A Review of Water Mist Fire Suppression Technology: Part II—Application Studies

ZHIGANG LIU* AND ANDREW K. KIM

Fire Risk Management Program, Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario, K1A 0R6, Canada

ABSTRACT: The progress on the research and application of water mist technology in fire suppression has been substantial over the last decade. This paper, following our previous review on water mist fundamental studies, reviews recent water mist applications for: the extinguishment of Class B spray and pool fires in machinery spaces, gas turbine enclosures, combat vehicles, and flammable liquid storage rooms; the extinguishment of Class A fires in residential occupancies, marine accommodations and public spaces, heritage buildings and libraries; the extinguishment of Class C fires in electronic equipment and computer rooms; and the protection of aircraft onboard cabin and cargo compartments. Some new applications, such as the use of water mist for the extinguishment of Class K fires in commercial cooking areas; and the use of water mist as a possible total-ship protection method, as well as the use of water mist for the protection of heavy goods vehicle shuttle trains, are also reviewed. Up-to-date development of corresponding test and design criteria for the installation of water mist fire protection systems and for the evaluation of the capabilities and limitations of water mist for fire suppression in some application areas, such as machinery spaces, ship's cabins and corridors, and turbine enclosures, are discussed.

KEY WORDS: water mist, fire suppression, flammable liquid hazards, call A combustible hazards, fire protection for aircraft onboard cabin and cargo compartment, electronic equipment, commercial cooking areas.

INTRODUCTION

WATER HAS FAVORABLE physical properties for fire suppression. Its high heat capacity (4.2 J/g·K) and high latent heat of vaporization (2442 J/g) can absorb a significant quantity of heat from flames and fuels. Water also expands 1700 times when it evaporates to steam, which results in the dilution of the surrounding oxygen and fuel vapors. With the formation of fine droplets, the effectiveness of water in fire suppression is increased, due to the significant increase in the surface area of water that is available for heat absorption and evaporation [1,2].

*Author to whom correspondence should be addressed.

1532-172X/01/01 0016–27 $10.00/0 DOI: 10.1106/MMGH-XUAG-HP5B-YTDG

Water mist refers to fine water droplets in which 99% of the volume of the spray is in drops with diameters less than 1000 microns [3]. Advantages of water mist over gaseous agents are that water is non-toxic, readily available, and lower in cost than most chemicals or patented mixtures. Water mist provides effective cooling for fuel and for the compartment that cannot be provided by the gaseous agents, potentially preventing re-ignition that may occur if a gaseous agent concentration cannot be maintained for a sufficient period of time [4]. With effective cooling and less clean-up time, water mist allows the space to be reoccupied and operational in a short time following a fire. Advantages of water mist over conventional sprinklers include reduced water flow rates and therefore less water damage to sensitive equipment or occupancies. Low water flow rates also provide a clear advantage in terms of space and weight requirement for the water supply. In addition, water mist is able to control flammable liquid fires that conventional sprinklers cannot control due to splashing and spillage of the fuel.

Over the last decade, water mist has been used to replace current fire protection techniques no longer deemed environmentally acceptable, such as halons, or to provide new answers to problems where traditional technologies have not been effective [4–6]. Water mist fire suppression technology has been used, or is being developed, for the extinguishment of Class B spray and pool fires in shipboard machinery and engine room spaces; the extinguishment of Class A fires in shipboard accommodation spaces and heritage property (wood stave churches, libraries); the extinguishment of Class C fires in computer and electronics equipment; as well as to provide fire protection for the aircraft onboard cabin and cargo compartments, engine dry bays and fuel tanks [4–8]. The applications of water mist fire suppression technology in other areas, such as portable water mist fire extinguishers or for use in commercial cooking areas, are also being developed. There are a number of water mist systems available, and more are entering the marketplace. Corresponding test and design criteria for the installation of water mist fire protection systems and for the evaluation of the capabilities and limitations of water mist fire suppression in some application areas, such as machinery spaces, ships' cabins and corridors and turbine enclosures, have been established [3,8–12]. In addition, some new technologies, such as the combination of total flooding and local application for the protection of machinery spaces [13], and the combination of zoned water mist systems with intelligent detection for use on electronic equipment [14], are being developed.

In order to identify future development and application of water mist fire suppression technology, as well as potential efficiency improvements, this paper, following our previous review on water mist fundamental studies [15], reviews the progress that has been made on various water mist applications over the last decade. The capabilities and limitations of water mist against various fire challenges, as well as some new technologies that can potentially improve water mist effectiveness, are discussed.

WATER MIST ON FLAMMABLE LIQUID HAZARDS

One of the primary water mist applications in fire suppression is the protection of flammable liquid hazards, including machinery spaces in ships or industrial settings, gas turbine enclosures, flammable liquid storage rooms, and combat vehicles. The liquid fuels involved in these hazards include fuels and lubricating and hydraulic oils. The fuel fluids may be in pressure lines, which will produce 3-dimensional spray fires and 2-dimensional pool fires ignited by hot engine parts, overheated bearings or electrical arcing [16]. The flash point of the fuels involved ranges from low temperature flash points (e.g., heptane or gasoline) to high flash points (e.g., lubricating and hydraulic oil).

Water Mist for the Protection of Machinery Spaces

Either CO_2 or halon fire suppression systems have been used in machinery spaces for many years [7]. With the recent phase-out of halon and with the safety issues surrounding the use of CO_2, halocarbon gaseous agents and water mist are considered to be acceptable alternatives to provide protection in the marine machinery space. However, current research indicates that with halocarbon agents, there are increasing concerns over their toxicity, environmental implications and limited capability to remove heat from hot surfaces [17]. For these reasons, water mist had been considered as an ideal alternative for fire protection in machinery spaces.

Since 1990, a number of manufacturers and research organizations [9,11, 17–34] have been involved in developing water mist technology for the protection of machinery compartments. The Fire Protection Subcommittee of the International Maritime Organization (IMO) has developed a fire test protocol [9] for water mist systems that are intended to replace sprinkler systems in marine machinery compartments. Underwriters Laboratories Inc. (UL), based on the IMO test protocols, also prepared draft Standard UL 2167 for performance requirements for water mist systems in machinery spaces [11].

Over the last decade, extensive tests, ranging from small-scale (24 m^3) to full-scale (up to Class III engine room defined by IMO), have been conducted to evaluate the capabilities and limitations of water mist in machinery space applications. The performance of various water mist systems, including modified industrial spray nozzles and commercially-available water mist systems, was evaluated based on IMO's fire test protocol, or under fire conditions that may occur in machinery spaces. These fire scenarios included various fire types (wood crib, spray, pool and cascading fires), fire sizes (up to 30 MW) and fire locations (shielded and unshielded), as well as various fuel types (from high viscosity heavy oils to diesel fuel and n-heptane fuel) and different ignition sources (e.g., heated engine block). For obstructed space scenarios, full-scale mock-ups of an engine, as recommended by the IMO test protocol, or reduction gear and associated supply and exhaust ducts, were placed in the compartment. The parameters studied in the tests included water mist characteristics (droplet momentum, spray pattern, droplet size distribution, etc.), the types of water mist system (single or twin fluid systems, different flow rates, discharge pressure, nozzle spacing, etc.), fire scenarios (fire type, size, and location), various ventilation conditions and firefighting additives.

Test results [17–34] showed that water mist fire suppression systems were able to extinguish a wide variety of exposed and shielded hydrocarbon pool, spray and cascading fires, as well as combined Class A and B fires representative of those that might occur in a machinery space. Compared to gaseous agents, the extinguishing time using water mist was long. However, water mist quickly controlled fires and cooled the compartment, keeping the combustion products (CO and CO_2) in the compartment at a low level. In the tests conducted by the National Research Council of Canada (NRC) [23], the compartment temperature was cooled down to 50°C in less than 15 s after the activation of the water mist system, and the maximum CO and CO_2 concentrations measured in the tests were below 0.08% and 3.5%, respectively, depending on the fire size and pre-burn period. Thermal conditions and gas concentrations in the compartment, after water mist application, were safe enough for firefighters to immediately enter the compartment.

The extinguishing performance of water mist systems in machinery spaces is mainly determined by fire size, the degree of obstruction, ventilation conditions, compartment geometry, spray characteristics of the water mist systems and their configuration in the compartment. Large fires, relative to the compartment size, are easier to extinguish than small fires, due to the depletion of oxygen consumed by large fires and due to the large amount of steam generated by water mist that is displacing oxygen in the compartment. In the tests carried out by Pepi [26,27], larger spray fires (6 MW, Low Pressure) in Scenarios 1 and 2 of the IMO test protocol were extinguished much faster than smaller fires (1 MW, Low Pressure/Low Flow) in Scenario 6. The extinguishing times ranged from 23 to 175 s for large spray fires and from 5 min 24 s to 21 min 10 s for smaller spray fires, depending on the type of nozzle and compartment size.

With increasing degrees of obstruction, the amount of water mist reaching the fire is reduced and the extinguishment of the obstructed fire is more difficult. Full-scale tests carried out by Pepi [26,27] showed that the 0.5 m^2 heptane pool fires positioned underneath the engine block (Scenario 9 of the IMO test protocol), within a ventilated enclosure, were the most challenging fire in the IMO test protocol, because the fires were fully shielded from the attack of water mist. Fires in the corners or located near the ceiling that could hardly be hit by the spray were also difficult to extinguish [23]. However, even for well-obstructed fires, water mist is able to control fire sizes effectively, due to the expansion of the water mist to steam as well as the redirected combustion products from the hot layer to the fire area that reduces the oxygen available for combustion.

An increase in the engine-room volumes and ceiling heights reduces the effectiveness of water mist in fire suppression [27,28], because it is difficult to deliver a sufficient concentration of fine spray to the fire location. The tests carried out by Bill, Hanseb and Richards [28] showed that, when the nozzles were installed at a 5 m height and 1.5 m spacing in a large test facility (2800 m^2 area and 18 m height), without any additional enclosure surrounding the nozzles, or when only a ceiling was placed directly over the nozzles, fires (1 to 6 MW shielded and unshielded spray fires, and a wood crib fire and a 2 m^2 pan fire) were not extinguished by either high pressure (69 bar) or low pressure (12 to 15 bar) water mist systems, even if the number of the nozzles was increased from 30 to 100. The oxygen concentration in the compartment was not reduced significantly by the discharge of water mist and remained above 20.5% during the tests. A 6 MW unshielded spray fire was extinguished only when a 940 m^3 enclosure was formed, using the previously installed ceiling and installing tarpaulins for walls. Based on their test results, Bill, Hanseb and Richards [28] suggested that current water mist technology, as represented by the two tested systems, was unlikely to be capable of extinguishing test fires in the IMO fire test protocol for Class III engine rooms.

The water mist effectiveness is further affected by an opening in the compartment, due to a leak of steam and hot gases and flow-in of fresh air. However, water mist demonstrates better effectiveness in extinguishing ventilated fires than gaseous agents such as halon, CO_2, and gaseous halon replacements. Studies on low pressure water mist systems [26,27] showed that the ventilated fires were extinguished but that the extinguishing times increased by 30% to 70% in Fire Scenarios 5, 6 and 11 of the IMO test protocol, when a 4 m^2 door was kept open in an 8 m high/1280 m^3 space. By increasing the number of doorway nozzles from 2 to 4, the water mist effectiveness against ventilated fires was increased, due to the increase in the density of water mist around the opening [27]. The impact of ventilation on water mist performance is also determined by the fire size in the compartment. The full-scale tests carried out by the U.S. Navy [30] showed that when three doors in the compartment were kept open, the extinguishing time had a slight increase for small fires, but there was no change for large fires.

Water mist effectiveness is also dependent on nozzle configuration in the compartment such as the nozzle spacing, the distance of the nozzles below the ceiling, and the number of nozzle levels in the compartment. The full-scale tests carried out by Back et al. in a 960 m^3 space [18] showed that the extinguishing performance of the water mist system was improved by installing the nozzles at two elevations in the compartment. In this configuration, the water mist system was capable of extinguishing all of the unventilated fires in less than 25 s using less than 100 L of water. The study on the feasibility of local water mist application for machinery protection [34] showed that water mist systems located above the fires had better extinguishing properties than systems located beside the fires (90% of successful spray fire extinguishment versus 5%). Furthermore, the nozzles located directly below the ceiling had better extinguishing performance than those 2 m below the ceiling because, with such a configuration, more water vapor could be produced in the hot layer, and steam and vitiated gases in the upper layer were more effectively redirected back to the fires, which increased the water mist capability against the fires.

Compared to low pressure single-fluid and twin-fluid systems, high pressure single-fluid water mist systems exhibited better fire extinguishing capabilities against most fire challenges, because a large amount of small and high momentum droplets were produced [17,18,26–30]. However, the low pressure water mist systems with higher water flow rates and larger droplet sizes demonstrated good performance in extinguishing unshielded pool fires and wood crib fires [17,18,29]. The selection of a water mist system is strongly dependent on matching the spray characteristics to the fire hazard, as well as considering the cost-effectiveness, simplicity, and reliability of the system. The U.S. Navy [18,29–31], based on their extensive tests, has identified that the best performing water mist nozzle for their applications is a modified Spraying Systems nozzle (Model 7N nozzle) flowing at 70 bar. The U.K. Royal Navy and some manufacturers [17,26,27,32], however, are showing interest in low pressure water mist systems (7 to 12 bar) that are available for applications in machinery spaces, particularly in marine applications. The U.K. Royal Navy [17,24,32] has evaluated 6 low pressure water mist systems (3.5 to 7 bars). Their test results showed that the performance of low pressure water mist systems (7 bar) in marine applications was acceptable.

When firefighting additives are introduced, the effectiveness of water mist is significantly improved. Tests carried out by the U.S. Navy [33] showed that the use of the additive Quad-Ex, ranging from 12–25%, increased a twin-fluid water mist system to extinguish fires by a factor of two or better. However, potential toxicity and corrosivity generated by the additive must be investigated before it could be used in manned machinery spaces [31,33]. Recently, the U.K. Royal Navy [32] studied the effect of five types of additives [2 types of AFFF (Mil Spec F2341C and Dcf Stan 42/40-1), a Film Forming Fluoro Protein (FFFP), Fire Stopper, and Fuel Buster] on the performance of sprinklers and water mist. The concentration of all additives was based on the recommendations of manufacturers. The test results showed that all five types of additives improved the performance of both sprinklers and water mist, but such improvement was much more significant for water mist (18% to 60% reduction in extinguishing time for sprinklers versus 74% to 90% reduction in extinguishing time for water mist). The additives especially improved the performance of low pressure water mist systems. The reductions in extinguishing times ranged from 85% to 99% and water usage for fire suppression was greatly reduced, compared to the use of sea water only. Water mist with additives had a performance similar to an inert gas system and far superior to existing warship sprinklers in extinguishing Class B fires. Further studies on the impact of these firefighting additives on water mist effectiveness in full-scale tests are continuing [32].

The test conditions recommended by IMO standards [9] are much more challenging to water mist than the early demonstration tests in which large fires were extinguished under limited ventilation conditions. The present IMO test protocol [9], however, is only used to evaluate the performance of overhead water mist deluge systems. Based on full-scale fire test results, Back and his co-researchers [29] suggested that the present IMO test protocol needs to be revised to address the inadequacies of the standard with respect to bilge areas, obstructions/shielding, water spray patterns and the effectiveness of water mist systems for large areas. As a result, the IMO Fire Protection Subcommittee, in its two sessions in 1996 (FP41) and 1997 (FP42), considered the requirements for water-based local fire extinguishing systems.

Current applications have demonstrated the capabilities of water mist for the protection of machinery spaces and their potential to replace halon or CO_2 systems. A number of water mist systems have been approved by various authorities and used on shipboard and in industrial applications. The U.S. Navy and the Royal Navy in the U.K. are continuing to conduct research on the application of water mist fire suppression systems in marine machinery spaces [31,32].

Water Mist for the Protection of Turbine Enclosures

Turbine enclosures are a type of machinery space. Unlike general machinery spaces that may contain many potential fire sources, the potential fire sources in a turbine enclosure are mainly limited to the turbine and its fuel lines [1]. Four key requirements for the protection of a turbine enclosure include [13]:

1. Rapid and efficient fire extinguishment
2. Minimal thermal shock and corrosion damage
3. Minimal clean-up time and costs
4. Minimal negative environment impact

Over the last decade, extensive studies on the use of water mist to replace existing halon or CO_2 systems in the turbine enclosure have been carried out [12,13,35–44]. These studies included the evaluation of the effectiveness of water mist for fire protection in the turbine enclosure, probable damage of turbine components due to rapid cooling by water sprays, and methods for improving water mist performance in the turbine enclosure [13,35–44]. The new methods include local applications and the combination of both total flooding and local applications. For the total flood application, the nozzles were located just below the ceiling. For the local application, water mist discharge nozzles were located to provide coverage directly to the identified fire hazards, or to specific equipment. For the combination of both total flooding and local applications, deluge systems with open nozzles in a pre-tested pattern were installed at the ceiling, around all sides and under a turbine.

In order to evaluate the capabilities and limitations of water mist systems in turbine enclosures, or machinery spaces, Factory Mutual Research Corporation (FMRC) [12] has developed a performance-based fire test protocol for both under and above 260 m^3 of volume. To pass the test protocol, water mist must extinguish all fires without damage to the turbine components (either by fire or due to excessive cooling of the turbine casing by fine water mist). Some water mist systems have satisfied the requirements set up by the FMRC fire test standard and have been approved by FMRC [37].

For more challenging fires in a compartment involving a jet engine and gas turbine compressor [13], the water mist systems using both the total flooding and local application methods extinguished lubricating oil and aviation jet spray fires, and pool fires located beneath the engine or the turbine. The local application method was less effective than the total flooding method, and the extinguishing times increased when a local application method was used for both high and low pressure water mist systems. The increase in the number of nozzles in the compartment by using either the total flooding or local application method (e.g., increasing from 11 to 22 nozzles in total flooding or from 7 to 14 nozzles in local application), had no significant impact on the effectiveness of water mist. The extinguishing times, using the lesser number of nozzles, were slightly longer than or equal to those using the large number of nozzles in the compartment. The test results, however, showed that the method that combined both total flooding and local application improved the extinguishing performance of water mist systems. For the combined shielded lubricating oil spray fire and heptane pool fire (1.5 MW) test, the combining application method (5 flood nozzles/4 local nozzles under low discharge pressure) extinguished the fires in 28 s, compared to 5 min using a total flooding method with 11 low pressure nozzles.

Water mist fire suppression systems have also shown much better performance against ventilated fires than gaseous agents, such as halon, CO_2 or halocarbon agents [13,35–44]. During FMRC's tests [37], a shielded 2 MW spray fire was extinguished when a 1.6 m^2 access door was deliberately left open. In the tests carried out by NRC [43], a shielded 520 kW spray fire and a shielded 500 kW pan fire under natural and forced ventilation conditions were extinguished. The performance (extinguishing time and water requirement) of water mist systems under ventilated conditions is dependent on the fire location in the compartment, the characteristics of the water mist system (spray momentum, droplet size, water density, etc.) and ventilation rate in the compartment [13,43]. With an increase in the number of nozzles in the compartment for either total flooding or local application, the effectiveness of the water mist against ventilated fires was substantially enhanced [13].

In order to evaluate probable damage of turbine components due to rapid cooling by water mist, the impact of both continuous water mist discharge and repeated short water mist discharges on turbine components were examined [13,35,41,44]. The metallurgical samples used in these full-scale tests were fabricated from stainless steel and varied in shape and size, including cylinders, cubes, rolled angles, rolled curves and tubes. Test results showed that only the surface temperature of the metal was substantially changed by the cooling of the water mist, while the changes in the temperature in the deeper part of the metal were very slow. In NRC's test program [41], the localized surface temperature of the metal was reduced from 360°C to 280°C within a 2 min discharge, and the metal temperature that was 1.3 cm from the surface was reduced from 360°C to 340°C in the same discharge period. Studies [13,35,41,44] showed that the temperature change generated by the cooling of the water mist would not create thermal shock damage to the metal.

In addition, studies carried out by NRC [41,42] demonstrated that the use of cycling discharge was capable of improving the extinguishing performance of a twin-fluid/low pressure water mist system, in comparison to continuous discharge. Cycling water mist discharge means that, during fire suppression, the discharge of water mist is turned "on" for a short period of time, followed by a short period during which the water discharge is turned "off," and this cycle is continuously repeated. When fire challenges were such that water mist could easily extinguish the fires (e.g., large spray or pool fires, compared to the size of the compartment), the reduction in the extinguishing times using the cycling discharge was not significant. However, even for these conditions, the amount of water required to extinguish the fire was reduced. For more challenging fire conditions, such as small fires, shielded fires or ventilated fires, the use of cycling discharge was able to significantly reduce the extinguishing times and the water requirements, or achieved extinguishment of fires that could not be extinguished by continuous discharge. In some cases, the use of cycling discharge reduced the extinguishing time by one-half and reduced the water requirement by two-thirds, compared to continuous discharge. The improvement in fire suppression was attributed to effective oxygen depletion and the recurrent dynamic mixing generated by the cycling water mist discharge in the compartment [41,42]. More efforts, however, are needed to study the optimum cycling frequency.

Based on the demonstrated capabilities of water mist fire suppression systems in turbine enclosures, Norwegian petroleum industry platform operators and regulators have accepted water mist as an alternative to halon in turbine enclosures [1,35]. The Securiplex water mist fire suppression system has been approved for turbine compartments up to 80 m^3 in size by FMRC [44] and the Marioff Oy Hi-Fog system has been approved for compartments up to 260 m^3.

Water Mist for the Protection of Other Flammable Liquid Hazards

Water mist is also considered to be a Halon 1301 alternative in military ground combat vehicles that are mainly involved in spray fires, pool fires as well as threedimensional spill fires. The performance of water mist, together with other gaseous agents, was evaluated using various fire scenarios. The research conducted by Bolt et al. [45,46] showed that water mist was effective in providing protection against fires in combat vehicles. However, the use of water mist in combat vehicles will increase the agent volume by 199%, compared to the use of Halon 1301 [45]. This will result in the requirement for new hardware in combat vehicles. Bolt et al. [46] also indicated that freezing and electrical conductivity issues associated with the use of water mist in the combat vehicles have to be considered.

Recently, the U.S. Army Research Laboratory conducted a series of tests to improve fire extinguishing capabilities of water at cold temperatures [47,48]. Test results demonstrated that water sprays with some freeze point suppressants, such as 60% potassium lactate and 40 wt. % potassium acetate (KAce), showed improved fire suppression performance and permitted low temperature storage and operation. The improvement in fire suppression is attributed to the fact that the evaporation of water from a salt-containing agent will lead to the formation of solid particles in the flame zone that will help quench the flames [47]. As a mist, water/additive solutions may not have a significant conductivity problem. However, water mist, together with the additive, could condense on exposed electrical equipment and shorting might occur. Also, cleanup problems caused by the water/additive need to be addressed [48]. Research in this area is still continuing.

In order to replace existing halon or CO_2 systems for fire protection in flammable liquid storerooms, the feasibility of using a total flooding water mist system in flammable liquid storerooms has been evaluated [49,50]. Six commercially-available water mist systems and two generic systems were evaluated in a simulated flammable liquid storeroom with dimensions of 3.0 × 3.0 × 3.0 m. These nozzles represented the available water mist technologies, including impinging nozzles, twin-fluid nozzles and pressure jet nozzles with different structures and working pressures (5.5 bar to 200 bar). The fire scenarios in the tests (a wood crib fire, a large pool fire and a cascading fuel fire) represented the majority of the fire threats associated with flammable liquid storerooms.

It was demonstrated that 90% of the test fire scenarios in the test program were extinguished by the water mist systems evaluated. The firefighting capabilities of the water mist systems were less than Halon 1301 but greater than conventional sprinklers. Many of the fires that could not be extinguished by conventional sprinklers were extinguished by water mist. The performance of water mist in fire suppression was strongly dependent on the characteristics of the water mist system and fire types, sizes and locations. The water mist systems, with low discharge pressure but high water flow rates, had superior performance in extinguished Class A fires due to surface wetting effects, compared to other systems with low momentum and low flow rates. The small droplets produced by high-pressure systems had superior performance against shielded/obstructed fires but their capabilities against deep-seated Class A fires were decreased.

The test results suggested that water mist technologies were capable of providing adequate protection to flammable liquid storerooms with relatively small space and somewhat simple geometry. The U.S. Navy study on the use of water mist for the protection of larger flammable liquid storerooms will continue [51].

WATER MIST ON CLASS “A” COMBUSTIBLES

The effectiveness of water mist systems against Class A fires has been confirmed in a wide range of applications. Such applications can be found in ship cabins and corridors, public spaces, residential occupancies, heritage buildings, high rack storages, and libraries [4].

Water Mist on Passenger Ships

The recent high incidence of arson fires on passenger ships prompted the IMO to require all passenger ships to have sprinkler systems fitted in accommodation spaces by 2005 or earlier. This requirement has stimulated interest in developing water mist systems for use on ordinary combustibles as equivalents to sprinkler systems [52,53] for such applications. Water mist systems can use less water and smaller diameter piping than standard sprinkler systems and so impose a lesser weight penalty. They are also more compatible with the water supply and control systems on a ship, compared to the existing sprinklers [7].

IMO has developed a test protocol to evaluate the use of water mist nozzles for fire protection in marine accommodation and public spaces [10]. Underwriters Laboratories Inc. has also proposed a first edition of a standard for water mist nozzles for this purpose [11], largely based on the IMO test procedures. Water mist systems, intended for installation in marine accommodation spaces, must be designed for Class A combustibles, such as bedding, foam mattresses, foam chairs and ordinary hazard type commodities in public areas. This IMO test protocol applies to passenger cabin areas up to 12 m^2. The public areas used for such fire tests are at least 80 m^2 in an area with no dimension less than 8 m. A water mist system that passes the IMO tests can be considered to be equivalent to a conventional, acceptable sprinkler system.

A series of tests was conducted to evaluate the use of water mist in marine cabin and public spaces by the Swedish National Testing and Research Institute, Marioff Oy of Finland and the Norwegian Fire Research Laboratory [25,54–56]. Fire scenarios in these tests included simulated arson fires, flashover fires and wood crib fires with open or closed doors. The effects of different types of nozzles, flux density and nozzle location on the efficiency of water mist fire suppression systems in marine accommodation spaces were investigated [25,54,55]. In these experimental programs, water mist systems were primarily evaluated to determine whether they could replace standard sprinkler systems.

Test results showed that the temperatures in cabin spaces were reduced rapidly to low levels and the fire was either controlled or extinguished as the water mist system was activated [25,54,55]. Compared to conventional sprinklers, water mist systems more effectively extinguished shielded fires and provided equivalent or better fire protection for the small cabin [57]. The performance of water mist systems was strongly dependent on the fire position, location of nozzles and water distribution patterns [54,55]. When the fire was far away from the nozzles or shielded by the upper bunk bed, high pressure water mist systems performed better in reducing heat release rate, total heat output and ceiling gas temperatures. When the fire was closer to the nozzles and unshielded, however, low pressure mist systems performed comparably or slightly better than high pressure mist systems. The effectiveness of water mist could be enhanced by early actuation (as with a smoke detector), and higher flow rates (e.g., 4.5 L/min).

Test results involving public space tests with sofa fires and wood crib fires in various configurations showed that water mist was able to control the fires but the effectiveness of water mist in controlling and suppressing fires decreased with the increase in compartment size and ceiling height [25,54,55,57]. Although there was no direct comparison with conventional sprinklers, studies suggested that water mist performance in the protection of public spaces can be either far inferior, comparable to or superior to conventional sprinklers, depending on the ceiling height, room area, nozzle actuation time, nozzle spacing and total water flow rates, as well as the generic system design [25,54,55,57]. Water mist systems must be selected or designed based on the fire scenario and compartment geometry.

Maritime authorities around the world, based on demonstrated capabilities of water mist in controlling fires in accommodation spaces on ships, will accept water mist systems that meet the IMO test protocol. Some thermally-activated sprinkler-type water mist systems have been developed and used to prevent flashover in a ship compartment and fire spread into the corridor. More work, however, is needed to investigate the relationships between the performance of water mist systems and the fire position, location of nozzles, as well as water distribution patterns. In addition, more appropriate guidelines should be written for cabins, public spaces and other areas, because it is inappropriate to utilize water mist systems with the existing installation and maintenance/inspection guidelines for automatic sprinklers [57].

Water Mist on Residential Buildings

A series of tests to study the feasibility of using water mist fire suppression technology for the protection of residential occupancies was conducted [58–60]. The UL 2167 draft standard [11] has provided residential area fire test protocols for water mist fire protection systems. Some important factors using water mist in residential occupancies, such as the performance limits, reliability, cost and corresponding design factors of water mist systems, were investigated in the tests. Various types of the water mist system were evaluated including commercial single-fluid/low pressure (2.1 to 6.9 bar) systems, single-fluid/high pressure (up to 200 bar) systems, and dual fluid/low pressure (6.9 bar air/1.4–5.5 bar water) systems. The fire scenarios used in the tests included UL 1626 and FMRC 2030 corner residential fuel packages, a bedroom fuel scenario, and a kitchen fuel scenario.

Test results showed that water mist systems were capable of providing fire protection at lower total flow rates than that of typical residential sprinklers (for the same challenging fire, a total water supply of 45 Lpm for water mist, compared to 70–100 Lpm for residential sprinklers). Primary factors affecting the fire control or extinguishment by water mist in the residential occupancies were drop size distribution, spray distribution in the enclosure, and spray penetration to the fuel location.

The small water requirements of water mist for fire suppression have made water mist systems suitable for use in residential occupancies that have limited water supplies. However, more efforts are needed in reducing the cost for producing fine water mist, or increasing extinguishing performance of water mist under low discharge pressure. Based on these studies, recommendations for approval testing and installation standards of water mist systems in residential occupancies have been made by FMRC [60].

Water Mist in Library Settings

The potential to use water mist in heritage buildings and library settings has also been investigated [61–64]. During fire suppression in library settings, librarians want not only the fire to be effectively controlled, but also water damage to books to be minimized.

Milke and Gerschefski have reported their water mist research for library applications [63]. The tests were conducted in a 7.92 × 3.96 × 2.29 m room. Three rows of book shelves with 500 hard and softbound books were located at one end of the room. The water mist system evaluated in the tests was a single fluid, high pressure system (69 bar). The nozzles were installed in the aisles and in the flue space. With the activation of water mist systems, the fire damage to the documents was controlled, and room temperatures quickly decreased. Post-fire observations found that folded newsprint two shelves above the fire had only suffered a minor amount of discoloration along the edge nearest the flue, and the newsprint above this shelf showed no signs of damage.

Mawhinney [64] further tested a prototype single-fluid/high-pressure water mist system for fixed library shelves, similar to those in the rare book vaults of the Library of Congress in Washington, DC. The fire scenarios included one involving archival materials on shelves, and another involving librarians' materials on a work cart in the center of an aisle. During the tests, two approaches to the design of water mist system for the protection of libraries were tested: one based on "total compartment application" in which water mist is discharged from open nozzles into all portions of the compartment, and a second based on a "zoned application" in which the compartment is divided into several zones and nozzles in each zone are activated on a signal from the detection system that pinpointed the location of the fire.

For total compartment application in the tests, the fire was controlled when the mist system was activated 50 s after ignition. However, the fire was unable to be controlled by water mist when the system was activated 100 s after ignition. The tests also showed that the majority of the water discharged in a total compartment application was wasted in areas far removed from the fire and caused water damage to the materials.

For the zoned application in the tests, the fire spread across aisles was effectively prevented, and the fire and water damage to the materials was minimized (the potentially catastrophic fire was stopped in less than 5 minutes of water application). Zoned water mist application discharged only 30% as much water as sprinklers.

The zoned application showed that water mist is able to either meet or exceed most of the fire suppression performance objectives for a water-based fire suppression system for archival applications. However, the zoned water mist system that is incorporated with detection/logic elements increases the complexity and cost of the system for the protection of library settings. In order to move from the prototype to a finished design of the zoned water mist system, further work will be required to simplify the system, ensure reliability and reduce installation costs.

WATER MIST ON AIRCRAFT

The feasibility of using water mist fire suppression systems for aircraft applications has been evaluated. These applications included the protection of onboard cabin and cargo compartments, and the protection of military aircraft engine nacelles, dry bays and fuel tanks.

Water Mist on Aircraft Cabin

A fine water spray fire control system for aircraft passenger compartments was evaluated and developed in the 1980s by an international consortium involving many aviation administrations and aviation industry agencies [1]. The performance objective of water mist systems in aircraft cabins was to prevent spread of fire into the cabin from an external pool fire and to cool the hot gases in the cabin to extend the available time for passenger evacuation and to have a greater evacuation rate of passengers [65].

During a series of full-scale fire tests, the capabilities of water mist systems, using both total flooding and zoned applications to extend the survivable time for passengers, were evaluated [1,65–69]. For the total flooding application, a large number of small nozzles were mounted throughout the ceiling of the cabin discharging fine water spray (mean droplet diameter of about 100 microns) for a period of 3 min.

In either a narrow-body test (120 nozzles discharging 272.5 L) or a wide body test (324 nozzles discharging 738 L of water) [66], water mist prevented flashover, cooled the cabin, reduced the production of toxic gases and maintained high oxygen concentration in the cabin. A survivable environment was maintained for the 7 min test duration. Compared to non-discharge of water mist, the increase in survivability was much greater than 2 min.

In order to improve the weight penalty associated with the water mist system, a zoned mist system was designed, tested and optimized in the cabin. The water mist system in the cabin was divided into a series of water spray zones, and water mist discharge within each zone was triggered by a sensor within the zone [65,71]. In the narrow-body test, with only 15.1 L of water, the zoned system was effective and increased available escape time by 53 s. Compared to the total application, visibility in the cabin was also improved by the zoned system, because disruption of the smoke layer by discharge of water mist was confined to the spray zones. In the wide-body test, 79.5 L of water provided a significant increase in survival time, ranging from 86 to 103 s.

These studies on the performance of water mist for the protection of aircraft cabins demonstrate that a zoned cabin water spray system is effective, safe and practical. Further development of a cabin water mist system, however, was discontinued after an industry-wide cost benefit study concluded that the cost of outfitting a fleet of aircraft with passenger-compartment water mist systems would be too high, compared to the benefits [70]. Lewis [71] indicated that further optimizing water mist systems for use in aircraft cabins, together with public pressure, may restart the interest in the use of water mist. The potential benefits of using a cabin water mist system may be even more pronounced in the future for high capacity double-decked airplanes [66].

Water Mist on Aircraft Cargo

The potential for using water mist in providing aircraft cargo fire protection has also been investigated [66,72]. Current aircraft cargo compartments are protected with Halon 1301 total flooding fire suppression systems. With the recent phase-out of halon gases, aircraft manufacturers and airlines generally favored a gaseous halon replacement agent in cargo compartments. However, currently-available gaseous halon replacements have some disadvantages, such as additional weight and volume, corrosivity for equipment, toxicity of combustion by-products, unknown future environmental restrictions, and high cost [66]. In order to evaluate water mist as a halon alternative in cargo compartments, a series of full-scale tests was conducted by the Federal Aviation Administration [65,66]. A cargo fire may be a deep-seated fire, potentially involving a wide variety of cargo and baggage materials. The performance objective of water mist systems in an aircraft cargo compartment is to provide the period of protection (180 min in some cases) that will allow the airplane to be landed safely.

During tests conducted by Marker et al. [66], the performance of both dual fluid/low pressure and single fluid/high pressure water mist systems were evaluated. Test results showed that the dual fluid system was effective in controlling the cargo fire, but the required water quantity was excessive, ranging from 303 to 416 L. The use of a high pressure water mist system exhibited some reduction in the water quantity requirement. In subsequent cargo container fire tests, the fire was controlled for 90 min by utilizing only 130 L of water, when a high pressure water mist system was used.

Water mist technology for providing protection in cargo compartments is continuing to develop. In Europe, a major R&D program for water mist fire suppression systems in cargo compartments was recently initiated by a consortium of organizations [72]. They will conduct a series of tests of water mist fire suppression systems using the fire test methodology and fire threats outlined in the draft minimum performance standard for a cargo compartment.

Water Mist on Aircraft Engine Nacelles

The utilization of water mist systems for fire protection of aircraft engine nacelles and explosion suppression in dry bays and fuel tanks was recently considered by the U.S. Naval Air Warfare Center (NAWC) [73–75]. Class B flammable liquid fires and high-explosive incendiary explosions are the main threats in an engine nacelle, dry bays and fuel tanks. Currently there is no design for an active explosion suppression system on board U.S. Navy aircraft.

Full-scale tests using water mist systems in engine nacelles, dry bays and fuel tanks, were conducted by the U.S. Naval Air Warfare Center [73–75]. These included the evaluation of two types of fine water mist nozzles (dual fluid and single fluid nozzles), the measurement of mist parameters, the use of heated water, and the development of design criteria under different fire scenarios and different air temperatures (–40°C to 20°C). The tests were conducted in a dry bay simulator and the nozzles were placed at various locations. It was shown that nozzles, which can produce fine water droplets with high velocity, are the most effective in extinguishing spray fires (2 s extinguishing time for an open bay fire). The fine water mist also provided excellent cooling capability (the high momentum nozzle cooled the fuel below the flash point in 5 s using 0.136 L of water).

Weight restrictions and the efficiency of water mist systems under cold operating temperatures are two major concerns for the use of water mist systems in aircraft engine nacelles. The tests conducted by DeSipio [75] showed that water mist systems, which were capable of operating at low ambient temperatures with additives in the water, could be designed successfully for applications in aircraft dry bays. High mass flows were more effective in extinguishing the dry bay fire threats. However, it was noted that water mist could not be treated as a total flooding extinguishing agent in the engine nacelle and dry bays due to the large number of obstructions [73]. The performance of water mist in these spaces was dependent on the nozzle location, water mass flow, spray characteristics and temperature [73]. Optimum configurations on nozzle location must be determined for individual applications, based on geometry and clutter arrangements. Studies on the use of water mist in suppressing explosions in engine nacelles and dry bays are continuing.

WATER MIST ON ELECTRONIC EQUIPMENT

Fires in switch gear cabinets and telecommunication control rooms are usually small and slow-growing [76,77]. Available fuels in such spaces range from cables with plastic coatings, circuit boards and wiring inside cabinets to plywood, paper and tape cartridges. The most serious threat to the property and the function of the equipment is the spread of corrosive smoke throughout the facility [77,78]. The main concerns for using fine water sprays on electronic and electrical equipment to replace current halon or CO_2 are the electrical conductivity of the water (that could lead to equipment damage and shock hazard to personnel), as well as pitting or corrosion of chips and connectors [78].

The fire protection community has, for a long time, recommended sprinklers in computer and other electronic rooms with the belief that the water damage is certainly no worse than the damage from an uncontrolled fire [79]. The technology to dry out and recommission electronic equipment has improved dramatically over the past several years. Water mist systems, with less water requirement than sprinklers to extinguish a fire, will have minimal, if any, water damage to the electronic environment.

Recently, extensive full-scale fire tests have been conducted to evaluate the feasibility of using water mist systems for the protection of electrical and electronic equipment [31,76–85]. The fire scenarios were similar to those that may occur in computer rooms, electrical switchgear cabinets, cables and main telephone exchange distribution frames. The water mist systems and their arrangements in the tests included conical and linear sprays in cabinets, single-point discharge nozzle with superheated water and lines of nozzles in cables. Some tests were conducted on live electrical circuits and energized electrical equipment, including three phase-450 VAC motors, motor controller, and switchboard [31,80].

Studies [80–82] showed that fine water mist was effective in extinguishing in-cabinet electronic fires, as well as fires in a computer room, without causing short circuits or other damage to electrical and electronic components. Water mist did not cause a serious electrical leakage over the test circuits nor did it produce a significant signal degradation [80]. Telephone calls were both received and sent while the test telephone exchange main distribution frame was sprayed with water. These calls remained completely unaffected by the drenching. Recent studies carried out by Applied Physics Laboratory/Johns Hopkins University [31] showed that shock hazards could only exist after a sustained mist flow, which results in plating out or pooling of water on an electrical equipment surface. There was essentially no current leakage for motors or motor controllers. The shock hazard with switchboards generated by water mist was negligible if the boards were clean and properly grounded.

Water mist has also demonstrated some advantages in suppressing fires in electrical and electronic equipment, in comparison to gaseous agents. For example, water spray appears to be the most effective extinguishant for a hot cable fire due to its efficient cooling, while other methods, such as smothering with CO_2, or flame inhibition by halon, failed to extinguish a flaming cable fire once the heat of combustion had penetrated to the copper conductors and temperatures exceeded the auto-ignition temperature of the plastics [80]. In addition, evacuation of the compartment may not be necessary and the electronic equipment can continuously be operated during discharge of the water mist system, especially if a zoned water mist system is used. On the contrary, when halocarbon gaseous agents are used, the compartment has to be evacuated completely due to high concentrations of corrosive gases generated by the agent in fire suppression, thus disabling the operation of the room [83]. The spread of thermal decomposition products in the compartment, such as HF, will further cause potential corrosion damage to the electronic facilities that are protected by the gaseous agents.

Water mist can also remove smoke and associated corrosive gases from electronic facilities [84,85]. Marioff Oy [85] has recently developed a water mist smoke scrubbing system for the sub-floor space. The scrubbing pipework is mounted around the periphery of the sub-floor area and special spray nozzles are located inside each tube section. The water mist system is a hybrid system that consists of two fluids, high-pressure nitrogen and water, using one pipe network. When the system is activated, the mist system provides a strong venturi effect where air, smoke and combustion products are sucked into the pipework and scrubbed by the ultra-fine water spray. The water mist containing the smoke and combustion products then condenses at the pipework bend and are collected for later retrieval. At the same time, the fires in the sub-floor are extinguished by the fine airborne water mist together with the nitrogen that escapes from the distribution pipes. Test results [85] showed that such a mist system extinguished small telltale fires and candle fires in the sub-floor space and in the cabinet, and harmful smoke (CO, HCl and CH_4) was significantly reduced.

The extinguishment performance of the water mist systems on electronic equipment was mainly determined by the spray characteristics of the water mist systems, their configuration in the compartment, the fire size, the degree of obstruction, the ventilation conditions, and compartment geometry. Grosshandler et al. [79] carried out a series of fire tests to study the performance of an externally-located nozzle with high discharge pressure in extinguishing an in-cabinet fire. During the tests, influence on extinguishing efficiency of the nozzle geometry, location relative to the fire, water application rate and the amount of shielding surrounding the fire within the simulated cabinet was examined. Test results showed that external fine water sprays were not effective against deep-seated fires within electronics cabinets. Extinguishment was possible only at a high pressure (5.5 MPa), with the object on the spray centerline, and with at least 40% of the top area of the cabinet directly open to the spray.

In order to enhance the effectiveness of water mist as a halon alternative to protect facilities with substantial amounts of electronic equipment, the National Research Council of Canada (NRC) [76–78] has initiated the IntelMist™ project. The basic principle of the IntelMist™ system is the use of state-of-the-art fire detection technology to control a zoned water-mist fire suppression system, so that water can be applied to the smallest possible area directly associated with a fire. The design parameters of a zoned water-mist fire suppression system examined in the IntelMist™ project included the water droplet size, spray angle, spray momentum, nozzle location as well as flow rate.

The experimental investigations, conducted in electronic cabinets, under floor cable plenums and overhead cable trays by NRC [76–78], demonstrated that water mist was able to effectively suppress fires in the electronic equipment. However, the traditional total-flooding approach (used with Halon 1301), whether in a single cabinet, an under-floor plenum or a large space with many cable trays, was unreliable when applied to water mist. Only by exercising rigorous control over spray direction to the hazard could reliable fire suppression be achieved using a water mist system. Coarser sprays ($200 < D_{v0.9} < 400$ microns), which produced wetting of surfaces and water dripping down into recessed areas, demonstrated better performance than very fine sprays ($D_{v0.9} < 90$ microns) against fires in electronic equipment. Very fine mists tended to drift beyond the intended area of application, increasing humidity throughout the cabinet.

The IntelMist™ project [76–78] also determined the detection system characteristics required to accurately locate a fire in electronic equipment. The tests were conducted to measure the strength of thermal signals from small fires in electronic equipment under ventilated and non-ventilated conditions. The possibility of using species signatures, such as CO and HCl as part of a multi-sensor detection system, was also examined. Guidance for selecting design fires and building a detection/decision matrix integrated with an early-detection system was provided.

Current studies have demonstrated the capability of water mist as a potential solution in replacing existing suppression systems in electronic facilities. A water mist smoke scrubbing system has been used for the protection of computer rooms and other high technology equipment. Further efforts, however, are required to develop a zoned water mist system incorporated with intelligent detection/logic elements, and to enhance the efficiency of water mist systems in scrubbing smoke and extinguishing fires in complex geometry. Such studies are continuing to be carried out by many research organizations, manufacturers and the U.S. Navy [31,85].

WATER MIST IN OTHER APPLICATIONS

Water mist applications in many areas are still continuing to expand. Recently, Underwriters Laboratories Inc. and Underwriters' Laboratories of Canada have listed one portable water mist fire extinguisher [86] for use on Class A and C fires. It is shown that a portable water mist extinguisher is capable of extinguishing Class A fires and the discharge of water mist does not cause electrical shock to the user when the extinguisher is used against energized electrical targets. Such a portable water mist extinguisher can be used for fire protection in hospitals, telecommunication facilities and health care facilities.

The National Research Council of Canada [88], in collaboration with Fountain Fire Protection Inc., has recently carried out a research project using a water mist fire suppression system for the protection of commercial cooking areas. Cooking oil or fat fires in cooking areas are the most difficult fires to be extinguished, because they burn at a high temperature and re-ignite easily. They cannot be effectively extinguished by foam, powder or carbon dioxide. Recently, cooking oil fires have been classified as a new class fire, Class K. Wet chemical agent is a major agent currently used in cooking areas. It extinguishes the cooking oil fire in 3 to 5 s but it takes a long time for the wet chemical agent to cool the oil below its auto-ignition temperature, which will increase re-ignition opportunities in the cooking oil [87]. Another concern is the toxic combustion by-products generated by the wet chemical agent during fire suppression that may result in evacuation of the cooking area as well as the whole restaurant immediately, and increase the clean-up time.

During the NRC tests, the extinguishing performance of water mist against the cooking oil fires was evaluated in a mock-up cooking area, following UL 300 "Standard for Fire Testing of Fire Extinguishing Systems for Protection of Restaurant Cooking Areas." The tests showed that water mist can effectively extinguish and cool cooking oil fires. In comparison to agents currently used in cooking areas, water mist is able to provide cost-effective protection for commercial cooking areas.

The feasibility of using water mist fire suppression systems for the protection of heavy goods vehicle (HGV) shuttle trains has been evaluated. The Eurotunnel [89] is developing an onboard fire suppression system for its HGV shuttle fleet. They have evaluated the performance of one low pressure water mist system (2–7 bar) and one high pressure water mist system (80–100 bar) in a 19.3 × 4.4 × 3.7 m HGV wagon. The low pressure water mist system comprised 14 nozzles per wagon side with a total water delivery of 500 L/min, while the high pressure water mist system comprised 25 nozzles per wagon side with a water delivery of 300 L/min. The fire loads used in the tests included up to 2 tonnes of new wooden pallets and mixed loads of empty cardboard boxes and EU standard plastic commodity. Test results showed that the on-board fire suppression system provided the ability to inhibit the spread of fire to adjacent vehicles, reducing collateral damage. The high pressure water mist system was more effective in fire protection (in terms of fire load saved and in cooling the tunnel atmosphere) than a low pressure water mist system. The high pressure mist system with low water delivery rate also increased the protection time for the HGV wagon.

The U.S. Navy has recently initiated a program to use a small self-contained water mist system for the protection of miscellaneous shipboard spaces, including flammable liquid storerooms, paint issue rooms, emergency diesel generators, and fuel pump rooms [31,90,91]. In this research program, performance of the hybrid inert gas/water mist systems will be evaluated for the protection of small shipboard compartments. It is believed that the hybrid water mist systems show the greatest potential for meeting performance objectives, because existence of inert gas in the compartment will further reduce oxygen concentration and increase water mist capabilities against fires, especially against small obstructed fires [90,91].

Another program, recently initiated by the U.S. Navy, is to use water mist as a possible total-ship protection method as well as for selected applications for flashover suppression in shipboard compartments and boundary cooling [31,92]. Studies conducted to date [92] have shown that flashover suppression can be achieved easily by using low water application rates and widely-spaced nozzles in ventilation-limited spaces with low ceilings. Ceiling temperatures dropped below 150°C with the injection of water mist. Boundary cooling has also been achieved with flashover suppression, and there is not sufficient heat transfer through boundaries to ignite combustibles in adjacent compartments. The next step of the program, based on the current studies, will develop design criteria for a water mist system that requires a lower discharge rate than commercial systems, but still provides a degree of fire control for flashover suppression.

SUMMARY

Water mist fire suppression systems have demonstrated their capabilities in extinguishing Class A, B, C, and K fires with effective cooling, non-toxicity, low cost, less water requirement, less water damage, and less clean-up time. They provide effective means in removing smoke and the associated corrosive gases from the compartment, and in extinguishing ventilated fires that cannot be extinguished by gaseous agents.

As a result, water mist fire suppression systems have been used in many applications, including the protection of machinery spaces, pump rooms, gas turbine enclosures, marine accommodations and public spaces. They are being considered/used for the protection of residential occupancies, heritage buildings, libraries, electronic environments, aircraft, commercial cooking areas, industrial oil cookers and combat vehicles. Studies on the use of water mist in other areas, such as for the protection of small shipboard compartments, and for flashover suppression in shipboard compartments and boundary cooling, are continuing.

The effectiveness of water mist in fire suppression is determined by many factors, including spray characteristics of a water mist system, its configuration in the compartment, fire size, the degree of obstruction, the ceiling height and ventilation rate in the compartment. For the protection of those sensitive and valuable compartments with complex geometry, such as libraries, aircraft and rooms containing electrical and electronic equipment, the total-flooding water mist approach is unreliable. Only by exercising zoned water mist systems directed to the hazard could reliable fire suppression be achieved.

It is important to evaluate the capabilities and limitations of water mist systems in applications, based on corresponding test and design criteria. Such test and design criteria have been established in some applications—machinery spaces, turbine enclosures, marine accommodation spaces, and industrial cookers. The limitation and capability of water mist systems in some applications, such as in restaurant cooking areas, can be evaluated following existing test protocols. However, there is no consensus yet on test protocols for many other applications, such as heritage properties, libraries, electronic environments, etc. More efforts in developing corresponding test protocols are required.

Good progress on improving water mist effectiveness in fire suppression has been made over the last decade. New methods include the combination of both total flooding and local applications, cycling water mist discharge mode, hybrid water mist systems, as well as the intelligent water mist system that combines zoned water mist application with intelligent detection. In order to further apply these new technologies in fire suppression, however, more research efforts are needed, including studies on optimum cycling frequency in the cycling discharge mode; reliable and cost-effective intelligent water mist systems, as well as the performance of hybrid water mist systems in the practical applications.

REFERENCES

1. Mawhinney, J.R., "Principles of Water Mist Fire Suppression Systems," NFPA Handbook—18th Edition, 1997.
2. Tatem, P.A., Beyler, C.L., DiNenno, P.J., Budnick, E.K, Back, G.G. and Younis, S.E., "A Review of Water Mist Technology for Fire Suppression," Naval Research Laboratory, NAL/MR/6180-94-7624, 1994.

3. NFPA 750, "Standard for the Installation of Water Mist Fire Protection Systems," 1996 Edition, National Fire Protection Association, Quincy, MA, 1996.
4. Notarianni, K.A., "Water Mist Fire Suppression Systems," Proceedings of Technical Symposium on Halon Alternatives, Society of Fire Protection Engineers and PLC Education Foundation, Knoxville, TN, 1994.
5. Back, G.G. "An Overview of Water Mist Fire Suppression System Technology," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1994, p. 327.
6. Mawhinney, J.R. and Richardson, J.K., "A Review of Water Mist Fire Suppression Research and Development," Fire Technology, Vol. 33, No. 1, 1997, pp. 54–90.
7. Mawhinney, J.R., "Engineering Criteria for Water Mist Fire Suppression Systems," Proceedings: Water Mist Fire Suppression Workshop, NIST, Gaithersburg, MD, 1993, p. 37.
8. Mawhinney, J.R., "Water Mist Fire Suppression Systems: Principles and Limitations," International Conference on Fire Protection in the HVDC Industry, Vancouver, Canada, 1995.
9. International Maritime Organization (IMO), "MSC/Circ. 668, ANNEX, APPENDIX A (Component manufacturing standards of equivalent water-based fire extinguishing systems) and APPENDIX B (Interim test method for equivalent water-based fire-extinguishing systems for machinery spaces of Category A and cargo pump rooms)," London, 1994.
10. International Maritime Organization, "Res.A. 800(19), ANNEX, APPENDIX A (Component manufacturing standards for water mist nozzles) and APPENDIX B (Fire test procedures for equivalent sprinkler systems in accommodation, public space and service areas on passenger ships)," London, 1995.
11. Underwriters Laboratories Inc., "First Edition of the Standard for Water Mist Nozzles for Fire Protection Service," UL 2167, Northbrook, IL, Jan. 1996.
12. Factory Mutual Research Corporation, "Draft Performance Requirements for Fine Water Spray Systems for the Protection of Machinery Spaces," Norwood, MA, 1996.
13. Dyer, J.H., "Water Mist Fire Suppression Systems: Application Assessment Tests on Full Scale Enclosure," Fire Engineers Journal, November 1997.
14. Kim, A., Mawhinney, J. and Su, J., "Water-mist System Can Replace Halon for Use on Electrical Equipment," Canadian Consulting Engineer, May/June, 1996, p. 30.
15. Liu, Z. and Kim, A.K., "A Review of Water Mist Fire Suppression Systems—Fundamental Studies," Journal of Fire Protection Engineering, Vol. 10, No. 3, 2000, pp. 32–50.
16. Mawhinney, J. R., Back, G.G., "Bridging the Gap Between Theory & Practice: Protecting Flammable Liquid Hazards Using Water Mist Fire Suppression Systems," Fire Suppression and Detection Research Application Symposium, Orlando, Florida, 1998.
17. Edwards, M. and Watkins, S., "Further Evaluation of Water Mist for the Royal Navy," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1997, p. 528.
18. Back, G.G., DiNenno, P.J., Leonard, J.T. and Darwin, R.L., "Full Scale Tests of Water Mist Fire Suppression Systems for Navy Shipboard Machinery Spaces: Part II—Obstructed Spaces," Naval Research Laboratory, NRL/MR/6180-96-7831, 1996.
19. Back, G.G., "Full Scale Tests of Water Mist Fire Suppression Systems for Navy Shipboard Machinery Spaces," Fire Safety Science—Proceedings of Fourth International Symposium, 1996, pp. 435–444.
20. Darwin, R.L., Leonard, J.T. and Back, G.G., "Development of Water Mist Systems for US Navy Shipboard Machinery Spaces," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1995, p. 411.
21. Leonard, J.T., Darwin, R.L and Back, G.G., "Full Scale Tests of Water Mist Fire Suppression Systems for Machinery Spaces," International Conference on Fire Research and Engineering, USA, 1995, pp. 109–114.
22. Darwin, R.L., "Water Mist Systems for US Navy Ships," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1997, p. 516.

23. Kim, A. K., Liu, Z. and Su, J.Z., National Research Council of Canada, Private Communication, 1997.
24. Buckley, C. and Rush, D., "Water Mist Developments for the Royal Navy," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1996, p. 37.
25. Turner, A.R.F., "Water Mist in Marine Applications," Proceedings: Water Mist Fire Suppression Workshop, U.S.A., 1993, pp. 105–122.
26. Pepi, J.S., "Performance Evaluation of a Low Pressure Water Mist System in a Marine Machinery Space with Open Doorway," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1995, p. 424.
27. Pepi, J.S., "Advances in the Technology of Intermediate Pressure Water Mist Systems for the Protection of Flammable Liquid Hazards," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1998, p. 417.
28. Bill, R.G., Hansen, R.L. and Richards, K., "Fine-Spray (Water Mist) Protection of Shipboard Engine Rooms," Fire Safety Journal, Vol. 29, 1997, p. 317.
29. Back, G.G., DiNenno, P.J., Hill, S.A. and Leonard, J.T., "Full-Scale Testing of Water Mist Fire Extinguishing Systems for Machinery Spaces on U.S. Army Watercraft," Naval Research Laboratory, NRL/MR/6189-96-7814, 1996.
30. Williams, F.W., Back, G.G., DiNenno, P.J., Darwin, R.L., Hill, Havlovick, S.S., Toomey, T.A., Farley, J.P. and Hill, J.M., "Full-Scale Machinery Space Water Mist Tests: Final Design Validation," Naval Research Laboratory, NRL/MR/6180-99-8380, 1999.
31. Darwin, R.L. and Williams, F.W., "Overview of the Development of Water-Mist Systems for US Navy Ships," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1999, p. 373.
32. Edwards, M., Watkins, S. and Glockling, J., "Low Pressure Water Mist, Fine Water Spray, Water Source and Additives: Evaluation for the Royal Navy," 8th International Fire Science and Engineering Conference, Edinburgh, Scotland, 1999.
33. Back, G.G. and Williams, F.W., "Full Scale Evaluation of the Water Mist Additive QUAD-EX," NRL Ltr Rep Ser 6180/0027, Washington, DC, 1997.
34. Hansen, R., "Local Application of Water Mist for Machinery Protection," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1998, p. 439.
35. Wighus, R., Aune, P., Drangsholt, G. and Stensaas, J.P., "Full Scale Water Mist Experiments," International Conference on Water Mist Fire Suppression Systems, Sweden, 1993.
36. Wighus, R., "Engineering Relations for Water Mist Fire Suppression Systems," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1995, p. 397.
37. Ural, E.A. and Bill, R.G., "Fire Suppression Performance Testing of Water Mist Systems for Combustion Turbine Enclosures," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1995, p. 449.
38. Gameiro, V.M., "Fine Water Spray Fire Suppression Alternative to Halon 1301 in Gas Turbine Enclosures," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1993, p. 317.
39. Berner, F. and Vemmestad, J., "Development of Fine Water Spray Technology for Application on BP Norwegian Continental Shelf Offshore Installations ULA and GYDA," Proceedings: Halon Alternatives Conference, Phoenix, AZ, 1993.
40. Bill, R.G., Jr. and Croce, P.A., "Perspectives on Fine Sprays (Water Mist) Technology at FMRC," International Conference on Water Mist Fire Suppression Systems, Sweden, 1993.
41. Liu, Z., Kim, A.K. and Su, J.Z., "Improvement of Efficacy of Water Mist in Fire Suppression by Cycling Discharges," 2nd International Conference on Fire Research and Engineering, Gaithersburg, MD, 1997.
42. Liu, Z., Kim, A.K. and Su, J.Z., "Examination of Extinguishment Performance of a Water Mist System Using Continuous and Cycling Discharges," Fire Technology, Vol. 35, No. 4, 1999, p. 336.

43. Liu, Z., Kim, A.K. and Su, J.Z. "The Effect of Air Convection on the Performance of Water Mist Fire Suppression Systems," 7th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Albuquerque, NM, 1998.

44. Ural, E.A. and Bill, R.G., Jr., "Fire Performance Tests of Securiplex Fine Water Spray System for Combustion Turbine Enclosure Protection in an 80 m^3 Volume," Factory Mutual Research, Technical Report: FMRC J.l. 0Y0R3.Rm, March 1995.

45. Bolt, W., Erdley, D. and Herud, C., "Current Status of the Halon Replacement Program for Army Ground Combat Vehicles," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1995, p. 467.

46. Bolt, W., Herud, C., Treanor, T. and McCormick, S., "A Status Report: Halon Replacement Program for Combat Vehicles," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1996, p. 87.

47. Finnerty, A.E., "Water-Based Fire-Extinguishing Agents," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1996, p. 461.

48. McCormick, S., Clauson, M. and Cross, H., "US Army Ground Vehicle Halon Replacement Programs," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1999, p. 27.

49. Back, G.G., DiNenno, P.J., Hill, S.A. and Leonard, J.T., "Evaluation of Water Mist Fire Extinguishing Systems for Flammable Liquid Storeroom Applications on US Army Watercraft," Naval Research Laboratory, NRL/MR/6180-95-7795, 1995.

50. Back, G.G., "An Experimental Evaluation of Water Mist Fire Suppression System Technology Applied to Flammable Liquid Storeroom Applications," Proceedings: International Conference on Fire Research and Engineering, USA, 1995, p. 103.

51. Maranghides, A. and Sheinson, R.S., "NRL-Chesapeake Bay Detachment: Full-Scale Fire Test Platform," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1999, p. 373.

52. NFPA 13, "Standard for the Installation of Automatic Sprinkler Systems," National Fire Protection Association, Quincy, MA, 1995.

53. Back, G.G., "1995 Progress Report: Water Mist Fire Suppression System Technologies," SFPE Bulletin, Fall 1995, p. 11.

54. Arvidson, M., "The Efficiency of Different Water Mist Systems in a Ship Cabin," International Conference on Water Mist Fire Suppression Systems, Sweden, 1993.

55. Jacobsen, S.E., "Approval of Water Mist Systems on Ships, Consideration of Equivalency to Sprinkler and Water Spray Systems," International Conference on Water Mist Fire Suppression Systems, Sweden, 1993.

56. SINTEF NBL—Norwegian Fire Research Laboratory, Annual Report, 1995.

57. Zalosh, R. and Gallagher, G., "Water Mist Sprinkler Requirements for Shipboard Fire Protection," CG-D-28-96, Center for Firesafety Studies, Worcester Polytechnic Institute, MA, 1996.

58. U.S. Fire Sprinkler Reporter, "Limited Water Supply Fire Suppression Technologies Demonstrated at NIST," April 1996.

59. Budnick, E.K., "USFA Residential Water Mist Test Program (Initial Feasibility)," presented at National Institute of Standards and Technology, Gaithersburg, MD, USA, 1996.

60. Bill, R.G., "Water Mist in Residential Occupancies," Factory Mutual Research Corporation, Norwood, MA, 1996.

61. Log, T. and Cannon-Brookes, P., "Water Mist for Fire Protection of Historic Buildings and Museums," Museum Management and Curatorship, Vol. 14, No. 3, 1995, pp. 283–298.

62. Meland, O., Jensen, G. and Sjur, H., "Water Mist to Protect Wooden Historic Structures," in Proceedings: Second International Symposium on Fire Protection of Ancient Monuments, Poland, 1994.

63. Milke, J.A. and Gerschefski, C.E., "Overview of Water Research for Library Applications," Proceedings: International Conference on Fire Research and Engineering, USA, 1995, p. 133.

64. Mawhinney, J.R., "A Linear Water Mist Fire Suppression System for Fixed Shelving in Archival Vaults," Proceedings: International Conference on Fire Research and Engineering, USA, 1997.
65. Marker, T.R., Sarkos, C.P. and Hill, R.G., "Water Spray System Development and Evaluation for Enhanced Postcrash Fire Survivability and In-Flight Protection in Cargo Compartments," 88th Symp. of the Propulsion and Energetics Panel on Aircraft Fire Safety, Oct. 1996.
66. Sarkos, C.P., "Development of Improved Fire Safety Standards Adopted by the Federal Administration," AGARD-CPP-467, Propulsion and Energetics Panel 73rd Symposium on Aircraft Fire Safety, Sintra, Portugal, 1989.
67. Hill, R.G. and Marker, T.R., "Evaluation and Optimization of an On-Board Water Spray Fire Suppression System in Aircraft," Proceedings: Water Mist Fire Suppression Workshop, USA, 1993, pp. 105–122.
68. Cousin, C.S., "The Potential of Fine Water Sprays as Halon Replacements for Fires in Enclosures," International Conference on Water Mist Fire Suppression Systems, Sweden, 1993.
69. Spring, D.J., Simpson, T., Smith, D.P. and Ball, D.N., "New Application of Aqueous Agents for Fire Suppression," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1993, p. 303.
70. Civil Aviation Authority, "International Cabin Water Spray Research Management Group: Conclusions of Research Programme," CAA Paper 93012, 1993
71. Lewis, R.H., "Aircraft Cabin Water Fire Suppression—Where to Now," Fire Prevention, Vol. 270, June 1994, p. 16.
72. Hill, R.G. and Sarkos, C.S., "Description and Status of Civil Aviation's Halon Replacement Program," 88th Symp. of the Propulsion and Energetics Panel on Aircraft Fire Safety, Oct. 1996.
73. Wolfe, J.E. and DeSipio P., "Use of Fine Water Mist for Naval Aircraft Fire Protection and Explosion Suppression," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1994, p. 335.
74. Wolfe, J.E. and DeSipio P., "Evaluation of Fine Water Mist for Application in Naval Aircraft Fire Protection and Explosion Suppression," Fluid Measurement and Instrumentation, FED-Vol. 211, ASME, 1995.
75. DeSipio P., "Evaluation of Fine Water Mist for Aircraft Dry Bay Fire Suppression," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1996, p. 27.
76. Mawhinney, J.R. and Taber, B.C., National Research Council of Canada, Private Communication, 1996.
77. Mawhinney, J.R., "Water-Mist Fire Suppression Systems for the Telecommunication and Utility Industries," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1994, p. 395.
78. Mawhinney, J.R., "Findings of Experiments Using Water Mist for Fire Suppression in an Electronic Equipment Room," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1996, p. 15.
79. Grosshandler, W., Lowe, D., Notarianni, K. and Rinkinen, W., "Protection of Dara Processing Equipment with Fine Water Sprays," NISTIR 5514, National Institute of Standards and Technology, Gaithersburg, MD, 1994.
80. Botting, R.E., "Fire Engineering and Research: Fire Detection and Protection of Telephone Exchange Main Distribution Frames, Telecom Corporation of New Zealand Ltd.," Annual Conference of the Institution of Fire Engineers (New Zealand Branch), 1990.
81. Hills, A.T., Simpson, T. and Smith, D.P., "Water Mist Fire Protection Systems for Telecommunication Switch Gear and Other Electronic Facilities," Proceedings: Water Mist Fire Suppression Workshop, USA, 1993, pp. 123–144.
82. Simpson, T. and Smith, D.P., "A Fully Integrated Water Mist Fire Suppression System For Telecommunications and Other Electronics Cabinets," International Conference on Water Mist Fire Suppression Systems, Boräs, Sweden, 1993.
83. Liu, Z. and Kim, A.K., "A Literature Review of Impact of Thermal Decomposition Products Gen-

erated by Halon Replacement on Electronic Equipment," IRC Internal Report 780, National Research Council of Canada, 1999.

84. Carlzon, B. "Fire Protection in Computer Rooms," Nordic Conference on Water Mist Applications, Swedish National Testing and Research Institute, SP Report 1997:02, 1997.
85. Tuomisaari, M., "Smoke Scrubbing in a Computer Room," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1999, p. 308.
86. Underwriters' Laboratories of Canada, "Report on 9 L Water Spray Fire Extinguisher (Stored Pressure Type)," Scarborough, ON, 1998.
87. ANSUL Inc., "Hybrid Fire Suppression Technology for Restaurant Cooking Equipment (PIRANHA™ SYSTEMS and PRX™ WET AGENT)," White Paper 1015, 1999.
88. Liu, Z. and Kim, A.K., "Fire Protection of a Restaurant Cooking Area with Water Mist System," Proceedings: 3rd International Conference on Fire Research and Engineering, USA, 1999.
89. Grant, G. and Southwood, P., "Development of an Onboard Fire Suppression System for Eurotunnel HGV Shuttle Trains," 8th International Fire Science and Engineering Conference, Edinburgh, Scotland, 1999.
90. Back, G.G., Williams, F.W., Darwin, R.L., Sheinson, R.S. and Maranghides, A., "Self-Contained Water Mist Literature Search," NRL Ltr Rpt Ser 6180/0471, Washington, DC, 1998.
91. Maranghides, A. and Sheinson, R.S., "Test Plan for Self-Contained Total Flooding Halon 1301 Alternative Technologies Evaluation – Phase I, Marioff Hi-Fog Water Mist System," NRL Ltr Rpt Ser 6180/0108, 1999.
92. Mawhinney, J R., DiNenno, P J. and Williams, F.W., "Using Water Mist For Flashover Suppression on Navy Ships," Proceedings: Halon Alternatives Technical Working Conference, Albuquerque, NM, 1999, p. 395.