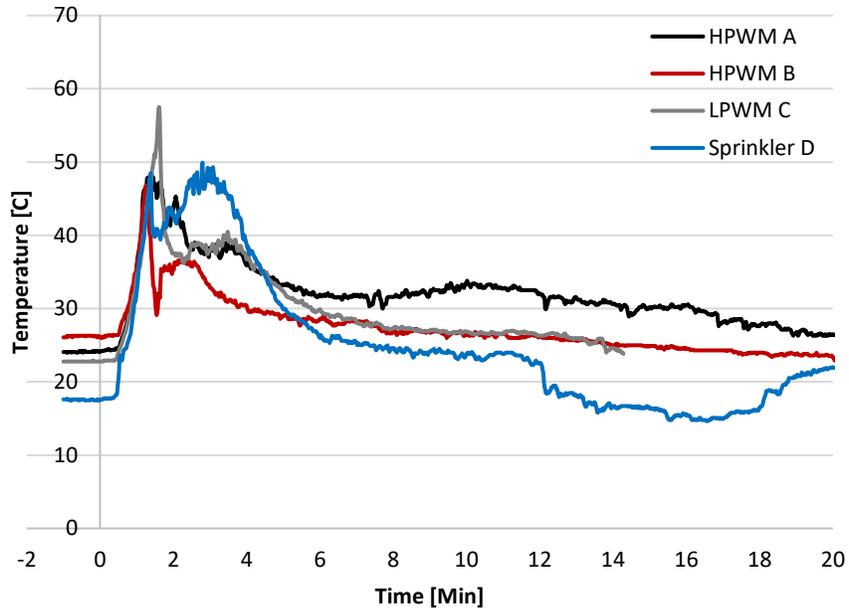


Figure A-2 Room Temperature measured at the center 1.6 m height

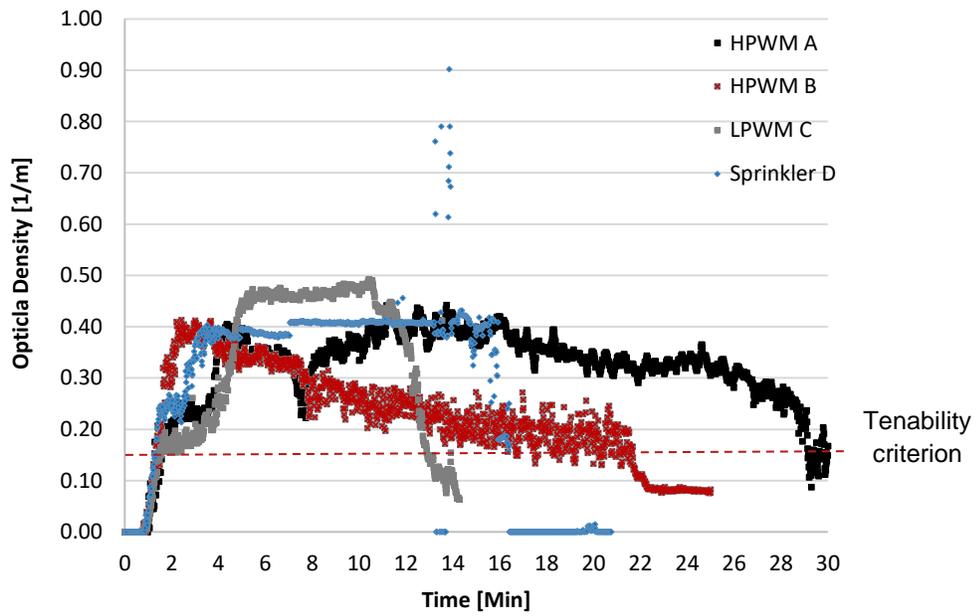


Figure A-3 Visibility measured in the test room at 1.6 m height

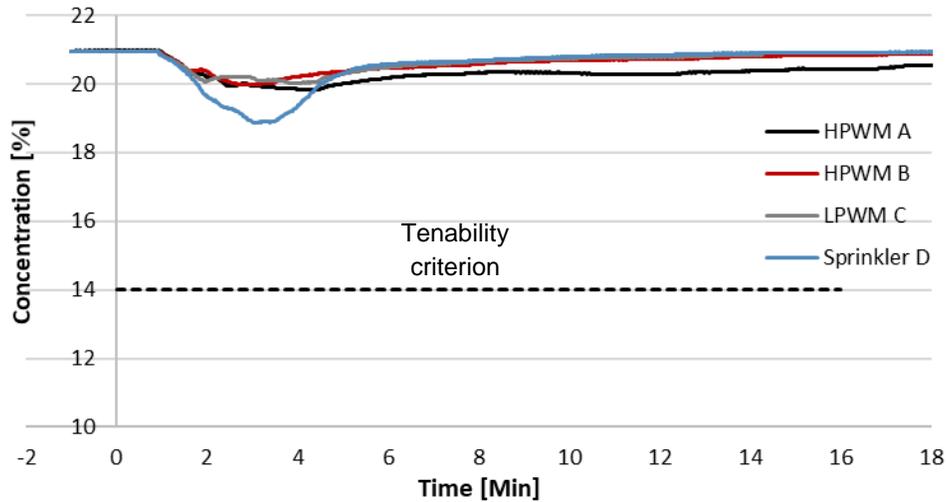


Figure A-4 Oxygen concentrations measured in the test room at 1.6 m height

A.5.2 Property protection

When the tested suppression systems were automatically activated, they prevented significant fire spread to the ceiling even though the ceiling temperature was rising rapidly. However, some fire damage on the CLT corner wall panels was seen. The largest damaged area was found with a HPWM nozzle (Type A in Table A-1) designed for minimum protection for life safety, and only slight damage was found with the other HPWM nozzle (Type B) designed for property protection. The sprinkler system also provided relatively good protection for the corner walls as the water spray angle was wide enough to wet the walls. It should be noted that current standards require to have a wide spray pattern for traditional sprinklers but not specifically for water mist systems since wetting is not the main fire suppression mechanism of the water mist systems.

On the other hand, the manually delayed activation of the water mist systems resulted in severe damage, as expected, to both the ceiling and wall CLT panels. In water-sensitive environment, such as mass timber buildings with exposed timber structures, dry-pipe/pre-action systems with inevitable lags in water discharge would be considered to prevent potential water damages in the case of false activations or inadvertent discharges. The dry-pipe/pre-action systems are discussed in Section 4.4.2.1.

The HPWM (Type B nozzle) designed for property protection demonstrated the most effective fire suppression among the tested systems. The HPWM system (Type A nozzle) used only $\frac{1}{4}$ of the total water used by the sprinkler (Type D nozzle) to demonstrate the comparable effectiveness on lowering the fire temperature. Consequently, the HPWM systems are expected to minimize the potential water damage to the building. After each fire suppression test, the wet CLT panel surfaces quickly dried, and they recovered the pre-test moisture content values within about 24 h in all tests, regardless of the water spray rates and the system type. However, a large water pool was formed on the floor in particular for the sprinkler system. For this reason, water penetrated the joints along the bottom edge of the CLT wall panels, which could bring concerns for water damage or mould issues.

Appendix B Existing generic testing protocols

This section discusses the protocols provided by FM 5560 (FM Approvals, 2021), UL 2167 (UL, 2021) and BS 8458 (BS, 2015) & BS 8489 (BS, 2016) Part 7 for testing water mist suppression systems designed for residential/light hazard areas. The details of the standard tests are summarized in Table B-1 and shown in Figure B-1, Figure B-2, Figure B-3.

FM 5560 (FM Approvals, 2021) provides fire test methods for HC-1 (formerly light hazard occupancies) in Appendix G, which provides small compartment, large compartment, and open space test.

UL 2167 (UL, 2021) provides residential testing protocols in Chapter 47 and LH testing protocols in Chapter 48.

The BS 8458 (BS, 2015) procedures involve 6 different tests²⁸ for residential applications;

- 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,
- e) the worst two tests from a), b) & c) to be repeated with only 2 walls in place (open room test), and
- f) higher ceiling test if approval is required.

BS 8489 (BS, 2016) Part 7 provides test methods and requirements for water mist systems for the protection of low hazard occupancies. It provides a small compartment test with bunk beds, large compartment test with corner crib and simulated furniture, open space test with sofa and the open space test with simulated workstation²⁹ (note: the open space test with simulated workstation is not introduced in Table B-1).

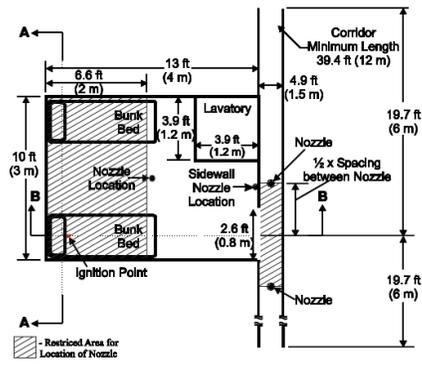
Table B-1 Test protocols for some water mist standards

	FM 5560 LH/HC-1			UL 2167 Residential		UL 2167 LH	BS 8458 Residential		BS 8489-7 Low Hazard		
	Small room & corridor	Large room	Open space	Pendant nozzle	Sidewall nozzle	Open space	Nozzle spacing 2–4 m	Nozzle spacing 4–5 m	Small room & corridor	Large room	Open space
Dimensions (m)	3x4x2.4	Square room, side is double nozzle spacing	Height = 5	Height ≥ 2.4, length and width depend on nozzle coverage		Height 2.5 and the maximum design height	4x8; height ≥ 2.5	5x10; height ≥ 2.5	3x4x2.4	Square room, side is double nozzle spacing, height 2.4	Height ≤ 5

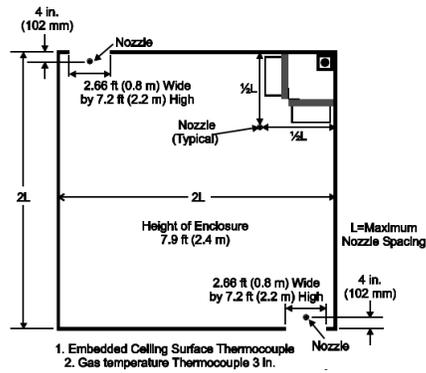
²⁸ Among the listed 6 tests, test e) and f) are optional for larger rooms and with higher ceilings.

²⁹ The simulated workstation tests are 30 min tests and address property protection.

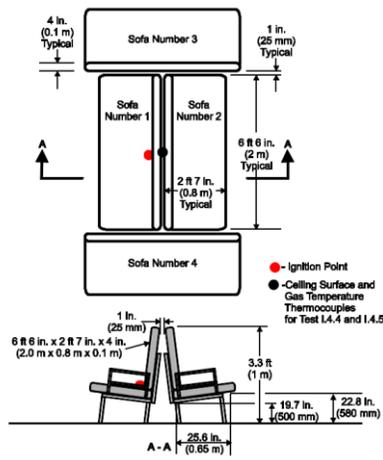
Ventilation	1 door	2 doors	Open	2 doors	open	2 doors Forced ventilation	1 door	2 doors	Open
Fuel	2 bunk beds	Wood crib+2 pieces of simulated furniture	4 sofas	Wood crib+2 pieces of simulated furniture	4 sofas	Wood crib+2 pieces of simulated furniture	2 bunk beds	Wood crib+2 pieces of simulated furniture	4 sofas
Duration	10 min from activation of nozzle			30 min after ignition of wood crib	30 min after ignition of wood crib	30 min after activation of nozzle	10 min from activation of nozzle		
Evaluation criteria	Ceiling surface temp.≤260°C Ceiling gas temp.≤315°C For the small room test, fuel damage not exceeding 40% for the bunk beds, and no dummy nozzle activated For the open space sofa tests, fuel damage not exceeding 50% for the 4 sofas			Only 1 nozzle activated, Ceiling gas temp. ≤ 316°C. Temp. at 1.6 m above floor≤93°C and ≤54°C for more than any continuous 2 min period. Temp. behind the ceiling over the fire ≤260°C	Fuel damage not exceeding 50% for the 4 sofas, Limited number of operated nozzles, Ceiling surface temp.≤360°C Ceiling gas temp.≤220°C	No activation of the 3 rd dummy nozzle. Nozzles should suppress the fire within 10 min for domestic premises or 30 min for residential premises, measured from nozzle operation, Ceiling gas temp. ≤ 320°C. Temp. at 1.6 m above floor≤93°C and ≤55°C for not more than any 2 min period.	Fuel damage not exceeding 40% Ceiling surface temp.≤260°C Ceiling gas temp.≤315°C Mean room temp. remains steady or decrease	No dummy nozzle activated, Ceiling surface temp.≤265°C Ceiling gas temp.≤315°C Mean room temp. remains steady or decrease	Fuel damage not exceeding 50% for the 4 sofas Ceiling surface temp.≤260°C Ceiling gas temp.≤315°C Mean room temp. remains steady or decrease



(a) small compartment



(b) large compartment



(c) open space

Figure B-1 Test rooms for testing water mist systems under FM 5560 standard (FM Approvals, 2021)

Numerous fire tests have been conducted to examine the fire performance of timber buildings (both light-frame and mass timber buildings). However, only a few fire suppression tests have been reported. Most of these tests have demonstrated the effectiveness of sprinkler systems in limited applications to timber buildings. Other than the NRC water mist test report (Ko et al., 2020, 2021), there is no test report 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. The following subsections briefly discuss some of these experiments.

C.1 AHC TWB fire suppression tests for heavy timber buildings

In order to support the proposed changes regarding type IV mass timber construction to the IBC 2021 code, a series of 5 full-scale apartment fire tests (Zelinka et al., 2018) was conducted by the ad hoc Committee on Tall Wood Buildings (AHC-TWB). A two-storey apartment building with one furnished unit on each floor was built using CLT assemblies. Each unit had one bedroom and a living/kitchen area. Two of these tests 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. All the walls and ceiling of the unit were protected with gypsum boards, except for one side wall and the ceiling of the living area and the bedroom (exposed CLT). Residential types of sidewall and pendent sprinkler heads were installed in various locations in the unit with a water spray discharge density of 2.0 l/min/m² (i.e., the report states that the sprinkler system was designed as per NFPA 13-2016 edition for light hazard).

In one test, a pendent type of nozzle with a temperature rating of 68.4°C installed in the kitchen was activated at 2.5 min and quickly extinguished the fire within about 2 min from the activation. In addition, the exposed CLT walls and ceilings were not damaged. In the other test, the sprinkler system was manually activated 23 min after ignition, by which time the fire had spread to the living area and the bedroom with measured hot layer temperatures exceeding 600°C. All 9 sprinkler heads were activated in that test and the fully developed fire (the heat release rate at the time of activation was approx. 5 MW) in the entire unit was effectively suppressed within approximately 10 min. However, the fire damaged the exposed CLT members severely.

These results showed that sprinkler systems designed and approved by NFPA 13 (NFPA, 2022a) 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 mass timber member could be exposed without gypsum board protections, yet with potential fire damages. The report does not provide rationales why the kitchen fire scenario with the flashover occurred at 11–13 min was selected for the tests. Kitchen fires are frequent but not as challenging as a living room fire scenario involving upholstered furniture, which could result in flashover within 4–5 min.

C.2 SFIT fire suppression tests for timber buildings

Swiss Federal Institute of Technology (SFIT) conducted full-scale fire tests of modular wooden hotel room (6.6 m (L) × 3.1 m (W) × 2.8 m (H)) to verify the efficiency of sprinkler systems (Frangi & Fontana, 2005). The room was built with light-frame construction and lined with Oriented Strand Board (OSB) panels for the walls and timber boards for the ceiling. 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 min in all three tests. No significant differences were observed between ceiling and wall sprinkler systems, 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.

C.3 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 side wall, listed per NFPA 13R (NFPA, 2019b)) for a living room fire scenario (Arvidson & Larsson, 2001). A living room of dimensions 4 m (W) × 5 m (L) was constructed using wood studs and ceiling joists. The living room was connected to a bedroom through a doorway and 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. An 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 facing the combustible wall to allow the fire spread to the wall.

Two high-pressure water mist nozzles (not listed for residential applications) 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 and 1.9 mm/min, and a dummy nozzle was also installed in the bedroom. 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, the fire burned continuously even with the mist system active, which resulted in the dummy nozzle activation in the connected bedroom.

C.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)³⁰ and activation temperature ratings (Arvidson, 2017). It is reported that earlier activation was observed with a lower RTI and operating temperature to a certain degree: however, the improvement in performance was negligible and inconsistent over simulated and real upholstered chair fire scenarios.

The tests used either a simulated or authentic upholstered chair placed in a corner of the test compartment dimensioned with 3.66 m 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. All systems were listed either for residential or light hazard type applications. It was concluded that the performance of the water mist nozzles was comparable or better than the residential sprinkler system at approximately half the water flow rate for the tested fire scenarios. Moreover, the ceiling temperature was lower in case of using the water mist systems, which confirms its effectiveness in cooling the area. The differences between the low and high-pressure water mist systems were small. This is an expected result always with systems listed for the same application, i.e., they meet the same performance requirements regardless of the system type. The smallest fire damages were observed in the tests with high water spray rates.

C.5 The effectiveness of a Water Mist System in an Open-plan Compartment with an Exposed Timber Ceiling: CodeRed #03

The research team conducted a series of full-scale fire experiments in a large compartment, in order to investigate compartment fires with exposed mass timber elements and large surface area (Kotsovinos et al., 2022). The performance of a standard low-pressure water mist system in an open-plan compartment with an

³⁰ RTI is a measure of nozzle sensitivity in responding to gas flow and is correlated with flow temperature and velocity.

exposed CLT (timber) ceiling was examined. The dimensions of the compartment were 10.27 m (L) × 34.27 m (W) × 3.1 m (H) with a total area of ~352 m². The compartment had several open windows and doors to replicate possible ventilation conditions in an office environment. The equivalent theoretical fire load was replicated by using a wood crib with a fuel load density of ~ 570 MJ/m² covering an area of ~50 m². Ignition was provided using 2 pans of methanol placed below the crib. Five low-pressure water mist nozzles were installed to achieve the requirements of Ordinary Hazard category 1 (OH1) of FM 5560 (FM Approvals, 2021).

During the test, all five nozzles activated over a period of 5 min 28 s. The system successfully controlled the fire where the maximum temperatures near the ceiling never exceeded 185 °C, and 85 °C elsewhere in the compartment. Compartment temperatures started to fall soon after the activation of the 5th nozzle, and ambient temperatures were reached after 20 min. The CLT ceiling did not ignite or char; however, it showed some discolouration. Thus, it was concluded that low-pressure water mist system installed in a large compartment with a combustible CLT can adequately control fire growth, even with open windows. However, the authors noted that the application of water mist systems in buildings with CLT needs to be discussed and agreed with the authority on a case-by-case basis.

C.6 KA PROJECT: Comparison of performances of fire fighting systems of interior and exterior applications at large wood buildings

The state-funded service organization for the churches of Norway (KA) engaged a consulting group to investigate conventional and new fire fighting systems for protection of church buildings built in the 19th century (Jensen, 2018).

Four water-based fire fighting systems (sprinklers, low-pressure water mist, high-pressure water mist and robotic ceiling nozzle) were tested in 10 × 10 × 10 m rooms constructed from wood to simulate congregation rooms of historical buildings with church naves, large attics, galleries, meeting rooms or halls which contains little or no inventory. The four fire fighting systems were tested for performance against exterior fires at 7 m high wooden clad walls. In addition, a demonstration (without fire) of exterior water barrier spray system, which is used to create a water shield between structures for protection of personnel and avoid fire spread to other buildings, was tested.

It was found that, the best performance (based on total water used, time to extinguish vs. burn-through, wetted area and charring depth) against interior fires was shown by robotic nozzle while for the exterior fires, the best performance (based on time to extinguish vs. burn-through and flow rate/water supply capacity) was exhibited by robotic nozzle or radiation activated low-pressure mist. Tests showed that fixed nozzles (sprinkler or mist) at ceilings need to extinguish fire before heat release rate (HRR) exceed 3–4 MW to avoid the effect of buoyancy. However, robot nozzles or manual water or foam application have the capacity to extinguish at higher HRR. All radiation activated systems extinguished the fire in seconds, while heat (bulb) activated systems often allowed time for fire growth, which challenged the spray. Moreover, heat-activated systems increased the wetted area and charred area by factors of 10 and 15 respectively, compared to the radiation activated systems.

Finally, the authors concluded that the major fire fighting factor for water-based systems was water density more than what system was applied.

Appendix D Case studies

Several water-mist protected wooden residential buildings already exist (e.g., PuuEra Wooden Residential Building, Heinola, Finland). However, there is no publicly available information on those. This section presents some of the currently existing exposed wood buildings that are protected by water mist system but none of them is a residential building.

D.1 The Finnish Nature Centre Haltia, exhibition & event center, Finland

The Finnish Nature Centre Haltia at Nuksio Natural Park is the first large building in Finland to be made of CLT. The walls, floors and roofs are made up of massive CLT panels and most of the key construction elements are entirely made of wood. The building consists of three floors, with a total area of 3300 m². It includes an exhibition, a restaurant, an auditorium, and meeting rooms.

The building is classified within the European Ordinary Hazard Group 1 (OH1 – corresponds to NFPA LH), while the restaurant, shops and exhibition area fall into the European Ordinary Hazard Group 3 (OH3 – corresponding to NFPA OH1 or OH2 depending on the exact application) classification (EN, 2021a).

Fire protection is provided in the building using 630 sprinklers. Since the building is in the wild, it needed a system that wouldn't require a municipal water supply and a 24 m² water tank was built to provide the required water for the sprinkler system. To reduce the risk of accidental discharge, the exhibition rooms and storage areas are protected by a pre-action unit that only activates after a fire has been detected and the ambient temperature is high enough to break the bulb (*Haltia – Finland 's Nature Centre*, n.d.).

D.2 Credit Valley Hospital/Peel Region Cancer Centre, Hospital, Canada

The atrium of Credit Valley Hospital's Carlo Fidani Peel Regional Cancer Centre, in Mississauga, Ontario consists of a grove of timber trees flourishing. Such design was chosen to provide patients with hopeful environment that appears to be alive and growing. The 11,500-ft.² space is made up of a triangular floor plan centred on four sprawling columns comprising Douglas fir glulam (glue-laminated) members ("A Tree-Filled Atrium to Inspire Patients," 2014). The glulam structures are protected by water mist systems.

D.3 Urnes Stave Church, Heritage buildings, Norway

Urnes Stave Church is one of the oldest buildings in Norway and included on UNESCO's World Heritage List. It was built around 1130 AD from mass timber and is protected using water mist systems. Another example of mass timber building protected by water mist is STÅLEKLEIVLOFTET, which is considered as the oldest profane wooden building in the world (*Stålekleivloftet - One of the Oldest Wooden Building in the World*, 2021).

D.4 Mount Vernon, Heritage buildings, US

Mount Vernon is the historic home of George Washington; the first president of the United States; and his wife Martha. The estate's buildings are built from mass timber and were recently equipped by state-of-the-art water mist suppression systems to protect them from fire (Vernon, 2020).

D.5 SKAIO, residential building, Germany

SKAIO residential building opened its doors in 2019 and is known as the first timber high-rise building in Germany. With a height of 34 m, it houses 60 residential units, an elevator and a rooftop with vegetable garden and social area. It is fully protected with water mist (Triple Wood, 2019).

D.6 Marcadet Belvédère, commercial and residential building complex, France

Marcadet, located in the heart of one of the liveliest districts of Paris, is distinguished by its resolutely low-carbon approach, which is a sign for the companies that will settle there. The existing base is maintained and restructured to limit CO₂ emissions. The elevation is made of CLT solid wood. The building embodies the new Parisian workspaces: open to the city, focused on the well-being and health of employees, with many green outdoor spaces and large horizontal platforms promoting exchanges. In 2021, the project was distinguished by the Federation of Real Estate Developers who awarded it the Golden Pyramid in Commercial Real Estate (WO2, 2021).

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